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Volume 2 of 3

MASTER

FINAL

ENVIRONMENTAL IMPACT STATEMENT

Management of Commercially Generated Radioactive Waste

Volume 2
Appendices

October 1980

U.S. Department of Energy
Assistant Secretary for Nuclear Energy
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FINAL

ENVIRONMENTAL IMPACT STATEMENT

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Office of Nuclear Waste Management
Washington, D.C. 20545

VOLUME 2

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APPENDIX A

WASTE-MANAGEMENT SYSTEMS SUPPLEMENTARY DATA

Appendix A contains supplementary data on the waste management systems simulation and related information. The data are presented in tables; types of data included are:

	Tables
Waste Logistics Tables	A.1.1 - A.1.23
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Brief descriptions of the types of data are given at the beginning of each section. The associated tables then follow.

A.1 WASTE LOGISTICS TABLES

The spent fuel logistics tables (A.1.1 through A.1.23) show the disposition and transportation of spent fuel in metric tons of heavy metal (MTHM) as a function of time. These tables correspond with the graphs of repository inventories shown in Chapter 7. A table is provided for each of the cases analyzed in both the once-through and the reprocessing cycles. Total waste quantities for disposal in the reprocessing cases are shown in Tables A.1.21 and A.1.22. The age of the HLW at the time of disposal is shown in Table A.1.23.

TABLE A.1.1. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 1, MTU

No Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY RECEIPTS	REPOSITORY INVENTORY	REPOSITORY RECEIVING AGE, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	2760.	9956.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1983
1984	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1984
1985	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1985
1986	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1986
1987	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1987
1988	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1988
1989	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1989
1990	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1990
1991	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1991
1992	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1992
1993	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1993
1994	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1994
1995	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1995
1996	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1996
1997	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1997
1998	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1998
1999	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1999
2000	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2000
2001	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2001
2002	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2002
2003	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2003
2004	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2004
2005	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2005
2006	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2006
2007	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2007
2008	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2008
2009	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2009
2010	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2010
2011	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2011
2012	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2012
2013	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2013
2014	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2014
2015	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2015
2016	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2016
2017	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2017
2018	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2018
2019	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2019
2020	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2020
2021	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2021
2022	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2022
2023	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2023
2024	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2024
2025	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2025
2026	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2026
2027	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2027
2028	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2028
2029	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2029
2030	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2030
2031	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2031
2032	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2032
2033	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2033
2034	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2034
2035	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2035
2036	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2036
2037	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2037
2038	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2038
2039	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2039
2040	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2040
RAIL SHIPMENTS =			0.0	0.0		0.0				
TRUCK SHIPMENTS =			0.0	0.0						

TABLE A.1.2. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 1, MTU

1990 Repository

							REPOSITORY			
YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	2760.	9956.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1983
1984	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1984
1985	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1985
1986	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1986
1987	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1987
1988	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1988
1989	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1989
1990	0.	9256.	0.	700.	0.	0.	700.	700.	18.0	1990
1991	0.	7956.	0.	1300.	0.	0.	1300.	2000.	16.4	1991
1992	0.	5956.	0.	2000.	0.	0.	2000.	4000.	15.3	1992
1993	0.	3956.	0.	2000.	0.	0.	2000.	6000.	14.4	1993
1994	0.	2760.	0.	1196.	0.	0.	1196.	7196.	14.0	1994
1995	0.	0.	0.	2760.	0.	0.	2760.	9956.	14.0	1995
1996	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	1996
1997	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	1997
1998	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	1998
1999	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	1999
2000	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2000
2001	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2001
RAIL SHIPMENTS =			0.0	2274.2		0.0				
TRUCK SHIPMENTS =			0.0	2315.3						

TABLE A.1.3. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 1, MTU

2010 Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY			YEAR
							RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	2760.	9956.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1983
1984	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1984
1985	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1985
1986	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1986
1987	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1987
1988	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1988
1989	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1989
1990	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1990
1991	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1991
1992	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1992
1993	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1993
1994	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1994
1995	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1995
1996	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1996
1997	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1997
1998	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1998
1999	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1999
2000	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2000
2001	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2001
2002	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2002
2003	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2003
2004	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2004
2005	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2005
2006	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2006
2007	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2007
2008	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2008
2009	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2009
2010	0.	9256.	0.	700.	0.	0.	700.	700.	38.0	2010
2011	0.	7956.	0.	1300.	0.	0.	1300.	2000.	36.4	2011
2012	0.	5956.	0.	2000.	0.	0.	2000.	4000.	35.3	2012
2013	0.	3956.	0.	2000.	0.	0.	2000.	6000.	34.4	2013
2014	0.	2760.	0.	1196.	0.	0.	1196.	7196.	34.0	2014
2015	0.	0.	0.	2760.	0.	0.	2760.	9956.	34.0	2015
2016	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2016
2017	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2017
2018	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2018
2019	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2019
2020	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2020
2021	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2021
RAIL SHIPMENTS =			0.0	2274.2		0.0				
TRUCK SHIPMENTS =			0.0	2315.3						

TABLE A.1.4. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 1, MTU

2030 Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY			YEAR
							RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	2760.	9956.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1983
1984	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1984
1985	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1985
1986	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1986
1987	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1987
1988	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1988
1989	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1989
1990	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1990
1991	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1991
1992	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1992
1993	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1993
1994	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1994
1995	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1995
1996	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1996
1997	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1997
1998	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1998
1999	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	1999
2000	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2000
2001	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2001
2002	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2002
2003	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2003
2004	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2004
2005	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2005
2006	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2006
2007	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2007
2008	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2008
2009	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2009
2010	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2010
2011	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2011
2012	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2012
2013	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2013
2014	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2014
2015	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2015
2016	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2016
2017	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2017
2018	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2018
2019	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2019
2020	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2020
2021	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2021
2022	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2022
2023	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2023
2024	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2024
2025	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2025
2026	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2026
2027	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2027
2028	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2028
2029	0.	9956.	0.	0.	0.	0.	0.	0.	0.0	2029
2030	0.	9256.	0.	700.	0.	0.	700.	700.	58.0	2030
2031	0.	7956.	0.	1300.	0.	0.	1300.	2000.	56.4	2031
2032	0.	5956.	0.	2000.	0.	0.	2000.	4000.	55.3	2032
2033	0.	3956.	0.	2000.	0.	0.	2000.	6000.	54.4	2033
2034	0.	2760.	0.	1196.	0.	0.	1196.	7196.	54.0	2034
2035	0.	0.	0.	2760.	0.	0.	2760.	9956.	54.0	2035
2036	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2036
2037	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2037
2038	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2038
2039	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2039
2040	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2040
2041	0.	0.	0.	0.	0.	0.	0.	9956.	0.0	2041
RAIL SHIPMENTS =			0.0	2274.2		0.0				
TRUCK SHIPMENTS =			0.0	2315.3						

TABLE A.1.5. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 2, MTU

No Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY RECEIPTS	REPOSITORY INVENTORY	REPOSITORY RECEIVING AGE, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1152.	8349.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1132.	9481.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1172.	9704.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	1243.	9998.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	1157.	10099.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	1116.	10099.	1116.	0.	4069.	0.	0.	0.	0.0	1986
1987	1194.	10161.	1132.	0.	5201.	0.	0.	0.	0.0	1987
1988	1224.	10214.	1172.	0.	6373.	0.	0.	0.	0.0	1988
1989	1153.	10226.	1141.	0.	7514.	0.	0.	0.	0.0	1989
1990	1114.	10226.	1114.	0.	8628.	0.	0.	0.	0.0	1990
1991	1170.	10280.	1116.	0.	9744.	0.	0.	0.	0.0	1991
1992	1241.	10327.	1194.	0.	10938.	0.	0.	0.	0.0	1992
1993	1124.	10318.	1132.	0.	12071.	0.	0.	0.	0.0	1993
1994	1168.	10333.	1153.	0.	13223.	0.	0.	0.	0.0	1994
1995	1130.	10349.	1114.	0.	14337.	0.	0.	0.	0.0	1995
1996	1224.	10403.	1170.	0.	15508.	0.	0.	0.	0.0	1996
1997	1196.	10472.	1127.	0.	16634.	0.	0.	0.	0.0	1997
1998	1143.	10491.	1124.	0.	17759.	0.	0.	0.	0.0	1998
1999	1119.	10472.	1138.	0.	18897.	0.	0.	0.	0.0	1999
2000	1193.	10540.	1124.	0.	20021.	0.	0.	0.	0.0	2000
2001	1202.	10574.	1168.	0.	21189.	0.	0.	0.	0.0	2001
2002	1124.	10574.	1124.	0.	22313.	0.	0.	0.	0.0	2002
2003	1040.	10574.	1040.	0.	23352.	0.	0.	0.	0.0	2003
2004	1035.	10574.	1035.	0.	24387.	0.	0.	0.	0.0	2004
2005	1118.	10574.	1118.	0.	25505.	0.	0.	0.	0.0	2005
2006	966.	10574.	966.	0.	26471.	0.	0.	0.	0.0	2006
2007	1010.	10574.	1010.	0.	27481.	0.	0.	0.	0.0	2007
2008	986.	10574.	986.	0.	28467.	0.	0.	0.	0.0	2008
2009	1032.	10574.	1032.	0.	29499.	0.	0.	0.	0.0	2009
2010	1125.	10659.	1040.	0.	30538.	0.	0.	0.	0.0	2010
2011	1066.	10759.	966.	0.	31504.	0.	0.	0.	0.0	2011
2012	1102.	10851.	1010.	0.	32514.	0.	0.	0.	0.0	2012
2013	1086.	10952.	986.	0.	33500.	0.	0.	0.	0.0	2013
2014	1262.	11182.	1032.	0.	34532.	0.	0.	0.	0.0	2014
2015	834.	11063.	953.	0.	35485.	0.	0.	0.	0.0	2015
2016	544.	11063.	544.	0.	36029.	0.	0.	0.	0.0	2016
2017	458.	11063.	458.	0.	36487.	0.	0.	0.	0.0	2017
2018	310.	11063.	310.	0.	36797.	0.	0.	0.	0.0	2018
2019	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2019
2020	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2020
2021	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2021
2022	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2022
2023	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2023
2024	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2024
2025	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2025
2026	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2026
2027	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2027
2028	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2028
2029	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2029
2030	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2030
2031	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2031
2032	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2032
2033	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2033
2034	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2034
2035	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2035
2036	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2036
2037	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2037
2038	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2038
2039	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2039
2040	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2040
RAIL SHIPMENTS =			8405.5	0.0		0.0				
TRUCK SHIPMENTS =			8557.6	0.0						

TABLE A.1.6. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 2, MTU

1990 Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY			YEAR
							RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1152.	8349.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1132.	9481.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1172.	9704.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	1243.	9998.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	1157.	10099.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	1116.	10099.	1116.	0.	4069.	0.	0.	0.	0.0	1986
1987	1194.	10161.	1132.	0.	5201.	0.	0.	0.	0.0	1987
1988	1224.	10214.	1172.	0.	6373.	0.	0.	0.	0.0	1988
1989	1153.	10226.	1141.	0.	7514.	0.	0.	0.	0.0	1989
1990	1114.	10226.	414.	700.	7928.	0.	700.	700.	18.0	1990
1991	1170.	10096.	0.	1300.	7928.	0.	1300.	2000.	16.4	1991
1992	1241.	9543.	0.	1794.	7722.	206.	2000.	4000.	15.3	1992
1993	1124.	10318.	12.	337.	6071.	1663.	2000.	6000.	14.4	1993
1994	1168.	10318.	1030.	137.	5238.	1863.	2000.	8000.	13.7	1994
1995	1130.	10323.	1114.	11.	4363.	1989.	2000.	10000.	12.9	1995
1996	1224.	10390.	988.	170.	3521.	1830.	2000.	12000.	12.2	1996
1997	1196.	9962.	0.	1623.	3144.	377.	2000.	14000.	11.5	1997
1998	1143.	9112.	0.	1994.	3138.	6.	2000.	16000.	10.8	1998
1999	1119.	9527.	0.	704.	1841.	1296.	2000.	18000.	10.1	1999
2000	1193.	10540.	1.	179.	21.	1821.	2000.	20000.	9.4	2000
2001	1202.	9762.	0.	1980.	1.	20.	2000.	22000.	8.7	2001
2002	1124.	8886.	0.	2000.	1.	0.	2000.	24000.	8.0	2002
2003	1040.	7926.	0.	1999.	0.	1.	2000.	26000.	7.2	2003
2004	1035.	6961.	0.	2000.	0.	0.	2000.	28000.	6.6	2004
2005	1118.	6079.	0.	2000.	0.	0.	2000.	30000.	5.8	2005
2006	966.	5282.	0.	1763.	0.	0.	1763.	31763.	5.2	2006
2007	1010.	5168.	0.	1124.	0.	0.	1124.	32887.	5.0	2007
2008	986.	5114.	0.	1040.	0.	0.	1040.	33926.	5.0	2008
2009	1032.	5112.	0.	1035.	0.	0.	1035.	34961.	5.0	2009
2010	1125.	5118.	0.	1118.	0.	0.	1118.	36079.	5.0	2010
2011	1066.	5218.	0.	966.	0.	0.	966.	37045.	5.0	2011
2012	1102.	5310.	0.	1010.	0.	0.	1010.	38055.	5.0	2012
2013	1086.	5410.	0.	986.	0.	0.	986.	39041.	5.0	2013
2014	1262.	5640.	0.	1032.	0.	0.	1032.	40073.	5.0	2014
2015	834.	5350.	0.	1125.	0.	0.	1125.	41198.	5.0	2015
2016	544.	4829.	0.	1066.	0.	0.	1066.	42263.	5.0	2016
2017	458.	4185.	0.	1102.	0.	0.	1102.	43365.	5.0	2017
2018	310.	3409.	0.	1086.	0.	0.	1086.	44451.	5.0	2018
2019	0.	2147.	0.	1262.	0.	0.	1262.	45713.	5.0	2019
2020	0.	1313.	0.	834.	0.	0.	834.	46548.	5.0	2020
2021	0.	768.	0.	544.	0.	0.	544.	47092.	5.0	2021
2022	0.	310.	0.	458.	0.	0.	458.	47550.	5.0	2022
2023	0.	0.	0.	310.	0.	0.	310.	47860.	5.0	2023
2024	0.	0.	0.	0.	0.	0.	0.	47860.	0.0	2024
2025	0.	0.	0.	0.	0.	0.	0.	47860.	0.0	2025
2026	0.	0.	0.	0.	0.	0.	0.	47860.	0.0	2026
RAIL SHIPMENTS =			2529.3	8403.2		2417.6				
TRUCK SHIPMENTS =			2575.1	8555.2						

TABLE A.1.7. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 2, MTU

2010 Repository

							REPOSITORY			
YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1152.	8349.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1132.	9481.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1172.	9704.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	1243.	9998.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	1157.	10099.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	1116.	10099.	1116.	0.	4069.	0.	0.	0.	0.0	1986
1987	1194.	10161.	1132.	0.	5201.	0.	0.	0.	0.0	1987
1988	1224.	10214.	1172.	0.	6373.	0.	0.	0.	0.0	1988
1989	1153.	10226.	1141.	0.	7514.	0.	0.	0.	0.0	1989
1990	1114.	10226.	1114.	0.	8628.	0.	0.	0.	0.0	1990
1991	1170.	10280.	1116.	0.	9744.	0.	0.	0.	0.0	1991
1992	1241.	10327.	1194.	0.	10938.	0.	0.	0.	0.0	1992
1993	1124.	10318.	1132.	0.	12071.	0.	0.	0.	0.0	1993
1994	1168.	10333.	1153.	0.	13223.	0.	0.	0.	0.0	1994
1995	1130.	10349.	1114.	0.	14337.	0.	0.	0.	0.0	1995
1996	1224.	10403.	1170.	0.	15508.	0.	0.	0.	0.0	1996
1997	1196.	10472.	1127.	0.	16634.	0.	0.	0.	0.0	1997
1998	1143.	10491.	1124.	0.	17759.	0.	0.	0.	0.0	1998
1999	1119.	10472.	1138.	0.	18897.	0.	0.	0.	0.0	1999
2000	1193.	10540.	1124.	0.	20021.	0.	0.	0.	0.0	2000
2001	1202.	10574.	1168.	0.	21189.	0.	0.	0.	0.0	2001
2002	1124.	10574.	1124.	0.	22313.	0.	0.	0.	0.0	2002
2003	1040.	10574.	1040.	0.	23352.	0.	0.	0.	0.0	2003
2004	1035.	10574.	1035.	0.	24387.	0.	0.	0.	0.0	2004
2005	1118.	10574.	1118.	0.	25505.	0.	0.	0.	0.0	2005
2006	966.	10574.	966.	0.	26471.	0.	0.	0.	0.0	2006
2007	1010.	10574.	1010.	0.	27481.	0.	0.	0.	0.0	2007
2008	986.	10574.	986.	0.	28467.	0.	0.	0.	0.0	2008
2009	1032.	10574.	1032.	0.	29499.	0.	0.	0.	0.0	2009
2010	1125.	10659.	340.	700.	29838.	0.	700.	700.	38.0	2010
2011	1066.	10425.	0.	1300.	29838.	0.	1300.	2000.	36.4	2011
2012	1102.	9733.	0.	1794.	29633.	206.	2000.	4000.	35.3	2012
2013	1086.	10482.	0.	337.	27969.	1663.	2000.	6000.	34.4	2013
2014	1262.	11063.	544.	137.	26651.	1863.	2000.	8000.	33.7	2014
2015	834.	11063.	823.	11.	25485.	1989.	2000.	10000.	32.9	2015
2016	544.	11063.	438.	106.	24029.	1894.	2000.	12000.	32.2	2016
2017	458.	11063.	419.	39.	22487.	1961.	2000.	14000.	31.5	2017
2018	310.	11063.	263.	48.	20797.	1952.	2000.	16000.	30.8	2018
2019	0.	11019.	0.	44.	18841.	1956.	2000.	18000.	30.1	2019
2020	0.	11019.	0.	0.	16841.	2000.	2000.	20000.	29.4	2020
2021	0.	10905.	0.	114.	14955.	1886.	2000.	22000.	28.7	2021
2022	0.	10873.	0.	31.	12987.	1969.	2000.	24000.	28.0	2022
2023	0.	10808.	0.	65.	11052.	1935.	2000.	26000.	27.2	2023
2024	0.	10660.	0.	148.	9200.	1852.	2000.	28000.	26.6	2024
2025	0.	10514.	0.	147.	7346.	1853.	2000.	30000.	25.8	2025
2026	0.	10219.	0.	294.	5641.	1706.	2000.	32000.	25.1	2026
2027	0.	10075.	0.	144.	3785.	1856.	2000.	34000.	24.4	2027
2028	0.	9349.	0.	726.	2511.	1274.	2000.	36000.	23.5	2028
2029	0.	7373.	0.	1976.	2487.	24.	2000.	38000.	22.5	2029
2030	0.	5879.	0.	1494.	1981.	506.	2000.	40000.	21.5	2030
2031	0.	5070.	0.	809.	790.	1191.	2000.	42000.	20.7	2031
2032	0.	3751.	0.	1319.	109.	681.	2000.	44000.	19.8	2032
2033	0.	1860.	0.	1891.	-0.	109.	2000.	46000.	19.1	2033
2034	0.	0.	0.	1860.	-0.	0.	1860.	47860.	17.8	2034
2035	0.	0.	0.	0.	-0.	0.	0.	47860.	0.0	2035
2036	0.	0.	0.	0.	-0.	0.	0.	47860.	0.0	2036
RAIL SHIPMENTS =			7383.9	3548.6		7057.9				
TRUCK SHIPMENTS =			7517.5	3612.8						

TABLE A.1.8. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 2, MTU

2030 Repository

EAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY RECEIPTS	REPOSITORY INVENTORY	REPOSITORY RECEIVING AGE, YEARS	YEAR
980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
981	1152.	8349.	0.	0.	0.	0.	0.	0.	0.0	1981
982	1132.	9481.	0.	0.	0.	0.	0.	0.	0.0	1982
983	1172.	9704.	949.	0.	949.	0.	0.	0.	0.0	1983
984	1243.	9998.	949.	0.	1897.	0.	0.	0.	0.0	1984
985	1157.	10099.	1056.	0.	2953.	0.	0.	0.	0.0	1985
986	1116.	10099.	1116.	0.	4069.	0.	0.	0.	0.0	1986
987	1194.	10161.	1132.	0.	5201.	0.	0.	0.	0.0	1987
988	1224.	10214.	1172.	0.	6373.	0.	0.	0.	0.0	1988
989	1153.	10226.	1141.	0.	7514.	0.	0.	0.	0.0	1989
990	1114.	10226.	1114.	0.	8628.	0.	0.	0.	0.0	1990
991	1170.	10280.	1116.	0.	9744.	0.	0.	0.	0.0	1991
992	1241.	10327.	1194.	0.	10938.	0.	0.	0.	0.0	1992
993	1124.	10318.	1132.	0.	12071.	0.	0.	0.	0.0	1993
994	1168.	10333.	1153.	0.	13223.	0.	0.	0.	0.0	1994
995	1130.	10349.	1114.	0.	14337.	0.	0.	0.	0.0	1995
996	1224.	10403.	1170.	0.	15508.	0.	0.	0.	0.0	1996
997	1196.	10472.	1127.	0.	16634.	0.	0.	0.	0.0	1997
998	1143.	10491.	1124.	0.	17759.	0.	0.	0.	0.0	1998
999	1119.	10472.	1138.	0.	18897.	0.	0.	0.	0.0	1999
000	1193.	10540.	1124.	0.	20021.	0.	0.	0.	0.0	2000
001	1202.	10574.	1168.	0.	21189.	0.	0.	0.	0.0	2001
002	1124.	10574.	1124.	0.	22313.	0.	0.	0.	0.0	2002
003	1040.	10574.	1040.	0.	23352.	0.	0.	0.	0.0	2003
004	1035.	10574.	1035.	0.	24387.	0.	0.	0.	0.0	2004
005	1118.	10574.	1118.	0.	25505.	0.	0.	0.	0.0	2005
006	966.	10574.	966.	0.	26471.	0.	0.	0.	0.0	2006
007	1010.	10574.	1010.	0.	27481.	0.	0.	0.	0.0	2007
008	986.	10574.	986.	0.	28467.	0.	0.	0.	0.0	2008
009	1032.	10574.	1032.	0.	29499.	0.	0.	0.	0.0	2009
010	1125.	10659.	1040.	0.	30538.	0.	0.	0.	0.0	2010
011	1066.	10759.	966.	0.	31504.	0.	0.	0.	0.0	2011
012	1102.	10851.	1010.	0.	32514.	0.	0.	0.	0.0	2012
013	1086.	10952.	986.	0.	33500.	0.	0.	0.	0.0	2013
014	1262.	11182.	1032.	0.	34532.	0.	0.	0.	0.0	2014
015	834.	11063.	953.	0.	35485.	0.	0.	0.	0.0	2015
016	544.	11063.	544.	0.	36029.	0.	0.	0.	0.0	2016
017	458.	11063.	458.	0.	36487.	0.	0.	0.	0.0	2017
018	310.	11063.	310.	0.	36797.	0.	0.	0.	0.0	2018
019	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2019
020	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2020
021	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2021
022	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2022
023	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2023
024	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2024
025	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2025
026	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2026
027	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2027
028	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2028
029	0.	11063.	0.	0.	36797.	0.	0.	0.	0.0	2029
030	0.	10363.	0.	700.	36797.	0.	700.	700.	58.0	2030
031	0.	9063.	0.	1300.	36797.	0.	1300.	2000.	56.4	2031
032	0.	7268.	0.	1794.	36592.	206.	2000.	4000.	55.3	2032
033	0.	6932.	0.	337.	34929.	1663.	2000.	6000.	54.4	2033
034	0.	6794.	0.	137.	33066.	1863.	2000.	8000.	53.7	2034
035	0.	6783.	0.	11.	31077.	1989.	2000.	10000.	52.9	2035
036	0.	6677.	0.	106.	29183.	1894.	2000.	12000.	52.2	2036
037	0.	6638.	0.	39.	27222.	1961.	2000.	14000.	51.5	2037
038	0.	6590.	0.	48.	25270.	1952.	2000.	16000.	50.8	2038
039	0.	6546.	0.	44.	23314.	1956.	2000.	18000.	50.1	2039
040	0.	6546.	0.	0.	21314.	2000.	2000.	20000.	49.4	2040
041	0.	6432.	0.	114.	19428.	1886.	2000.	22000.	48.7	2041
042	0.	6401.	0.	31.	17459.	1969.	2000.	24000.	48.0	2042
043	0.	6336.	0.	65.	15524.	1935.	2000.	26000.	47.2	2043
044	0.	6188.	0.	148.	13672.	1852.	2000.	28000.	46.6	2044
045	0.	6041.	0.	147.	11819.	1853.	2000.	30000.	45.8	2045
046	0.	5747.	0.	294.	10113.	1706.	2000.	32000.	45.1	2046
047	0.	5603.	0.	144.	8257.	1856.	2000.	34000.	44.4	2047
048	0.	5527.	0.	76.	6333.	1924.	2000.	36000.	43.5	2048
049	0.	5522.	0.	6.	4339.	1994.	2000.	38000.	42.5	2049
050	0.	5522.	0.	0.	2339.	2000.	2000.	40000.	41.5	2050
051	0.	4957.	0.	564.	903.	1436.	2000.	42000.	40.7	2051
052	0.	3731.	0.	1226.	129.	774.	2000.	44000.	39.8	2052
053	0.	1860.	0.	1871.	-0.	129.	2000.	46000.	39.1	2053
054	0.	0.	0.	1860.	-0.	0.	1860.	47860.	37.8	2054
055	0.	0.	0.	0.	-0.	0.	0.	47860.	0.0	2055
056	0.	0.	0.	0.	-0.	0.	0.	47860.	0.0	2056
ALL SHIPMENTS =			8405.5	2527.0		8034.4				
BULK SHIPMENTS =			8557.6	2572.7						

TABLE A.1.9. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 3, MTU

No Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY RECEIPTS	REPOSITORY INVENTORY	REPOSITORY RECEIVING AGE, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3858.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3938.	0.	40798.	0.	0.	0.	0.0	2000
2001	5854.	37534.	4235.	0.	45033.	0.	0.	0.	0.0	2001
2002	5752.	38906.	4380.	0.	49413.	0.	0.	0.	0.0	2002
2003	5749.	40067.	4588.	0.	54001.	0.	0.	0.	0.0	2003
2004	5692.	40905.	4854.	0.	58854.	0.	0.	0.	0.0	2004
2005	5766.	41589.	5083.	0.	63937.	0.	0.	0.	0.0	2005
2006	5627.	41912.	5303.	0.	69240.	0.	0.	0.	0.0	2006
2007	5727.	42040.	5599.	0.	74839.	0.	0.	0.	0.0	2007
2008	5647.	42040.	5647.	0.	80486.	0.	0.	0.	0.0	2008
2009	5725.	42073.	5692.	0.	86178.	0.	0.	0.	0.0	2009
2010	5788.	42095.	5766.	0.	91944.	0.	0.	0.	0.0	2010
2011	5631.	42100.	5627.	0.	97570.	0.	0.	0.	0.0	2011
2012	5700.	42079.	5721.	0.	103291.	0.	0.	0.	0.0	2012
2013	5669.	42122.	5627.	0.	108918.	0.	0.	0.	0.0	2013
2014	5796.	42193.	5725.	0.	114643.	0.	0.	0.	0.0	2014
2015	5182.	42191.	5184.	0.	119827.	0.	0.	0.	0.0	2015
2016	4993.	42191.	4993.	0.	124820.	0.	0.	0.	0.0	2016
2017	4856.	42191.	4856.	0.	129676.	0.	0.	0.	0.0	2017
2018	4570.	42191.	4570.	0.	134246.	0.	0.	0.	0.0	2018
2019	4313.	42191.	4313.	0.	138559.	0.	0.	0.	0.0	2019
2020	4655.	42191.	4655.	0.	143214.	0.	0.	0.	0.0	2020
2021	4786.	42191.	4786.	0.	148000.	0.	0.	0.	0.0	2021
2022	4617.	42191.	4617.	0.	152617.	0.	0.	0.	0.0	2022
2023	4543.	42191.	4543.	0.	157160.	0.	0.	0.	0.0	2023
2024	4150.	42191.	4150.	0.	161310.	0.	0.	0.	0.0	2024
2025	3789.	42191.	3789.	0.	165099.	0.	0.	0.	0.0	2025
2026	3375.	42191.	3375.	0.	168474.	0.	0.	0.	0.0	2026
2027	3224.	42191.	3224.	0.	171698.	0.	0.	0.	0.0	2027
2028	2949.	42191.	2949.	0.	174647.	0.	0.	0.	0.0	2028
2029	2813.	42191.	2813.	0.	177460.	0.	0.	0.	0.0	2029
2030	2598.	42191.	2598.	0.	180058.	0.	0.	0.	0.0	2030
2031	2353.	42191.	2353.	0.	182410.	0.	0.	0.	0.0	2031
2032	2268.	42191.	2268.	0.	184678.	0.	0.	0.	0.0	2032
2033	2033.	42191.	2033.	0.	186711.	0.	0.	0.	0.0	2033
2034	1818.	42191.	1818.	0.	188529.	0.	0.	0.	0.0	2034
2035	1732.	42191.	1732.	0.	190261.	0.	0.	0.	0.0	2035
2036	1810.	42191.	1810.	0.	192071.	0.	0.	0.	0.0	2036
2037	1519.	42191.	1519.	0.	193590.	0.	0.	0.	0.0	2037
2038	1265.	42191.	1265.	0.	194855.	0.	0.	0.	0.0	2038
2039	1194.	42191.	1194.	0.	196049.	0.	0.	0.	0.0	2039
2040	752.	42191.	752.	0.	196801.	0.	0.	0.	0.0	2040
2041	0.	42191.	0.	0.	196801.	0.	0.	0.	0.0	2041
RAIL SHIPMENTS =			44954.5	0.0		0.0				
TRUCK SHIPMENTS =			45767.6	0.0						

TABLE A.1.10. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 3, MTU

1990 Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY RECEIPTS	REPOSITORY INVENTORY	REPOSITORY RECEIVING AGE, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1070.	700.	9161.	0.	700.	700.	18.0	1990
1991	3646.	22862.	854.	1300.	10015.	0.	1300.	2000.	16.4	1991
1992	3858.	24384.	540.	1794.	10350.	206.	2000.	4000.	15.3	1992
1993	3938.	25717.	2268.	337.	10955.	1663.	2000.	6000.	14.4	1993
1994	4235.	27121.	2673.	157.	11785.	1843.	2000.	8000.	13.7	1994
1995	4380.	28457.	2489.	556.	12130.	2144.	2700.	10700.	12.9	1995
1996	4588.	29886.	2145.	1014.	11989.	2286.	3300.	14000.	12.2	1996
1997	4854.	31371.	970.	2398.	11357.	1602.	4000.	18000.	11.6	1997
1998	5083.	32808.	712.	2934.	11003.	1066.	4000.	22000.	11.1	1998
1999	5303.	34254.	2968.	889.	10860.	3111.	4000.	26000.	10.7	1999
2000	5599.	35915.	2455.	1483.	8798.	4517.	6000.	32000.	10.2	2000
2001	5854.	36660.	0.	5108.	5906.	2892.	8000.	40000.	9.2	2001
2002	5752.	38477.	0.	3936.	1842.	4064.	8000.	48000.	8.2	2002
2003	5749.	38068.	0.	6158.	-0.	1842.	8000.	56000.	7.3	2003
2004	5692.	35760.	0.	8000.	-0.	0.	8000.	64000.	6.7	2004
2005	5766.	33526.	0.	8000.	-0.	0.	8000.	72000.	6.1	2005
2006	5627.	31152.	0.	8000.	-0.	0.	8000.	80000.	5.6	2006
2007	5727.	28879.	0.	8000.	-0.	0.	8000.	88000.	5.3	2007
2008	5647.	28458.	0.	6068.	-0.	0.	6068.	94068.	5.0	2008
2009	5725.	28491.	0.	5692.	-0.	0.	5692.	99760.	5.0	2009
2010	5788.	28514.	0.	5766.	-0.	0.	5766.	105526.	5.0	2010
2011	5631.	28518.	0.	5627.	-0.	0.	5627.	111152.	5.0	2011
2012	5700.	28491.	0.	5727.	-0.	0.	5727.	116879.	5.0	2012
2013	5669.	28514.	0.	5647.	-0.	0.	5647.	122526.	5.0	2013
2014	5796.	28585.	0.	5725.	-0.	0.	5725.	128251.	5.0	2014
2015	5182.	27979.	0.	5788.	-0.	0.	5788.	134039.	5.0	2015
2016	4993.	27341.	0.	5631.	-0.	0.	5631.	139670.	5.0	2016
2017	4856.	26497.	0.	5700.	-0.	0.	5700.	145370.	5.0	2017
2018	4570.	25397.	0.	5669.	-0.	0.	5669.	151039.	5.0	2018
2019	4313.	23914.	0.	5796.	-0.	0.	5796.	156836.	5.0	2019
2020	4655.	23388.	0.	5182.	-0.	0.	5182.	162018.	5.0	2020
2021	4786.	23180.	0.	4993.	-0.	0.	4993.	167011.	5.0	2021
2022	4617.	22941.	0.	4856.	-0.	0.	4856.	171867.	5.0	2022
2023	4543.	22914.	0.	4570.	-0.	0.	4570.	176437.	5.0	2023
2024	4150.	22751.	0.	4313.	-0.	0.	4313.	180750.	5.0	2024
2025	3789.	21885.	0.	4655.	-0.	0.	4655.	185405.	5.0	2025
2026	3375.	20474.	0.	4786.	-0.	0.	4786.	190192.	5.0	2026
2027	3224.	19081.	0.	4617.	-0.	0.	4617.	194808.	5.0	2027
2028	2948.	17487.	0.	4543.	-0.	0.	4543.	199351.	5.0	2028
2029	2813.	16150.	0.	4150.	-0.	0.	4150.	203501.	5.0	2029
2030	2598.	14958.	0.	3789.	-0.	0.	3789.	207290.	5.0	2030
2031	2353.	13936.	0.	3375.	-0.	0.	3375.	210665.	5.0	2031
2032	2268.	12980.	0.	3224.	-0.	0.	3224.	213889.	5.0	2032
2033	2033.	12064.	0.	2948.	-0.	0.	2948.	216838.	5.0	2033
2034	1818.	11070.	0.	2813.	-0.	0.	2813.	219651.	5.0	2034
2035	1732.	10203.	0.	2598.	-0.	0.	2598.	222249.	5.0	2035
2036	1810.	9661.	0.	2353.	-0.	0.	2353.	224601.	5.0	2036
2037	1519.	8912.	0.	2268.	-0.	0.	2268.	226869.	5.0	2037
2038	1265.	8144.	0.	2033.	-0.	0.	2033.	228902.	5.0	2038
2039	1194.	7519.	0.	1818.	-0.	0.	1818.	230721.	5.0	2039
2040	752.	6540.	0.	1732.	-0.	0.	1732.	232452.	5.0	2040
2041	0.	4729.	0.	1810.	-0.	0.	1810.	234263.	5.0	2041
2042	0.	3211.	0.	1519.	-0.	0.	1519.	235781.	5.0	2042
2043	0.	1946.	0.	1265.	-0.	0.	1265.	237046.	5.0	2043
2044	0.	752.	0.	1194.	-0.	0.	1194.	238240.	5.0	2044
2045	0.	0.	0.	752.	-0.	0.	752.	238992.	5.0	2045
2046	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2046
2047	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2047
2048	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2048
2049	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2049
2050	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2050
2051	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2051
RAIL SHIPMENTS =			6221.3	48370.7		5946.6				
TRUCK SHIPMENTS =			6333.9	49245.7						

TABLE A.1.11. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 3, MTU

2010 Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY			YEAR
							RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3858.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3938.	0.	40798.	0.	0.	0.	0.0	2000
2001	5854.	37534.	4235.	0.	45033.	0.	0.	0.	0.0	2001
2002	5752.	38906.	4380.	0.	49413.	0.	0.	0.	0.0	2002
2003	5749.	40067.	4588.	0.	54001.	0.	0.	0.	0.0	2003
2004	5692.	40905.	4854.	0.	58854.	0.	0.	0.	0.0	2004
2005	5766.	41589.	5083.	0.	63937.	0.	0.	0.	0.0	2005
2006	5627.	41912.	5303.	0.	69240.	0.	0.	0.	0.0	2006
2007	5727.	42040.	5599.	0.	74839.	0.	0.	0.	0.0	2007
2008	5647.	42040.	5647.	0.	80486.	0.	0.	0.	0.0	2008
2009	5725.	42073.	5692.	0.	86178.	0.	0.	0.	0.0	2009
2010	5788.	42079.	5082.	700.	91260.	0.	700.	700.	38.0	2010
2011	5631.	42079.	4331.	1300.	95591.	0.	1300.	2000.	36.4	2011
2012	5700.	42079.	3906.	1794.	99291.	206.	2000.	4000.	35.3	2012
2013	5669.	42122.	5290.	337.	102918.	1663.	2000.	6000.	34.4	2013
2014	5796.	42191.	5569.	157.	106644.	1843.	2000.	8000.	33.7	2014
2015	5182.	42191.	4626.	556.	109127.	2144.	2700.	10700.	32.9	2015
2016	4993.	42191.	4013.	981.	110820.	2319.	3300.	14000.	32.2	2016
2017	4856.	42191.	4011.	845.	111676.	3155.	4000.	18000.	31.6	2017
2018	4570.	42191.	3882.	688.	112246.	3312.	4000.	22000.	31.1	2018
2019	4313.	42191.	3788.	526.	112559.	3474.	4000.	26000.	30.7	2019
2020	4655.	42191.	4036.	620.	111214.	5380.	6000.	32000.	30.2	2020
2021	4786.	42191.	3819.	967.	108000.	7033.	8000.	40000.	29.2	2021
2022	4617.	42191.	3729.	888.	102617.	9112.	10000.	50000.	28.0	2022
2023	4543.	42191.	3462.	1081.	95160.	10919.	12000.	62000.	26.5	2023
2024	4150.	42191.	2879.	1271.	85310.	12729.	14000.	76000.	24.9	2024
2025	3789.	42191.	2990.	799.	75099.	13201.	14000.	90000.	23.4	2025
2026	3375.	42191.	2800.	575.	64474.	13425.	14000.	104000.	22.0	2026
2027	3224.	42047.	0.	3368.	53843.	10632.	14000.	118000.	20.5	2027
2028	2948.	42191.	1609.	1195.	42647.	12805.	14000.	132000.	19.1	2028
2029	2813.	41089.	0.	3916.	32562.	10084.	14000.	146000.	17.6	2029
2030	2598.	39389.	0.	4298.	22860.	9702.	14000.	160000.	16.2	2030
2031	2353.	38477.	0.	3265.	12124.	10735.	14000.	174000.	14.5	2031
2032	2268.	35978.	0.	4767.	2891.	9233.	14000.	188000.	12.4	2032
2033	2033.	26902.	0.	11109.	-0.	2891.	14000.	202000.	10.5	2033
2034	1818.	14721.	0.	14000.	-0.	0.	14000.	216000.	8.0	2034
2035	1732.	10203.	0.	6249.	-0.	0.	6249.	222249.	5.7	2035
2036	1810.	9661.	0.	2353.	-0.	0.	2353.	224601.	5.0	2036
2037	1519.	8912.	0.	2268.	-0.	0.	2268.	226869.	5.0	2037
2038	1265.	8144.	0.	2033.	-0.	0.	2033.	228902.	5.0	2038
2039	1194.	7519.	0.	1818.	-0.	0.	1818.	230721.	5.0	2039
2040	752.	6540.	0.	1732.	-0.	0.	1732.	232452.	5.0	2040
2041	0.	4729.	0.	1810.	-0.	0.	1810.	234263.	5.0	2041
2042	0.	3211.	0.	1519.	-0.	0.	1519.	235781.	5.0	2042
2043	0.	1946.	0.	1265.	-0.	0.	1265.	237046.	5.0	2043
2044	0.	752.	0.	1194.	-0.	0.	1194.	238240.	5.0	2044
2045	0.	0.	0.	752.	-0.	0.	752.	238992.	5.0	2045
2046	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2046
2047	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2047
2048	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2048
2049	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2049
2050	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2050
2051	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2051
RAIL SHIPMENTS =			35634.2	18957.8		34060.9				
TRUCK SHIPMENTS =			36278.8	19300.7						

TABLE A.1.12. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 3, MTU

2030 Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY			YEAR
							RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1898.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6606.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3858.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3938.	0.	40798.	0.	0.	0.	0.0	2000
2001	5854.	37534.	4235.	0.	45033.	0.	0.	0.	0.0	2001
2002	5752.	38906.	4380.	0.	49413.	0.	0.	0.	0.0	2002
2003	5749.	40067.	4588.	0.	54001.	0.	0.	0.	0.0	2003
2004	5692.	40905.	4854.	0.	58854.	0.	0.	0.	0.0	2004
2005	5766.	41589.	5083.	0.	63937.	0.	0.	0.	0.0	2005
2006	5627.	41912.	5303.	0.	69240.	0.	0.	0.	0.0	2006
2007	5727.	42040.	5599.	0.	74839.	0.	0.	0.	0.0	2007
2008	5647.	42040.	5647.	0.	80486.	0.	0.	0.	0.0	2008
2009	5725.	42073.	5692.	0.	86178.	0.	0.	0.	0.0	2009
2010	5788.	42095.	5766.	0.	91944.	0.	0.	0.	0.0	2010
2011	5631.	42100.	5627.	0.	97570.	0.	0.	0.	0.0	2011
2012	5700.	42079.	5721.	0.	103291.	0.	0.	0.	0.0	2012
2013	5669.	42122.	5627.	0.	108918.	0.	0.	0.	0.0	2013
2014	5796.	42193.	5725.	0.	114643.	0.	0.	0.	0.0	2014
2015	5182.	42191.	5184.	0.	119827.	0.	0.	0.	0.0	2015
2016	4993.	42191.	4993.	0.	124820.	0.	0.	0.	0.0	2016
2017	4856.	42191.	4856.	0.	129676.	0.	0.	0.	0.0	2017
2018	4570.	42191.	4570.	0.	134246.	0.	0.	0.	0.0	2018
2019	4313.	42191.	4313.	0.	138559.	0.	0.	0.	0.0	2019
2020	4655.	42191.	4655.	0.	143214.	0.	0.	0.	0.0	2020
2021	4786.	42191.	4786.	0.	148000.	0.	0.	0.	0.0	2021
2022	4617.	42191.	4617.	0.	152617.	0.	0.	0.	0.0	2022
2023	4543.	42191.	4543.	0.	157160.	0.	0.	0.	0.0	2023
2024	4150.	42191.	4150.	0.	161310.	0.	0.	0.	0.0	2024
2025	3789.	42191.	3789.	0.	165099.	0.	0.	0.	0.0	2025
2026	3375.	42191.	3375.	0.	168474.	0.	0.	0.	0.0	2026
2027	3224.	42191.	3224.	0.	171698.	0.	0.	0.	0.0	2027
2028	2948.	42191.	2948.	0.	174647.	0.	0.	0.	0.0	2028
2029	2813.	42191.	2813.	0.	177460.	0.	0.	0.	0.0	2029
2030	2598.	42191.	1898.	700.	179358.	0.	700.	700.	58.0	2030
2031	2353.	42191.	1053.	1300.	180410.	0.	1300.	2000.	56.4	2031
2032	2268.	42191.	474.	1794.	180678.	206.	2000.	4000.	55.3	2032
2033	2033.	42191.	1696.	337.	180711.	1663.	2000.	6000.	54.4	2033
2034	1818.	42191.	1661.	157.	180529.	1843.	2000.	8000.	53.7	2034
2035	1732.	42191.	1176.	556.	179561.	2144.	2700.	10700.	52.9	2035
2036	1810.	42191.	830.	981.	178071.	2319.	3300.	14000.	52.2	2036
2037	1519.	42191.	674.	845.	175590.	3155.	4000.	18000.	51.6	2037
2038	1265.	42191.	577.	688.	172855.	3312.	4000.	22000.	51.1	2038
2039	1194.	42191.	668.	526.	170049.	3474.	4000.	26000.	50.7	2039
2040	752.	42191.	132.	620.	164801.	5380.	6000.	32000.	50.2	2040
2041	0.	41224.	0.	967.	157768.	7033.	8000.	40000.	49.2	2041
2042	0.	40336.	0.	888.	148656.	9112.	10000.	50000.	48.0	2042
2043	0.	39256.	0.	1081.	137736.	10919.	12000.	62000.	46.5	2043
2044	0.	37985.	0.	1271.	125007.	12729.	14000.	76000.	44.9	2044
2045	0.	37185.	0.	799.	111807.	13201.	14000.	90000.	43.4	2045
2046	0.	37113.	0.	72.	97879.	13928.	14000.	104000.	42.0	2046
2047	0.	37103.	0.	10.	83889.	13990.	14000.	118000.	40.5	2047
2048	0.	36695.	0.	408.	70296.	13592.	14000.	132000.	39.1	2048
2049	0.	34878.	0.	1817.	58114.	12183.	14000.	146000.	37.6	2049
2050	0.	32096.	0.	2782.	46896.	11218.	14000.	160000.	36.2	2050
2051	0.	31433.	0.	664.	33559.	13336.	14000.	174000.	34.5	2051
2052	0.	29624.	0.	1809.	21368.	12191.	14000.	188000.	32.4	2052
2053	0.	25137.	0.	4487.	11855.	9513.	14000.	202000.	30.5	2053
2054	0.	16793.	0.	8344.	6199.	5656.	14000.	216000.	28.0	2054
2055	0.	8595.	0.	8198.	397.	5802.	14000.	230000.	24.2	2055
2056	0.	0.	0.	8595.	-0.	397.	8992.	238992.	19.3	2056
2057	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2057
2058	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2058
2059	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2059
2060	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2060
2061	0.	0.	0.	0.	-0.	0.	0.	238992.	0.0	2061
RAIL SHIPMENTS =			43012.0	11580.1		41112.9				
TRUCK SHIPMENTS =			43790.0	11789.5						

TABLE A.1.13. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 4, MTU

2000 Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY			YEAR
							RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2955.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3858.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3238.	700.	40098.	0.	700.	700.	28.0	2000
2001	5854.	37534.	2935.	1300.	43033.	0.	1300.	2000.	26.4	2001
2002	5757.	38911.	2586.	1794.	45413.	206.	2000.	4000.	25.3	2002
2003	5761.	40083.	4251.	337.	48001.	1663.	2000.	6000.	24.4	2003
2004	5705.	40934.	4696.	157.	50854.	1843.	2000.	8000.	23.7	2004
2005	5779.	41631.	4527.	556.	53237.	2144.	2700.	10700.	22.9	2005
2006	5639.	41967.	4323.	981.	55240.	2319.	3300.	14000.	22.2	2006
2007	5740.	42107.	4754.	845.	56839.	3155.	4000.	18000.	21.6	2007
2008	5661.	42107.	4973.	688.	58500.	3312.	4000.	22000.	21.1	2008
2009	5763.	42114.	5231.	526.	60257.	3474.	4000.	26000.	20.7	2009
2010	5850.	42203.	5141.	620.	60017.	5380.	6000.	32000.	20.2	2010
2011	5761.	42260.	4737.	967.	57722.	7033.	8000.	40000.	19.2	2011
2012	5885.	42366.	4397.	1382.	53501.	8618.	10000.	50000.	18.0	2012
2013	5995.	42722.	1174.	4465.	47140.	7535.	12000.	62000.	16.5	2013
2014	6263.	43245.	3956.	1783.	40880.	10217.	12000.	74000.	15.1	2014
2015	5868.	43452.	3012.	2649.	34540.	9351.	12000.	86000.	13.9	2015
2016	5844.	43532.	4245.	1518.	28304.	10482.	12000.	98000.	12.9	2016
2017	5797.	43532.	4302.	1495.	22101.	10505.	12000.	110000.	11.8	2017
2018	5618.	43532.	78.	5541.	15719.	6459.	12000.	122000.	10.7	2018
2019	5520.	43532.	501.	5019.	9239.	6981.	12000.	134000.	9.6	2019
2020	5810.	43532.	2472.	3338.	3049.	8662.	12000.	146000.	8.5	2020
2021	6064.	38163.	0.	11433.	2482.	567.	12000.	158000.	7.5	2021
2022	6094.	34739.	0.	9518.	-0.	2482.	12000.	170000.	6.5	2022
2023	6309.	29796.	0.	11252.	-0.	0.	11252.	181252.	5.5	2023
2024	6300.	30577.	0.	5520.	-0.	0.	5520.	186771.	5.0	2024
2025	6120.	30886.	0.	5810.	-0.	0.	5810.	192581.	5.0	2025
2026	5973.	30795.	0.	6064.	-0.	0.	6064.	198645.	5.0	2026
2027	6047.	30749.	0.	6094.	-0.	0.	6094.	204739.	5.0	2027
2028	5990.	30430.	0.	6309.	-0.	0.	6309.	211048.	5.0	2028
2029	5968.	30098.	0.	6300.	-0.	0.	6300.	217348.	5.0	2029
2030	5960.	29938.	0.	6120.	-0.	0.	6120.	223468.	5.0	2030
2031	5991.	29957.	0.	5973.	-0.	0.	5973.	229440.	5.0	2031
2032	6123.	30032.	0.	6047.	-0.	0.	6047.	235487.	5.0	2032
2033	5965.	30007.	0.	5990.	-0.	0.	5990.	241478.	5.0	2033
2034	6052.	30090.	0.	5968.	-0.	0.	5968.	247446.	5.0	2034
2035	6106.	30236.	0.	5960.	-0.	0.	5960.	253406.	5.0	2035
2036	6391.	30636.	0.	5991.	-0.	0.	5991.	259397.	5.0	2036
2037	6369.	30883.	0.	6123.	-0.	0.	6123.	265520.	5.0	2037
2038	6345.	31263.	0.	5965.	-0.	0.	5965.	271484.	5.0	2038
2039	6488.	31699.	0.	6052.	-0.	0.	6052.	277536.	5.0	2039
2040	6332.	31926.	0.	6106.	-0.	0.	6106.	283642.	5.0	2040
2041	0.	25535.	0.	6391.	-0.	0.	6391.	290033.	5.0	2041
2042	0.	19165.	0.	6369.	-0.	0.	6369.	296403.	5.0	2042
2043	0.	12820.	0.	6345.	-0.	0.	6345.	302748.	5.0	2043
2044	0.	6332.	0.	6488.	-0.	0.	6488.	309236.	5.0	2044
2045	0.	0.	0.	6332.	-0.	0.	6332.	315568.	5.0	2045
2046	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2046
2047	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2047
2048	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2048
2049	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2049
2050	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2050
2051	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2051
RAIL SHIPMENTS =			25672.4	46411.6		24538.9				
TRUCK SHIPMENTS =			26136.8	47251.1						

TABLE A.1.14. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 4, MTU

2020 Repository

							REPOSITORY			
YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3858.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3938.	0.	40798.	0.	0.	0.	0.0	2000
2001	5854.	37534.	4235.	0.	45033.	0.	0.	0.	0.0	2001
2002	5757.	38911.	4380.	0.	49413.	0.	0.	0.	0.0	2002
2003	5761.	40083.	4588.	0.	54001.	0.	0.	0.	0.0	2003
2004	5705.	40934.	4854.	0.	58854.	0.	0.	0.	0.0	2004
2005	5779.	41631.	5083.	0.	63937.	0.	0.	0.	0.0	2005
2006	5639.	41967.	5303.	0.	69240.	0.	0.	0.	0.0	2006
2007	5740.	42107.	5599.	0.	74839.	0.	0.	0.	0.0	2007
2008	5661.	42107.	5661.	0.	80500.	0.	0.	0.	0.0	2008
2009	5763.	42166.	5705.	0.	86204.	0.	0.	0.	0.0	2009
2010	5850.	42237.	5779.	0.	91984.	0.	0.	0.	0.0	2010
2011	5761.	42359.	5639.	0.	97622.	0.	0.	0.	0.0	2011
2012	5885.	42504.	5740.	0.	103362.	0.	0.	0.	0.0	2012
2013	5995.	42839.	5661.	0.	109023.	0.	0.	0.	0.0	2013
2014	6263.	43338.	5763.	0.	114786.	0.	0.	0.	0.0	2014
2015	5868.	43452.	5754.	0.	120540.	0.	0.	0.	0.0	2015
2016	5844.	43535.	5761.	0.	126301.	0.	0.	0.	0.0	2016
2017	5797.	43532.	5799.	0.	132101.	0.	0.	0.	0.0	2017
2018	5618.	43532.	5618.	0.	137719.	0.	0.	0.	0.0	2018
2019	5520.	43532.	5520.	0.	143239.	0.	0.	0.	0.0	2019
2020	5810.	43532.	5110.	700.	148349.	0.	700.	700.	48.0	2020
2021	6064.	43532.	4764.	1300.	153112.	0.	1300.	2000.	46.4	2021
2022	6094.	43758.	4074.	1794.	156981.	206.	2000.	4000.	45.3	2022
2023	6309.	44224.	5507.	337.	160824.	1663.	2000.	6000.	44.4	2023
2024	6300.	44846.	5520.	157.	164502.	1843.	2000.	8000.	43.7	2024
2025	6120.	45228.	5182.	556.	167540.	2144.	2700.	10700.	42.9	2025
2026	5973.	45681.	4539.	981.	169760.	2319.	3300.	14000.	42.2	2026
2027	6047.	45918.	4965.	845.	171569.	3155.	4000.	18000.	41.6	2027
2028	5990.	45918.	5302.	688.	173560.	3312.	4000.	22000.	41.1	2028
2029	5968.	45918.	5442.	526.	175528.	3474.	4000.	26000.	40.7	2029
2030	5960.	45918.	5340.	620.	175488.	5380.	6000.	32000.	40.2	2030
2031	5991.	45918.	5024.	967.	173479.	7033.	8000.	40000.	39.2	2031
2032	6123.	45921.	5232.	888.	169599.	9112.	10000.	50000.	38.0	2032
2033	5965.	45921.	4884.	1081.	163563.	10919.	12000.	62000.	36.5	2033
2034	6052.	45926.	4776.	1271.	155611.	12729.	14000.	76000.	34.9	2034
2035	6106.	46041.	5187.	803.	147601.	13197.	14000.	90000.	33.4	2035
2036	6391.	46464.	5897.	71.	139569.	13929.	14000.	104000.	32.0	2036
2037	6369.	46874.	5960.	0.	131529.	14000.	14000.	118000.	30.5	2037
2038	6345.	47227.	5932.	59.	123520.	13941.	14000.	132000.	29.1	2038
2039	6488.	47593.	5992.	131.	115643.	13869.	14000.	146000.	27.7	2039
2040	6332.	47960.	4611.	1353.	107608.	12647.	14000.	160000.	26.3	2040
2041	0.	45127.	0.	2834.	96441.	11166.	14000.	174000.	25.0	2041
2042	0.	44397.	0.	730.	83171.	13270.	14000.	188000.	23.5	2042
2043	0.	41756.	0.	2641.	71812.	11359.	14000.	202000.	22.1	2043
2044	0.	39568.	0.	2188.	60000.	11812.	14000.	216000.	20.8	2044
2045	0.	37581.	0.	1987.	47987.	12013.	14000.	230000.	19.6	2045
2046	0.	35231.	0.	2350.	36337.	11650.	14000.	244000.	18.2	2046
2047	0.	33698.	0.	1533.	23870.	12467.	14000.	258000.	16.9	2047
2048	0.	33475.	0.	223.	10093.	13777.	14000.	272000.	15.6	2048
2049	0.	29568.	0.	3907.	-0.	10093.	14000.	286000.	14.3	2049
2050	0.	15568.	0.	14000.	-0.	0.	14000.	300000.	13.0	2050
2051	0.	1568.	0.	14000.	-0.	0.	14000.	314000.	11.8	2051
2052	0.	0.	0.	1568.	-0.	0.	1568.	315568.	11.6	2052
2053	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2053
2054	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2054
2055	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2055
2056	0.	0.	0.	0.	-0.	0.	0.	315568.	0.0	2056
RAIL SHIPMENTS =			57673.1	14411.0		55126.6				
TRUCK SHIPMENTS =			58716.3	14671.6						

TABLE A.1.15. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 5, MTU

2000 Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY RECEIPTS	REPOSITORY INVENTORY	REPOSITORY RECEIVING AGE, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3858.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3238.	700.	40098.	0.	700.	700.	28.0	2000
2001	5854.	37534.	2935.	1300.	43033.	0.	1300.	2000.	26.4	2001
2002	5902.	39056.	2586.	1794.	45413.	206.	2000.	4000.	25.3	2002
2003	6051.	40520.	4251.	337.	48001.	1663.	2000.	6000.	24.4	2003
2004	6146.	41812.	4696.	157.	50854.	1843.	2000.	8000.	23.7	2004
2005	6376.	43105.	4527.	556.	53237.	2144.	2700.	10700.	22.9	2005
2006	6364.	44166.	4323.	981.	55240.	2319.	3300.	14000.	22.2	2006
2007	6626.	45192.	4754.	845.	56839.	3155.	4000.	18000.	21.6	2007
2008	6683.	46022.	5166.	688.	58693.	3312.	4000.	22000.	21.1	2008
2009	6906.	47026.	5377.	526.	60595.	3474.	4000.	26000.	20.7	2009
2010	7150.	48124.	5432.	620.	60647.	5380.	6000.	32000.	20.2	2010
2011	7225.	49204.	5179.	967.	58793.	7033.	8000.	40000.	19.2	2011
2012	7470.	50298.	4994.	1382.	55168.	8618.	10000.	50000.	18.0	2012
2013	7736.	51670.	1899.	4465.	49532.	7535.	12000.	62000.	16.5	2013
2014	8116.	53160.	4843.	1783.	44158.	10217.	12000.	74000.	15.1	2014
2015	7934.	54411.	3965.	2719.	38841.	9281.	12000.	86000.	13.9	2015
2016	7988.	55492.	5105.	1801.	33748.	10199.	12000.	98000.	12.9	2016
2017	8093.	56435.	5321.	1829.	28897.	10171.	12000.	110000.	12.0	2017
2018	8073.	57283.	3550.	3676.	24122.	8324.	12000.	122000.	11.1	2018
2019	8144.	57956.	1862.	5608.	19593.	6392.	12000.	134000.	10.3	2019
2020	8533.	58754.	3185.	4551.	15328.	7449.	12000.	146000.	9.6	2020
2021	8973.	59611.	4010.	4106.	11444.	7894.	12000.	158000.	9.0	2021
2022	9087.	60645.	0.	8053.	7497.	3947.	12000.	170000.	8.4	2022
2023	9500.	62276.	736.	7133.	3366.	4867.	12000.	182000.	7.9	2023
2024	9625.	62531.	0.	9370.	736.	2630.	12000.	194000.	7.4	2024
2025	9617.	60884.	0.	11264.	-0.	736.	12000.	206000.	6.9	2025
2026	9559.	58443.	0.	12000.	-0.	0.	12000.	218000.	6.4	2026
2027	9805.	56248.	0.	12000.	-0.	0.	12000.	230000.	6.1	2027
2028	9931.	54180.	0.	12000.	-0.	0.	12000.	242000.	5.7	2028
2029	10012.	52192.	0.	12000.	-0.	0.	12000.	254000.	5.5	2029
2030	10141.	50333.	0.	12000.	-0.	0.	12000.	266000.	5.2	2030
2031	10318.	50208.	0.	10443.	-0.	0.	10443.	276443.	5.0	2031
2032	10593.	50995.	0.	9805.	-0.	0.	9805.	286248.	5.0	2032
2033	10550.	51614.	0.	9931.	-0.	0.	9931.	296180.	5.0	2033
2034	10815.	52417.	0.	10012.	-0.	0.	10012.	306192.	5.0	2034
2035	10891.	53166.	0.	10141.	-0.	0.	10141.	316333.	5.0	2035
2036	11334.	54182.	0.	10318.	-0.	0.	10318.	326651.	5.0	2036
2037	11463.	55053.	0.	10593.	-0.	0.	10593.	337244.	5.0	2037
2038	11522.	56025.	0.	10550.	-0.	0.	10550.	347793.	5.0	2038
2039	11754.	56963.	0.	10815.	-0.	0.	10815.	358609.	5.0	2039
2040	11815.	57887.	0.	10891.	-0.	0.	10891.	369499.	5.0	2040
2041	0.	46554.	0.	11334.	-0.	0.	11334.	380833.	5.0	2041
2042	0.	35090.	0.	11463.	-0.	0.	11463.	392296.	5.0	2042
2043	0.	23569.	0.	11522.	-0.	0.	11522.	403818.	5.0	2043
2044	0.	11815.	0.	11754.	-0.	0.	11754.	415572.	5.0	2044
2045	0.	-0.	0.	11815.	-0.	0.	11815.	427387.	5.0	2045
2046	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2046
2047	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2047
2048	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2048
2049	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2049
2050	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2050
2051	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2051
RAIL SHIPMENTS =			29418.9	68207.5		28120.0				
TRUCK SHIPMENTS =			29951.0	69441.2						

TABLE A.1.16. Spent Fuel Logistics for the Once-Through Fuel Cycle--Growth Case 5, MTU

2020 Repository

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	REPOSITORY RECEIPTS	REPOSITORY INVENTORY	REPOSITORY RECEIVING AGE, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3858.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3938.	0.	40798.	0.	0.	0.	0.0	2000
2001	5854.	37534.	4235.	0.	45033.	0.	0.	0.	0.0	2001
2002	5902.	39056.	4380.	0.	49413.	0.	0.	0.	0.0	2002
2003	6051.	40520.	4588.	0.	54001.	0.	0.	0.	0.0	2003
2004	6146.	41812.	4854.	0.	58854.	0.	0.	0.	0.0	2004
2005	6376.	43105.	5083.	0.	63937.	0.	0.	0.	0.0	2005
2006	6364.	44166.	5303.	0.	69240.	0.	0.	0.	0.0	2006
2007	6626.	45192.	5599.	0.	74839.	0.	0.	0.	0.0	2007
2008	6683.	46022.	5854.	0.	80693.	0.	0.	0.	0.0	2008
2009	6906.	47026.	5902.	0.	86595.	0.	0.	0.	0.0	2009
2010	7150.	48124.	6051.	0.	92647.	0.	0.	0.	0.0	2010
2011	7225.	49204.	6146.	0.	98793.	0.	0.	0.	0.0	2011
2012	7470.	50298.	6376.	0.	105168.	0.	0.	0.	0.0	2012
2013	7736.	51670.	6364.	0.	111532.	0.	0.	0.	0.0	2013
2014	8116.	53160.	6626.	0.	118158.	0.	0.	0.	0.0	2014
2015	7934.	54411.	6683.	0.	124841.	0.	0.	0.	0.0	2015
2016	7988.	55492.	6906.	0.	131748.	0.	0.	0.	0.0	2016
2017	8093.	56435.	7150.	0.	138897.	0.	0.	0.	0.0	2017
2018	8073.	57283.	7225.	0.	146122.	0.	0.	0.	0.0	2018
2019	8144.	57956.	7470.	0.	153593.	0.	0.	0.	0.0	2019
2020	8533.	58754.	7036.	700.	160628.	0.	700.	700.	48.0	2020
2021	8973.	59611.	6816.	1300.	167444.	0.	1300.	2000.	46.4	2021
2022	9087.	60764.	6140.	1794.	173378.	206.	2000.	4000.	45.3	2022
2023	9500.	62276.	7651.	337.	179366.	1663.	2000.	6000.	44.4	2023
2024	9625.	63808.	7935.	157.	185458.	1843.	2000.	8000.	43.7	2024
2025	9617.	65353.	7517.	556.	190831.	2144.	2700.	10700.	42.9	2025
2026	9559.	66768.	7163.	981.	195675.	2319.	3300.	14000.	42.2	2026
2027	9805.	68040.	7688.	845.	200208.	3155.	4000.	18000.	41.6	2027
2028	9931.	68999.	8285.	688.	205181.	3312.	4000.	22000.	41.1	2028
2029	10012.	69924.	8562.	526.	210268.	3474.	4000.	26000.	40.7	2029
2030	10141.	70565.	8880.	620.	213768.	5380.	6000.	32000.	40.2	2030

TABLE A.1.16. (Contd)

							REPOSITORY			
YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPOSITORY	AFR INVENTORY	SHIPMENT AFR TO REPOSITORY	RECEIPTS	INVENTORY	RECEIVING AGE, YEARS	YEAR
2031	10318.	71258.	8657.	967.	215393.	7033.	8000.	40000.	39.2	2031
2032	10593.	72234.	8730.	888.	215010.	9112.	10000.	50000.	38.0	2032
2033	10550.	73224.	8479.	1081.	212569.	10919.	12000.	62000.	36.5	2033
2034	10815.	74234.	8534.	1271.	208375.	12729.	14000.	76000.	34.9	2034
2035	10891.	75193.	8961.	970.	204306.	13030.	14000.	90000.	33.4	2035
2036	11334.	76515.	9452.	561.	200318.	13439.	14000.	104000.	32.1	2036
2037	11463.	77837.	9595.	546.	196459.	13454.	14000.	118000.	30.9	2037
2038	11522.	79041.	9707.	611.	192777.	13389.	14000.	132000.	29.8	2038
2039	11754.	80202.	9830.	763.	189370.	13237.	14000.	146000.	28.7	2039
2040	11815.	81467.	9842.	708.	185920.	13292.	14000.	160000.	27.8	2040
2041	0.	80307.	0.	1161.	173080.	12839.	14000.	174000.	27.0	2041
2042	0.	78356.	0.	1950.	161030.	12050.	14000.	188000.	26.3	2042
2043	0.	76239.	0.	2118.	149148.	11882.	14000.	202000.	25.5	2043
2044	0.	75426.	0.	812.	135961.	13188.	14000.	216000.	24.8	2044
2045	0.	72985.	0.	2441.	124402.	11559.	14000.	230000.	24.2	2045
2046	0.	70982.	0.	2003.	112405.	11997.	14000.	244000.	23.6	2046
2047	0.	69397.	0.	1585.	99990.	12415.	14000.	258000.	23.2	2047
2048	0.	68233.	0.	1164.	87153.	12836.	14000.	272000.	22.7	2048
2049	0.	66766.	0.	1468.	74621.	12532.	14000.	286000.	22.2	2049
2050	0.	64722.	0.	2044.	62665.	11956.	14000.	300000.	21.8	2050
2051	0.	62900.	0.	1822.	50487.	12178.	14000.	314000.	21.4	2051
2052	0.	61635.	0.	1265.	37752.	12735.	14000.	328000.	21.0	2052
2053	0.	60384.	0.	1250.	25002.	12750.	14000.	342000.	20.7	2053
2054	0.	59174.	0.	1210.	12213.	12790.	14000.	356000.	20.4	2054
2055	0.	57387.	0.	1787.	-0.	12213.	14000.	370000.	20.1	2055
2056	0.	43387.	0.	14000.	-0.	0.	14000.	384000.	19.8	2056
2057	0.	29387.	0.	14000.	-0.	0.	14000.	398000.	19.6	2057
2058	0.	15387.	0.	14000.	-0.	0.	14000.	412000.	19.4	2058
2059	0.	1387.	0.	14000.	-0.	0.	14000.	426000.	19.2	2059
2060	0.	0.	0.	1387.	-0.	0.	1387.	427387.	19.6	2060
2061	0.	0.	0.	0.	-0.	0.	0.	427387.	0.0	2061
2062	0.	0.	0.	0.	-0.	0.	0.	427387.	0.0	2062
2063	0.	0.	0.	0.	-0.	0.	0.	427387.	0.0	2063
2064	0.	0.	0.	0.	-0.	0.	0.	427387.	0.0	2064
2065	0.	0.	0.	0.	-0.	0.	0.	427387.	0.0	2065
2066	0.	0.	0.	0.	-0.	0.	0.	427387.	0.0	2066
RAIL SHIPMENTS =			75164.0	22462.4		71845.3				
TRUCK SHIPMENTS =			76523.6	22868.7						

TABLE A.1.17. Spent Fuel L ,tics for the Reprocessing Fuel Cycle--Growth Case 3, MTU

1990 Reprocessing

EAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPROCESS	AFR INVENTORY	SHIPMENT AFR TO REPROCESS	REPROCESS ANNUAL	REPROCESS CUMULATIVE	REPROCESS RECEIVING FUEL, YEARS	YEAR
980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
990	3368.	21370.	1070.	700.	9161.	0.	700.	700.	18.0	1990
991	3646.	22862.	854.	1300.	10015.	0.	1300.	2000.	16.4	1991
992	3858.	24384.	335.	2000.	10350.	0.	2000.	4000.	15.3	1992
993	3938.	25717.	605.	2000.	10955.	0.	2000.	6000.	14.4	1993
994	4235.	27121.	830.	2000.	11785.	0.	2000.	8000.	13.7	1994
995	4380.	28457.	1688.	1357.	12130.	1343.	2700.	10700.	12.9	1995
996	4588.	29886.	1527.	1632.	11989.	1668.	3300.	14000.	12.2	1996
997	4854.	31371.	1311.	2057.	11357.	1943.	4000.	18000.	11.6	1997
998	5083.	32808.	1463.	2183.	11003.	1817.	4000.	22000.	11.1	1998
999	5303.	34254.	1616.	2241.	10860.	1759.	4000.	26000.	10.7	1999
2000	5599.	35915.	588.	3349.	10098.	1351.	4700.	30700.	10.4	2000
001	5854.	37114.	0.	4654.	9452.	646.	5300.	36000.	9.9	2001
002	5752.	37984.	0.	4883.	8335.	1117.	6000.	42000.	9.4	2002
003	5749.	39488.	0.	4245.	5880.	2455.	6700.	48700.	8.9	2003
004	5692.	40130.	0.	5050.	3630.	2250.	7300.	56000.	8.3	2004
005	5766.	40362.	0.	5534.	1164.	2466.	8000.	64000.	7.7	2005
006	5627.	38452.	0.	7536.	0.	1164.	8700.	72700.	7.0	2006
007	5727.	34879.	0.	9300.	0.	0.	9300.	82000.	6.4	2007
008	5647.	30526.	0.	10000.	0.	0.	10000.	92000.	5.7	2008
009	5725.	25551.	0.	10700.	0.	0.	10700.	102700.	4.9	2009
010	5788.	20039.	0.	11300.	0.	0.	11300.	114000.	4.0	2010
011	5631.	13670.	0.	12000.	0.	0.	12000.	126000.	2.9	2011
012	5700.	8550.	0.	10821.	0.	0.	10821.	136821.	2.0	2012
013	5669.	8513.	0.	5706.	0.	0.	5706.	142527.	1.5	2013
014	5796.	8652.	0.	5657.	0.	0.	5657.	148183.	1.5	2014
015	5182.	7990.	0.	5844.	0.	0.	5844.	154028.	1.5	2015
016	4993.	7510.	0.	5474.	0.	0.	5474.	159501.	1.5	2016
017	4856.	7281.	0.	5084.	0.	0.	5084.	164586.	1.5	2017
018	4570.	7014.	0.	4837.	0.	0.	4837.	169422.	1.5	2018
019	4313.	6504.	0.	4824.	0.	0.	4824.	174246.	1.5	2019
020	4655.	6832.	0.	4327.	0.	0.	4327.	178573.	1.5	2020
021	4786.	7172.	0.	4447.	0.	0.	4447.	183020.	1.5	2021
022	4617.	7001.	0.	4787.	0.	0.	4787.	187807.	1.5	2022
023	4543.	6878.	0.	4666.	0.	0.	4666.	192473.	1.5	2023
024	4150.	6368.	0.	4660.	0.	0.	4660.	197134.	1.5	2024
025	3789.	5877.	0.	4280.	0.	0.	4280.	201414.	1.5	2025
026	3375.	5220.	0.	4032.	0.	0.	4032.	205446.	1.5	2026
027	3224.	4884.	0.	3560.	0.	0.	3560.	209006.	1.5	2027
028	2948.	4524.	0.	3308.	0.	0.	3308.	212314.	1.5	2028
029	2813.	4271.	0.	3066.	0.	0.	3066.	215379.	1.5	2029
030	2598.	3932.	0.	2938.	0.	0.	2938.	218317.	1.5	2030

TABLE A.1.17. (Contd)

EAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPROCESS	AFR INVENTORY	SHIPMENT AFR TO REPROCESS	REPROCESS ANNUAL	REPROCESS CUMULATIVE	REPROCESS RECEIVING FUEL, YEARS	YEAR
031	2353.	3606.	0.	2678.	0.	0.	2678.	220995.	1.5	2031
032	2268.	3430.	0.	2445.	0.	0.	2445.	223440.	1.5	2032
033	2033.	3126.	0.	2337.	0.	0.	2337.	225777.	1.5	2033
034	1818.	2859.	0.	2085.	0.	0.	2085.	227862.	1.5	2034
035	1732.	2603.	0.	1987.	0.	0.	1987.	229849.	1.5	2035
036	1810.	2698.	0.	1715.	0.	0.	1715.	231564.	1.5	2036
037	1519.	2414.	0.	1803.	0.	0.	1803.	233367.	1.5	2037
038	1265.	1977.	0.	1702.	0.	0.	1702.	235069.	1.5	2038
039	1194.	1797.	0.	1374.	0.	0.	1374.	236443.	1.5	2039
040	752.	1317.	0.	1232.	0.	0.	1232.	237675.	1.5	2040
041	0.	237.	0.	1080.	0.	0.	1080.	238755.	1.5	2041
042	0.	-0.	0.	237.	0.	0.	237.	238992.	1.7	2042
043	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2043
044	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2044
045	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2045
046	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2046
047	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2047
048	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2048
049	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2049
050	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2050
051	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2051
052	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2052
053	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2053
054	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2054
055	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2055
056	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2056
057	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2057
058	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2058
059	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2059
060	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2060
061	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2061
062	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2062
063	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2063
064	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2064
065	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2065
066	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2066
067	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2067
068	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2068
069	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2069
070	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2070
071	0.	-0.	0.	0.	0.	0.	0.	238992.	0.0	2071
AIL SHIPMENTS =			4563.6	50028.5		8362.1				
RUCK SHIPMENTS =			4646.1	50933.4						

TABLE A.1.18. Spent Fuel Logistics for the Reprocessing Fuel Cycle--Growth Case 3, MTU

2010 Reprocessing

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPROCESS	AFR INVENTORY	SHIPMENT AFR TO REPROCESS	REPROCESS ANNUAL	REPROCESS CUMULATIVE	REPROCESS RECEIVING FUEL, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3858.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3938.	0.	40798.	0.	0.	0.	0.0	2000
2001	5854.	37534.	4235.	0.	45033.	0.	0.	0.	0.0	2001
2002	5752.	38906.	4380.	0.	49413.	0.	0.	0.	0.0	2002
2003	5749.	40067.	4588.	0.	54001.	0.	0.	0.	0.0	2003
2004	5692.	40905.	4854.	0.	58854.	0.	0.	0.	0.0	2004
2005	5766.	41589.	5083.	0.	63937.	0.	0.	0.	0.0	2005
2006	5627.	41912.	5303.	0.	69240.	0.	0.	0.	0.0	2006
2007	5727.	42040.	5599.	0.	74839.	0.	0.	0.	0.0	2007
2008	5647.	42040.	5647.	0.	80486.	0.	0.	0.	0.0	2008
2009	5725.	42118.	5647.	0.	86133.	0.	0.	0.	0.0	2009
2010	5788.	42079.	5127.	700.	91260.	0.	700.	700.	38.0	2010
2011	5631.	42079.	4331.	1300.	95591.	0.	1300.	2000.	36.4	2011
2012	5700.	42079.	3700.	2000.	99291.	0.	2000.	4000.	35.3	2012
2013	5669.	42122.	3627.	2000.	102918.	0.	2000.	6000.	34.4	2013
2014	5796.	42191.	3727.	2000.	106644.	0.	2000.	8000.	33.7	2014
2015	5182.	42191.	3825.	1357.	109127.	1343.	2700.	10700.	32.9	2015
2016	4993.	42191.	3361.	1632.	110820.	1668.	3300.	14000.	32.2	2016
2017	4856.	42191.	2799.	2057.	111676.	1943.	4000.	18000.	31.6	2017
2018	4570.	42191.	2387.	2183.	112246.	1817.	4000.	22000.	31.1	2018
2019	4313.	42191.	2359.	1954.	112559.	2046.	4000.	26000.	30.7	2019
2020	4655.	42191.	2814.	1841.	112514.	2859.	4700.	30700.	30.4	2020
2021	4786.	42191.	2919.	1867.	112000.	3433.	5300.	36000.	29.9	2021
2022	4617.	42191.	2810.	1806.	110617.	4194.	6000.	42000.	29.4	2022
2023	4543.	42191.	2664.	1879.	108460.	4821.	6700.	48700.	28.9	2023
2024	4150.	42191.	2178.	1972.	105310.	5328.	7300.	56000.	28.3	2024
2025	3789.	42191.	1824.	1965.	101099.	6035.	8000.	64000.	27.7	2025
2026	3375.	42191.	1186.	2189.	95774.	6511.	8700.	72700.	27.0	2026
2027	3224.	42191.	915.	2309.	89698.	6991.	9300.	82000.	26.4	2027
2028	2948.	42191.	1068.	1880.	82647.	8120.	10000.	92000.	25.7	2028
2029	2813.	42191.	1646.	1167.	74760.	9533.	10700.	102700.	24.9	2029
2030	2598.	42191.	2304.	294.	66058.	11006.	11300.	114000.	24.0	2030

TABLE A.1.18. (Contd)

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPROCESS	AFR INVENTORY	SHIPMENT AFR TO REPROCESS	REPROCESS ANNUAL	REPROCESS CUMULATIVE	REPROCESS RECEIVING FUEL, YEARS	YEAR
2031	2353.	42191.	1950.	403.	56410.	11597.	12000.	126000.	22.9	2031
2032	2268.	41409.	0.	3051.	47461.	8949.	12000.	138000.	21.9	2032
2033	2033.	39209.	0.	4233.	39693.	7767.	12000.	150000.	20.7	2033
2034	1818.	36885.	0.	4142.	31835.	7858.	12000.	162000.	19.6	2034
2035	1732.	32915.	0.	5702.	25537.	6298.	12000.	174000.	18.3	2035
2036	1810.	30066.	0.	4660.	18196.	7340.	12000.	186000.	16.7	2036
2037	1519.	26240.	0.	5344.	11561.	6556.	12000.	198000.	15.1	2037
2038	1265.	19898.	0.	7607.	7168.	4393.	12000.	210000.	13.4	2038
2039	1194.	16053.	0.	5039.	187.	6961.	12000.	222000.	10.8	2039
2040	752.	6992.	0.	9813.	-0.	187.	10000.	232000.	7.4	2040
2041	0.	237.	0.	6755.	-0.	0.	6755.	238755.	3.8	2041
2042	0.	-0.	0.	237.	-0.	0.	237.	238992.	1.7	2042
2043	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2043
2044	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2044
2045	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2045
2046	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2046
2047	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2047
2048	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2048
2049	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2049
2050	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2050
2051	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2051
2052	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2052
2053	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2053
2054	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2054
2055	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2055
2056	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2056
2057	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2057
2058	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2058
2059	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2059
2060	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2060
2061	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2061
2062	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2062
2063	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2063
2064	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2064
2065	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2065
2066	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2066
2067	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2067
2068	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2068
2069	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2069
2070	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2070
2071	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2071
2072	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2072
2073	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2073
2074	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2074
2075	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2075
2076	0.	-0.	0.	0.	-0.	0.	0.	238992.	0.0	2076
RAIL SHIPMENTS =			33271.3	21320.8		31502.3				
TRUCK SHIPMENTS =			33873.1	21706.4						

TABLE A.1.19. Spent Fuel Logistics for the Reprocessing Fuel Cycle--Growth Case 4, MTU

2000 Reprocessing

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPROCESS	AFR INVENTORY	SHIPMENT AFR TO REPROCESS	REPROCESS ANNUAL	REPROCESS CUMULATIVE	REPROCESS RECEIVING FUEL, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3858.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3238.	700.	40098.	0.	700.	700.	28.0	2000
2001	5854.	37534.	2935.	1300.	43033.	0.	1300.	2000.	26.4	2001
2002	5757.	38911.	2380.	2000.	45413.	0.	2000.	4000.	25.3	2002
2003	5761.	40083.	2588.	2000.	48001.	0.	2000.	6000.	24.4	2003
2004	5705.	40934.	2854.	2000.	50854.	0.	2000.	8000.	23.7	2004
2005	5779.	41631.	3726.	1357.	53237.	1343.	2700.	10700.	22.9	2005
2006	5639.	41967.	3671.	1632.	55240.	1668.	3300.	14000.	22.2	2006
2007	5740.	42107.	3542.	2057.	56839.	1943.	4000.	18000.	21.6	2007
2008	5661.	42107.	3478.	2183.	58500.	1817.	4000.	22000.	21.1	2008
2009	5763.	42114.	3803.	1954.	60257.	2046.	4000.	26000.	20.7	2009
2010	5850.	42203.	3919.	1841.	61317.	2859.	4700.	30700.	20.4	2010
2011	5761.	42260.	3837.	1867.	61722.	3433.	5300.	36000.	19.9	2011
2012	5885.	42366.	3973.	1806.	61501.	4194.	6000.	42000.	19.4	2012
2013	5995.	42722.	3760.	1879.	60440.	4821.	6700.	48700.	18.9	2013
2014	6263.	43245.	3767.	1972.	58880.	5328.	7300.	56000.	18.3	2014
2015	5868.	43452.	3696.	1965.	56540.	6035.	8000.	64000.	17.7	2015
2016	5844.	43532.	2506.	3257.	53604.	5443.	8700.	72700.	17.0	2016
2017	5797.	43532.	750.	5047.	50101.	4253.	9300.	82000.	16.4	2017
2018	5618.	43532.	258.	5360.	45719.	4640.	10000.	92000.	15.7	2018
2019	5520.	43532.	1427.	4093.	40539.	6607.	10700.	102700.	14.9	2019
2020	5810.	43532.	1566.	4244.	35049.	7056.	11300.	114000.	14.0	2020
2021	6064.	43532.	1959.	4105.	29112.	7895.	12000.	126000.	13.0	2021
2022	6094.	43758.	1924.	3944.	22981.	8056.	12000.	138000.	11.9	2022
2023	6309.	44224.	1568.	4276.	16824.	7724.	12000.	150000.	10.8	2023
2024	6300.	44727.	318.	5479.	10621.	6521.	12000.	162000.	9.8	2024
2025	6120.	40633.	0.	10213.	8835.	1787.	12000.	174000.	8.8	2025
2026	5973.	37452.	0.	9153.	5988.	2847.	12000.	186000.	7.7	2026
2027	6047.	35397.	0.	8103.	2090.	3897.	12000.	198000.	6.6	2027
2028	5990.	31425.	0.	9962.	53.	2038.	12000.	210000.	5.6	2028
2029	5968.	25446.	0.	11947.	-0.	53.	12000.	222000.	4.7	2029
2030	5960.	21406.	0.	10000.	-0.	0.	10000.	232000.	3.9	2030

TABLE A.1.19. (Contd)

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPROCESS	AFR INVENTORY	SHIPMENT AFR TO REPROCESS	REPROCESS ANNUAL	REPROCESS CUMULATIVE	RECEIVING FUEL, YEARS	YEAR
2031	5991.	17397.	0.	10000.	-0.	0.	10000.	242000.	3.2	2031
2032	6123.	13520.	0.	10000.	-0.	0.	10000.	252000.	2.6	2032
2033	5965.	9484.	0.	10000.	-0.	0.	10000.	262000.	1.9	2033
2034	6052.	9059.	0.	6477.	-0.	0.	6477.	268477.	1.5	2034
2035	6106.	9094.	0.	6071.	-0.	0.	6071.	274548.	1.5	2035
2036	6391.	9507.	0.	5978.	-0.	0.	5978.	280526.	1.5	2036
2037	6369.	9604.	0.	6272.	-0.	0.	6272.	286798.	1.5	2037
2038	6345.	9501.	0.	6448.	-0.	0.	6448.	293247.	1.5	2038
2039	6488.	9699.	0.	6290.	-0.	0.	6290.	299537.	1.5	2039
2040	6332.	9610.	0.	6421.	-0.	0.	6421.	305958.	1.5	2040
2041	0.	3094.	0.	6516.	-0.	0.	6516.	312474.	1.5	2041
2042	0.	-0.	0.	3094.	-0.	0.	3094.	315568.	1.7	2042
2043	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2043
2044	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2044
2045	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2045
2046	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2046
2047	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2047
2048	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2048
2049	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2049
2050	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2050
2051	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2051
2052	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2052
2053	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2053
2054	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2054
2055	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2055
2056	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2056
2057	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2057
2058	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2058
2059	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2059
2060	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2060
2061	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2061
2062	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2062
2063	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2063
2064	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2064
2065	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2065
2066	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2066
2067	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2067
2068	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2068
2069	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2069
2070	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2070
2071	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2071
2072	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2072
2073	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2073
2074	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2074
2075	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2075
2076	0.	-0.	0.	0.	-0.	0.	0.	315568.	0.0	2076
RAIL SHIPMENTS =			23825.6	48258.2		22773.6				
TRUCK SHIPMENTS =			24256.5	49131.4						

TABLE A.1.20. Spent Fuel Logistics for the Reprocessing Fuel Cycle--Growth Case 5, MTU

2000 Reprocessing

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPROCESS	AFR INVENTORY	SHIPMENT AFR TO REPROCESS	REPROCESS ANNUAL	REPROCESS CUMULATIVE	REPROCESS RECEIVING FUEL, YEARS	YEAR
1980	1160.	7196.	0.	0.	0.	0.	0.	0.	0.0	1980
1981	1282.	8478.	0.	0.	0.	0.	0.	0.	0.0	1981
1982	1486.	9964.	0.	0.	0.	0.	0.	0.	0.0	1982
1983	1770.	10786.	949.	0.	949.	0.	0.	0.	0.0	1983
1984	2154.	11991.	949.	0.	1897.	0.	0.	0.	0.0	1984
1985	2335.	13271.	1056.	0.	2953.	0.	0.	0.	0.0	1985
1986	2605.	14666.	1209.	0.	4163.	0.	0.	0.	0.0	1986
1987	2830.	16336.	1160.	0.	5323.	0.	0.	0.	0.0	1987
1988	3045.	18099.	1282.	0.	6604.	0.	0.	0.	0.0	1988
1989	3159.	19772.	1486.	0.	8090.	0.	0.	0.	0.0	1989
1990	3368.	21370.	1770.	0.	9861.	0.	0.	0.	0.0	1990
1991	3646.	22862.	2154.	0.	12015.	0.	0.	0.	0.0	1991
1992	3858.	24384.	2335.	0.	14350.	0.	0.	0.	0.0	1992
1993	3938.	25717.	2605.	0.	16955.	0.	0.	0.	0.0	1993
1994	4235.	27121.	2830.	0.	19785.	0.	0.	0.	0.0	1994
1995	4380.	28457.	3045.	0.	22830.	0.	0.	0.	0.0	1995
1996	4588.	29886.	3159.	0.	25989.	0.	0.	0.	0.0	1996
1997	4854.	31371.	3368.	0.	29357.	0.	0.	0.	0.0	1997
1998	5083.	32808.	3646.	0.	33003.	0.	0.	0.	0.0	1998
1999	5303.	34254.	3856.	0.	36860.	0.	0.	0.	0.0	1999
2000	5599.	35915.	3238.	700.	40098.	0.	700.	700.	28.0	2000
2001	5854.	37534.	2935.	1300.	43033.	0.	1300.	2000.	26.4	2001
2002	5902.	39056.	2380.	2000.	45413.	0.	2000.	4000.	25.3	2002
2003	6051.	40520.	2588.	2000.	48001.	0.	2000.	6000.	24.4	2003
2004	6146.	41812.	2854.	2000.	50854.	0.	2000.	8000.	23.7	2004
2005	6376.	43105.	3726.	1357.	53237.	1343.	2700.	10700.	22.9	2005
2006	6364.	44166.	3671.	1632.	55240.	1668.	3300.	14000.	22.2	2006
2007	6626.	45192.	3542.	2057.	56839.	1943.	4000.	18000.	21.6	2007
2008	6683.	46022.	3671.	2183.	58693.	1817.	4000.	22000.	21.1	2008
2009	6906.	47026.	3949.	1954.	60595.	2046.	4000.	26000.	20.7	2009
2010	7150.	48124.	4210.	1841.	61947.	2859.	4700.	30700.	20.4	2010
2011	7225.	49204.	4279.	1867.	62793.	3433.	5300.	36000.	19.9	2011
2012	7470.	50298.	4570.	1806.	63168.	4194.	6000.	42000.	19.4	2012
2013	7736.	51670.	4485.	1879.	62832.	4821.	6700.	48700.	18.9	2013
2014	8116.	53160.	4654.	1972.	62158.	5328.	7300.	56000.	18.3	2014
2015	7934.	54411.	4718.	1965.	60841.	6035.	8000.	64000.	17.7	2015
2016	7988.	55492.	3650.	3257.	59048.	5443.	8700.	72700.	17.0	2016
2017	8093.	56435.	2103.	5047.	56897.	4253.	9300.	82000.	16.4	2017
2018	8073.	57283.	1709.	5517.	54122.	4483.	10000.	92000.	15.7	2018
2019	8144.	57956.	2855.	4615.	50893.	6085.	10700.	102700.	15.0	2019
2020	8533.	58754.	2807.	4929.	47328.	6371.	11300.	114000.	14.3	2020
2021	8973.	59611.	2983.	5132.	43444.	6868.	12000.	126000.	13.5	2021
2022	9087.	60764.	2906.	5028.	38678.	7672.	12700.	138700.	12.7	2022
2023	9500.	62276.	2900.	5087.	33366.	8213.	13300.	152000.	11.9	2023
2024	9625.	63808.	2454.	5639.	27458.	8361.	14000.	166000.	11.0	2024
2025	9617.	65353.	495.	7578.	20831.	7122.	14700.	180700.	10.2	2025
2026	9559.	63278.	0.	11634.	17165.	3666.	15300.	196000.	9.4	2026
2027	9805.	62667.	0.	10416.	11581.	5584.	16000.	212000.	8.4	2027
2028	9931.	61515.	0.	11083.	5964.	5617.	16700.	228700.	7.5	2028
2029	10012.	59272.	0.	12255.	919.	5045.	17300.	246000.	6.6	2029
2030	10141.	54333.	0.	15081.	-0.	919.	16000.	262000.	5.8	2030

TABLE A.1.20. (Contd)

YEAR	REACTOR DISCHARGE	REACTOR STORAGE	SHIPMENT REACTOR TO AFR	SHIPMENT REACTOR TO REPROCESS	AFR INVENTORY	SHIPMENT AFR TO REPROCESS	REPROCESS			YEAR
							ANNUAL	CUMULATIVE	RECEIVING FUEL, YEARS	
2031	10318.	48651.	0.	16000.	-0.	0.	16000.	278000.	5.2	2031
2032	10593.	43244.	0.	16000.	-0.	0.	16000.	294000.	4.5	2032
2033	10550.	37793.	0.	16000.	-0.	0.	16000.	310000.	3.9	2033
2034	10815.	32609.	0.	16000.	-0.	0.	16000.	326000.	3.3	2034
2035	10891.	29499.	0.	14000.	-0.	0.	14000.	340000.	2.9	2035
2036	11334.	26833.	0.	14000.	-0.	0.	14000.	354000.	2.6	2036
2037	11463.	24296.	0.	14000.	-0.	0.	14000.	368000.	2.3	2037
2038	11522.	21818.	0.	14000.	-0.	0.	14000.	382000.	2.0	2038
2039	11754.	19572.	0.	14000.	-0.	0.	14000.	396000.	1.8	2039
2040	11815.	17758.	0.	13629.	-0.	0.	13629.	409629.	1.6	2040
2041	0.	5917.	0.	11841.	-0.	0.	11841.	421470.	1.5	2041
2042	0.	-0.	0.	5917.	-0.	0.	5917.	427387.	1.8	2042
2043	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2043
2044	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2044
2045	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2045
2046	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2046
2047	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2047
2048	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2048
2049	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2049
2050	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2050
2051	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2051
2052	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2052
2053	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2053
2054	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2054
2055	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2055
2056	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2056
2057	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2057
2058	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2058
2059	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2059
2060	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2060
2061	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2061
2062	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2062
2063	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2063
2064	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2064
2065	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2065
2066	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2066
2067	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2067
2068	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2068
2069	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2069
2070	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2070
2071	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2071
2072	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2072
2073	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2073
2074	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2074
2075	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2075
2076	0.	-0.	0.	0.	-0.	0.	0.	427387.	0.0	2076
RAIL SHIPMENTS =			27682.9	69943.6		26460.6				
TRUCK SHIPMENTS =			28183.6	71208.7						

TABLE A.1.21. Number of Containers Sent to Repository in Once-Through Cases

Growth Assumption	Repository Date	BWR Canisters	PWR Canisters	Total Canisters
Present Inventory	1990	2.37×10^4	1.19×10^4	3.56×10^4
	2010	2.37×10^4	1.19×10^4	3.56×10^4
	2030	2.37×10^4	1.19×10^4	3.56×10^4
Present Capacity to Retirement	1990	1.04×10^5	6.12×10^4	1.65×10^5
	2010	1.04×10^5	6.12×10^4	1.65×10^5
	2030	1.04×10^5	6.12×10^4	1.65×10^5
250 GWe in 2000 and Decline to 0 in 2040	1990	4.91×10^5	3.17×10^5	8.08×10^5
	2010	4.91×10^5	3.17×10^5	8.08×10^5
	2030	4.91×10^5	3.17×10^5	8.08×10^5
250 GWe in 2000 and Steady State to 2040	2000	6.46×10^5	4.20×10^5	1.07×10^6
	2020	6.46×10^5	4.20×10^5	1.07×10^6
250 GWe in 2000 and Increase to 500 GWe in 2040	2000	8.71×10^5	5.70×10^5	1.44×10^6
	2020	8.71×10^5	5.70×10^5	1.44×10^6

TABLE A.1.22. Number of Containers Sent to Repository in Reprocessing Cases

			HLW Canisters				RH-TRU Canisters			RH-TRU Drums			CH-TRU(a)	
Growth Assumption	Reprocessing Date	Repository Date	Salt 3.2 kW/Can	Granite 1.7 kW/Can	Shale 1.2 kW/Can	Basalt 1.3 kW/Can	10 + R/hr	1-10 R/hr	.2-1 R/hr	10 + R/hr	1-10 R/hr	.2-1 R/hr	Drums	Boxes
250 GWe in 2000 and Decline to 0 in 2040	1990	1990	1.28×10^5	2.37×10^5	4.29×10^5	3.74×10^5	5.71×10^4	4.78×10^2	8.01×10^3	5.06×10^5	2.35×10^5	2.31×10^5	7.81×10^5	1.14×10^4
	1990	2010	1.02×10^5	1.81×10^5	2.64×10^5	2.28×10^5	5.71×10^4	4.78×10^2	8.01×10^3	5.06×10^5	2.35×10^5	2.31×10^5	7.81×10^5	1.14×10^4
	2010	2010	7.87×10^4	1.17×10^5	1.77×10^5	1.69×10^5	5.71×10^4	4.78×10^2	8.01×10^3	5.06×10^5	2.35×10^5	2.31×10^5	5.34×10^5	8.86×10^3
	1990	2030	8.17×10^4	1.14×10^5	1.60×10^5	1.47×10^5	5.71×10^4	4.78×10^2	8.01×10^3	5.06×10^5	2.35×10^5	2.31×10^5	7.81×10^5	1.14×10^4
	2010	2030	7.87×10^4	9.67×10^4	1.33×10^5	1.25×10^5	5.71×10^4	4.78×10^2	8.01×10^3	5.06×10^5	2.35×10^5	2.31×10^5	5.34×10^5	8.86×10^3
250 GWe in 2000 and Steady State to 2040	2000	2000	1.37×10^5	2.48×10^5	3.47×10^5	3.09×10^5	7.54×10^4	6.31×10^2	1.06×10^4	6.68×10^5	3.11×10^5	3.06×10^5	8.59×10^5	1.34×10^4
	2000	2020	1.14×10^5	1.92×10^5	2.69×10^5	2.51×10^5	7.54×10^4	6.31×10^2	1.06×10^4	6.68×10^5	3.11×10^5	3.06×10^5	8.59×10^5	1.34×10^4
250 GWe in 2000 and Increase to 500 GWe in 2040	2000	2000	1.87×10^5	3.59×10^5	5.32×10^5	4.54×10^5	1.02×10^5	8.55×10^2	1.43×10^4	9.05×10^5	4.21×10^5	4.14×10^5	1.20×10^6	1.86×10^4
	2000	2020	1.61×10^5	2.76×10^5	3.88×10^5	3.65×10^5	1.02×10^5	8.55×10^2	1.43×10^4	9.05×10^5	4.21×10^5	4.14×10^5	1.20×10^6	1.86×10^4

(a) Includes waste from FRP and MOX decommissioning.

TABLE A.1.23. Age of HLW at Time of Disposal

	Case:	3	3	3	3	3	4	4	5	5
	Reprocessing:	1990	1990	2010	1990	2010	2000	2000	2000	2000
Year	Repository:	1990	2010	2010	2030	2030	2000	2020	2000	2020
1995		23.0								
1996		21.4								
1997		20.3								
1998		19.4								
1999		18.7								
2000		17.9								
2001		17.2								
2002		16.6								
2003		16.1								
2004		15.7								
2005		15.4					33.0		33.0	
2006		14.9					31.4		31.4	
2007		14.4					30.3		30.3	
2008		13.9					29.4		29.4	
2009		13.3					28.7		28.7	
2010		12.7	38.0				27.9		27.9	
2011		12.0	36.4				27.2		27.2	
2012		11.4	35.3				26.6		26.6	
2013		10.7	34.4				26.1		26.1	
2014		9.9	33.7				25.7		25.7	
2015		9.0	32.9	43.0			25.4		25.4	
2016		7.9	32.2	41.4			24.9		24.9	
2017		7.0	31.6	40.3			24.4		24.4	
2018		6.5	31.1	39.4			23.9		23.9	
2019		6.5	30.7	38.7			23.3		23.3	
2020		6.5	29.7	37.9			22.7	48.0	22.7	48.0
2021		6.5	28.1	37.2			22.0	46.4	22.0	46.4
2022		6.5	26.4	36.6			21.4	45.3	21.4	45.3
2023		6.5	24.7	36.1			20.7	44.4	20.7	44.4
2024		6.5	22.6	35.7			19.9	43.7	20.0	43.7
2025		6.5	20.6	35.4			19.0	42.9	19.3	42.9
2026		6.5	18.3	34.9			18.0	42.2	18.5	42.2
2027		6.5	16.4	34.4			16.9	41.6	17.7	41.6
2028		6.5	15.1	33.9			15.8	41.1	16.9	41.1
2029		6.5	14.4	33.3			14.8	40.7	16.0	40.7
2030		6.5	13.7	32.7	58.0	58.0	13.8	39.7	15.2	39.7
2031		6.5	13.0	32.0	56.4	56.4	12.7	38.1	14.4	38.1
2032		6.5	12.0	31.4	55.3	55.3	11.6	36.4	13.4	36.4
2033		6.5	11.3	30.7	54.4	54.4	10.6	34.7	12.5	34.7
2034		6.5	10.7	29.9	53.7	53.7	9.7	32.6	11.6	32.7
2035		6.5	10.0	29.0	52.9	52.9	8.9	30.6	10.8	30.7
2036		6.5	9.1	27.9	52.2	52.2	8.2	28.2	10.2	28.7
2037		6.5	8.4	26.9	51.6	51.6	7.6	25.7	9.5	26.6
2038		6.5	7.7	25.7	51.1	51.1	6.9	23.0	8.9	24.3
2039		6.5	7.0	24.6	50.7	50.7	6.5	20.4	8.3	22.0
2040		6.5	6.5	23.3	48.9	49.7	6.5	17.9	7.9	19.7
2041		6.5	6.5	21.7	45.7	48.1	6.5	15.8	7.6	17.6
2042		6.5	6.5	20.1	42.3	46.4	6.5	13.5	7.3	15.5
2043		6.5	6.5	18.4	38.6	44.7	6.5	11.9	7.0	13.7
2044		6.5	6.5	15.8	34.6	42.6	6.5	10.7	6.8	12.2
2045		6.5	6.5	12.4	31.9	40.6	6.5	9.9	6.6	10.8
2046		6.5	6.5	8.8	30.2	38.2	6.5	9.1	6.5	9.5
2047		6.7	6.7	6.7	28.4	35.6	6.7	8.4	6.8	8.5
2048					26.6	32.6		8.1		8.1
2049					24.9	29.3				
2050					23.2	25.6				
2051					21.5	20.5				
2052					19.7	14.7				
2053					17.9	12.7				
2054					16.3					
2055					15.3					

A.2 RADIOACTIVE INVENTORY TABLES

The radioactivity inventory tables (A.2.1a through A.2.9b) differ from similar tables in Chapter 7 by showing the inventory of each major radionuclide as a function of time. These tables appear in sets of two tables; one table shows the inventory of fission and activation products and the other table shows the inventory of actinides. Tables are provided only for the different growth cases in the once-through cycle since repository opening dates have no effect on the inventory after the year 2070. Two tables are shown for the Reprocessing Case 3. This case has two different reprocessing startup dates and inventories are a function of reprocessing startup time, since that controls the amount of fuel that is recycled, which affects the quantities of plutonium and other actinides in the wastes.

TABLE A.2.1a. Radioactivity Inventory--Once-Through Cycle--Growth Case 1, Curies(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
H-3	1.01E+06	6.07E+04	1.97E+04	2.31E-06	0.	0.	0.	0.	0.	0.	0.
C-14	6.17E+03	6.13E+03	6.11E+03	5.82E+03	5.48E+03	3.38E+03	1.85E+03	1.47E+01	3.48E-02	0.	0.
MN-54	1.55E+02	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	9.18E+05	1.50E+00	7.30E-03	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	3.86E+06	5.34E+03	3.83E+02	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	2.32E+04	2.32E+04	2.32E+04	2.31E+04	2.30E+04	2.22E+04	2.13E+04	1.50E+04	9.76E+03	3.06E+02	4.03E+00
NI-63	3.18E+06	2.18E+06	1.88E+06	8.82E+04	2.04E+03	1.70E-10	0.	0.	0.	0.	0.
SE-79	2.63E+03	2.62E+03	2.62E+03	2.61E+03	2.60E+03	2.49E+03	2.36E+03	1.54E+03	9.05E+02	1.27E+01	6.18E-02
KR-85	2.17E+07	8.80E+05	2.44E+05	1.20E-06	0.	0.	0.	0.	0.	0.	0.
RB-87	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01
SR-90+Y-90	6.27E+08	1.83E+08	1.12E+08	5.03E+03	2.23E-02	0.	0.	0.	0.	0.	0.
ZR-93	1.25E+04	1.25E+04	1.25E+04	1.25E+04	1.25E+04	1.25E+04	1.25E+04	1.22E+04	1.19E+04	9.93E+03	7.88E+03
NB-93M	8.26E+03	1.22E+04	1.24E+04	1.25E+04	1.25E+04	1.25E+04	1.25E+04	1.22E+04	1.20E+04	9.94E+03	7.89E+03
TC-99	9.69E+04	9.69E+04	9.68E+04	9.67E+04	9.66E+04	9.53E+04	9.37E+04	8.21E+04	6.97E+04	1.86E+04	3.58E+03
RU-106+RH-106	9.02E+05	9.67E-10	0.	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	7.05E+02	7.05E+02	7.05E+02	7.05E+02	7.05E+02	7.05E+02	7.05E+02	7.02E+02	6.98E+02	6.71E+02	6.39E+02
AG-110M	3.78E+01	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	1.89E+04	1.59E+03	5.92E+02	1.12E-06	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	1.10E+06	2.96E+00	1.75E-02	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	1.03E+04	1.03E+04	1.03E+04	1.03E+04	1.03E+04	9.99E+03	9.65E+03	7.31E+03	5.17E+03	3.24E+02	1.02E+01
I-129	2.45E+02	2.45E+02	2.45E+02	2.45E+02	2.45E+02	2.45E+02	2.45E+02	2.45E+02	2.44E+02	2.40E+02	2.35E+02
CS-134	3.51E+06	2.53E-01	2.94E-04	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	1.92E+03	1.92E+03	1.92E+03	1.92E+03	1.92E+03	1.92E+03	1.91E+03	1.90E+03	1.88E+03	1.71E+03	1.52E+03
CS-137+BA-137	8.59E+08	2.71E+08	1.71E+08	1.45E+04	1.40E-01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	3.60E+05	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	1.78E+07	3.23E+01	1.63E-01	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	8.05E+06	5.41E+06	4.61E+06	1.82E+05	3.40E+03	0.	0.	0.	0.	0.	0.
EU-152	3.22E+04	1.60E+03	5.66E+02	3.76E-08	0.	0.	0.	0.	0.	0.	0.
EU-154	1.50E+07	1.72E+06	7.24E+05	1.68E-02	0.	0.	0.	0.	0.	0.	0.
EU-155	1.23E+05	6.00E-04	2.84E-07	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	1.45E+01	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	1.57E+09	4.64E+08	2.90E+08	4.56E+05	1.71E+05	1.61E+05	1.57E+05	1.33E+05	1.12E+05	4.18E+04	2.18E+04

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.2.1b. Radioactivity Inventory--Once-Through Cycle--Growth Case 1, Curies$^{(A)}$

Actinides

RADIONUCLIDES (B)	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
CM-245	9.09E+02	9.05E+02	9.03E+02	8.73E+02	8.37E+02	5.99E+02	3.04E+02	1.37E+01	2.07E-01	0.	0.
CM-244	2.99E+06	4.41E+05	2.05E+05	3.62E-02	1.75E-10	0.	0.	0.	0.	0.	0.
CM-243	1.39E+04	4.71E+03	3.05E+03	4.62E-01	9.14E-06	0.	0.	0.	0.	0.	0.
CM-242	5.00E+04	3.98E+04	3.63E+04	5.70E+03	5.83E+02	6.98E-06	0.	0.	0.	0.	0.
AM-243+NP-239	1.56E+05	1.56E+05	1.55E+05	1.50E+05	1.43E+05	9.97E+04	6.33E+04	1.69E+03	1.82E+01	0.	0.
AM-242M+AM-242	1.22E+05	9.70E+04	8.85E+04	1.39E+04	1.42E+03	1.70E-05	0.	0.	0.	0.	0.
AM-241	1.78E+07	2.54E+07	2.92E+07	1.34E+07	6.01E+06	1.06E+04	3.08E+02	1.38E+01	2.08E-01	0.	0.
PU-242	9.98E+03	9.98E+03	9.98E+03	9.97E+03	9.96E+03	9.89E+03	9.80E+03	9.11E+03	8.31E+03	4.00E+03	1.60E+03
PU-241	3.09E+08	2.97E+07	1.16E+07	8.74E+02	8.39E+02	6.00E+02	3.04E+02	1.38E+01	2.08E-01	0.	0.
PU-240	3.68E+06	3.67E+06	3.66E+06	3.51E+06	3.34E+06	2.21E+06	1.33E+06	2.19E+04	1.30E+02	0.	0.
PU-239	2.72E+06	2.72E+06	2.72E+06	2.69E+06	2.65E+06	2.37E+06	2.06E+06	6.66E+05	1.61E+05	1.87E+00	1.27E-06
PU-238	1.09E+07	7.42E+06	6.35E+06	2.79E+05	6.80E+03	1.68E-05	0.	0.	0.	0.	0.
PU-236	2.30E+01	1.21E-04	9.30E-07	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	4.38E+03	5.13E+03	5.46E+03	1.02E+04	1.34E+04	1.58E+04	1.58E+04	1.56E+04	1.53E+04	1.35E+04	1.15E+04
U-238+TH-234+PA-234M	9.52E+03	9.52E+03	9.52E+03	9.52E+03	9.52E+03	9.52E+03	9.52E+03	9.52E+03	9.52E+03	9.52E+03	9.52E+03
U-236	1.76E+03	1.77E+03	1.77E+03	1.81E+03	1.86E+03	2.18E+03	2.43E+03	2.80E+03	2.80E+03	2.77E+03	2.73E+03
U-235+TH-231	4.29E+02	4.30E+02	4.30E+02	4.32E+02	4.35E+02	4.54E+02	4.76E+02	5.72E+02	6.07E+02	6.18E+02	6.18E+02
U-234	9.82E+03	1.11E+04	1.15E+04	1.36E+04	1.38E+04	1.36E+04	1.35E+04	1.24E+04	1.12E+04	5.78E+03	3.81E+03
U-233	7.54E-01	1.26E+00	1.49E+00	8.23E+00	2.13E+01	1.52E+02	3.16E+02	1.50E+03	2.70E+03	6.28E+03	6.08E+03
U-232	9.58E+01	5.98E+01	4.93E+01	9.90E-01	8.03E-03	0.	0.	0.	0.	0.	0.
PA-231	2.39E-01	4.71E-01	5.64E-01	2.35E+00	4.46E+00	2.24E+01	4.37E+01	1.73E+02	2.55E+02	3.09E+02	3.09E+02
TH-230	1.67E+00	6.22E+00	8.17E+00	5.20E+01	1.12E+02	5.74E+02	1.13E+03	4.48E+03	7.10E+03	6.79E+03	4.12E+03
TH-229+7 DAUGHTERS	4.10E-03	4.20E-02	6.28E-02	1.39E+00	6.83E+00	2.31E+02	8.73E+02	9.44E+03	1.97E+04	5.04E+04	4.89E+04
TH-228+6 DAUGHTERS	6.77E+02	4.30E+02	3.55E+02	7.12E+00	5.84E-02	3.40E-03	7.39E-03	4.07E-02	9.28E-02	4.75E-01	9.48E-01
AC-227+7 DAUGHTERS	3.82E-01	2.54E+00	3.32E+00	1.85E+01	3.73E+01	1.79E+02	3.50E+02	1.39E+03	2.04E+03	2.47E+03	2.47E+03
TH-232+2 DAUGHTERS	1.42E-06	1.25E-05	1.77E-05	1.23E-04	2.61E-04	1.46E-03	3.17E-03	1.42E-02	3.98E-02	2.04E-01	4.06E-01
RA-226+5 DAUGHTERS	4.85E-02	5.50E-01	9.17E-01	2.89E+01	1.22E+02	2.03E+03	5.26E+03	2.76E+04	4.29E+04	4.07E+04	2.47E+04
PB-210+2 DAUGHTERS	5.31E-03	1.30E-01	2.47E-01	1.41E+01	6.12E+01	1.02E+03	2.63E+03	1.38E+04	2.15E+04	2.04E+04	1.24E+04
TOTAL	3.47E+08	6.97E+07	5.01E+07	2.01E+07	1.22E+07	4.75E+06	3.51E+06	7.98E+05	3.05E+05	1.64E+05	1.29E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.2.2a. Radioactivity Inventory--Once-Through Cycle--Growth Case 2, Curies(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	3.20E+06	1.06E+06	3.43E+05	4.03E-05	0.	0.	0.	0.	0.	0.	0.
C-14	1.61E+04	3.83E+04	3.82E+04	3.64E+04	3.43E+04	2.11E+04	1.15E+04	9.17E+01	2.17E-01	0.	0.
MN-54	3.49E+02	5.57E-07	0.	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	3.06E+06	3.40E+03	1.45E+01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	1.31E+07	4.68E+05	3.36E+04	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	5.96E+04	1.43E+05	1.43E+05	1.42E+05	1.42E+05	1.37E+05	1.31E+05	9.26E+04	6.01E+04	1.88E+03	2.48E+01
NI-63	8.37E+06	1.91E+07	1.30E+07	6.10E+05	1.41E+04	1.18E-09	0.	0.	0.	0.	0.
SE-79	6.80E+03	1.65E+04	1.64E+04	1.64E+04	1.63E+04	1.56E+04	1.48E+04	9.66E+03	5.67E+03	7.99E+01	3.88E-01
KR-85	6.62E+07	1.73E+07	4.81E+06	2.36E-05	0.	0.	0.	0.	0.	0.	0.
RB-87	3.35E-01	8.12E-01	8.12E-01	8.12E-01	8.12E-01	8.12E-01	8.12E-01	8.12E-01	8.12E-01	8.12E-01	8.12E-01
SR-90+Y-90	1.73E+09	1.69E+09	1.03E+09	4.66E+04	2.07E-01	0.	0.	0.	0.	0.	0.
ZR-93	3.23E+04	7.81E+04	7.81E+04	7.81E+04	7.81E+04	7.79E+04	7.78E+04	7.63E+04	7.46E+04	6.20E+04	4.92E+04
NB-93M	1.95E+04	7.31E+04	7.64E+04	7.82E+04	7.82E+04	7.80E+04	7.78E+04	7.64E+04	7.47E+04	6.21E+04	4.93E+04
TC-99	2.51E+05	6.05E+05	6.05E+05	6.04E+05	6.03E+05	5.95E+05	5.85E+05	5.13E+05	4.35E+05	1.16E+05	2.23E+04
RU-106+RH-106	3.06E+06	1.25E-01	1.29E-07	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	1.93E+03	4.60E+03	4.60E+03	4.60E+03	4.60E+03	4.60E+03	4.59E+03	4.57E+03	4.55E+03	4.38E+03	4.16E+03
AG-110M	3.88E+02	9.08E-09	0.	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	7.46E+04	3.01E+04	1.12E+04	2.11E-05	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	4.85E+06	6.60E+03	3.90E+01	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	2.79E+04	6.68E+04	6.68E+04	6.66E+04	6.64E+04	6.46E+04	6.24E+04	4.73E+04	3.34E+04	2.09E+03	6.57E+01
I-129	6.49E+02	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.54E+03	1.52E+03	1.49E+03
CS-134	3.32E+07	5.62E+03	6.53E+00	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	5.16E+03	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.26E+04	1.25E+04	1.23E+04	1.12E+04	1.00E+04
CS-137+BA-137	2.42E+09	2.48E+09	1.57E+09	1.33E+05	1.29E+00	0.	0.	0.	0.	0.	0.
CE-144+PR-144	7.32E+05	3.38E-04	0.	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	4.13E+07	5.68E+04	2.87E+02	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	1.98E+07	3.52E+07	3.00E+07	1.18E+06	2.91E+04	3.26E-10	0.	0.	0.	0.	0.
EU-152	9.81E+04	3.15E+04	9.93E+03	6.59E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	5.49E+07	2.75E+07	1.16E+07	2.69E-01	1.07E-10	0.	0.	0.	0.	0.	0.
EU-155	6.79E+05	3.85E+01	1.83E-02	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	2.73E+01	2.22E-10	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	4.40E+09	4.28E+09	2.64E+09	3.01E+06	1.07E+06	1.01E+06	9.79E+05	8.34E+05	7.02E+05	2.62E+05	1.37E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.2.2b. Radioactivity Inventory--Once-Through Cycle--Growth Case 2, Curies(A)

Actinides

RADIONUCLIDES (B)	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	3.31E+03	8.03E+03	8.02E+03	7.75E+03	7.43E+03	5.31E+03	3.49E+03	1.32E+02	1.84E+00	0.	0.
CM-244	1.34E+07	7.90E+06	3.67E+06	6.48E-01	3.13E-09	0.	0.	0.	0.	0.	0.
CM-243	5.37E+04	5.75E+04	3.73E+04	5.65E+00	1.12E-04	0.	0.	0.	0.	0.	0.
CM-242	1.50E+05	3.22E+05	2.04E+05	4.61E+04	4.71E+03	5.64E-05	0.	0.	0.	0.	0.
AM-243+NP-239	5.27E+05	1.27E+06	1.26E+06	1.22E+06	1.16E+06	8.11E+05	5.15E+05	1.37E+04	1.48E+02	0.	0.
AM-242M+AM-242	3.68E+05	7.88E+05	7.15E+05	1.12E+05	1.19E+04	1.37E-04	0.	0.	0.	0.	0.
AM-241	4.22E+07	1.58E+08	1.62E+08	8.79E+07	3.45E+07	7.09E+04	3.52E+03	1.32E+02	1.84E+00	0.	0.
PU-242	3.09E+04	7.41E+04	7.41E+04	7.41E+04	7.40E+04	7.35E+04	7.28E+04	6.77E+04	6.17E+04	2.97E+04	1.19E+04
PU-241	1.01E+09	4.44E+08	1.74E+08	7.76E+03	7.45E+03	5.32E+03	3.50E+03	1.32E+02	1.84E+00	0.	0.
PU-240	8.97E+06	2.12E+07	2.12E+07	2.03E+07	1.93E+07	1.28E+07	7.47E+06	1.27E+05	7.53E+02	0.	0.
PU-239	5.80E+06	1.38E+07	1.38E+07	1.36E+07	1.34E+07	1.20E+07	1.05E+07	3.40E+06	8.22E+05	9.54E+00	6.46E-06
PU-238	3.61E+07	6.51E+07	5.57E+07	2.44E+06	5.97E+04	1.36E-04	0.	0.	0.	0.	0.
PU-236	1.80E+02	3.10E-01	2.39E-03	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	1.22E+04	3.31E+04	3.52E+04	6.55E+04	8.68E+04	1.03E+05	1.03E+05	1.02E+05	1.00E+05	8.79E+04	7.48E+04
U-238+TH-234+ PA-234M	1.90E+04	4.54E+04	4.54E+04	4.54E+04	4.54E+04	4.54E+04	4.54E+04	4.54E+04	4.54E+04	4.54E+04	4.54E+04
U-236	4.34E+03	1.06E+04	1.06E+04	1.09E+04	1.12E+04	1.30E+04	1.45E+04	1.66E+04	1.66E+04	1.64E+04	1.62E+04
U-235+TH-231	6.57E+02	1.68E+03	1.69E+03	1.70E+03	1.71E+03	1.81E+03	1.92E+03	2.41E+03	2.59E+03	2.64E+03	2.64E+03
U-234	1.96E+04	5.83E+04	6.17E+04	7.98E+04	8.17E+04	8.10E+04	8.01E+04	7.32E+04	6.56E+04	3.16E+04	1.92E+04
U-233	1.75E+00	6.90E+00	8.36E+00	5.07E+01	1.37E+02	9.84E+02	2.06E+03	9.78E+03	1.76E+04	4.10E+04	3.97E+04
U-232	3.15E+02	5.45E+02	4.49E+02	9.02E+00	7.32E-02	0.	0.	0.	0.	0.	0.
PA-231	6.11E-01	2.20E+00	2.56E+00	9.39E+00	1.86E+01	8.87E+01	1.74E+02	7.18E+02	1.08E+03	1.32E+03	1.32E+03
TH-230	3.21E+00	2.60E+01	3.64E+01	2.83E+02	6.46E+02	3.38E+03	6.67E+03	2.71E+04	4.18E+04	3.79E+04	2.11E+04
TH-229+7 DAUGHTERS	6.14E-03	1.91E-01	3.06E-01	8.15E+00	4.30E+01	1.49E+03	5.68E+03	6.28E+04	1.29E+05	3.29E+05	3.19E+05
TH-228+6 DAUGHTERS	2.14E+03	3.92E+03	3.23E+03	6.48E+01	5.30E-01	2.02E-02	4.40E-02	2.65E-01	5.50E-01	2.81E+00	5.61E+00
AC-227+7 DAUGHTERS	6.38E-01	1.16E+01	1.52E+01	7.36E+01	1.49E+02	7.10E+02	1.40E+03	5.74E+03	8.62E+03	1.06E+04	1.06E+04
TH-232+2 DAUGHTERS	3.47E-06	5.83E-05	8.94E-05	7.05E-04	1.35E-03	8.67E-03	1.89E-02	1.14E-01	2.36E-01	1.21E+00	2.40E+00
RA-226+5 DAUGHTERS	8.69E-02	1.92E+00	3.52E+00	1.47E+02	6.84E+02	1.19E+04	3.11E+04	1.43E+05	2.53E+05	2.28E+05	1.27E+05
PB-210+2 DAUGHTERS	8.87E-03	4.13E-01	8.81E-01	7.09E+01	3.42E+02	5.96E+03	1.55E+04	7.15E+04	1.27E+05	1.14E+05	6.33E+04
TOTAL	1.11E+09	7.13E+08	4.33E+08	1.26E+08	7.38E+07	2.61E+07	1.91E+07	4.30E+06	1.69E+06	9.75E+05	7.52E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.2.3a. Radioactivity Inventory--Once-Through Cycle--Growth Case 3, Curies(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
H-3	5.24E+06	1.72E+07	3.95E+06	4.64E-04	0.	0.	0.	0.	0.	0.	0.
C-14	2.59E+04	1.99E+05	1.98E+05	1.89E+05	1.78E+05	1.10E+05	5.09E+04	4.76E+02	1.13E+00	0.	0.
MN-54	5.78E+02	1.15E+02	6.65E-06	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	5.84E+06	2.93E+06	1.23E+04	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	2.29E+07	2.11E+07	1.91E+06	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	9.27E+04	7.22E+05	7.22E+05	7.20E+05	7.17E+05	6.92E+05	6.63E+05	4.49E+05	3.04E+05	9.52E+03	1.25E+02
NI-63	1.32E+07	8.43E+07	7.95E+07	5.41E+06	7.00E+04	6.58E-09	0.	0.	0.	0.	0.
SE-79	1.03E+04	4.26E+04	8.25E+04	8.22E+04	8.18E+04	7.83E+04	7.43E+04	4.45E+04	2.45E+04	4.01E+02	1.95E+00
KR-85	1.09E+08	2.27E+08	6.30E+07	3.09E-04	0.	0.	0.	0.	0.	0.	0.
RB-87	5.05E-01	4.08E+00	4.08E+00	4.08E+00	4.08E+00	4.08E+00	4.08E+00	4.08E+00	4.08E+00	4.08E+00	4.08E+00
SR-90+Y-90	2.72E+09	1.19E+10	7.29E+09	3.28E+05	1.66E+00	0.	0.	0.	0.	0.	0.
ZR-93	8.90E+04	3.92E+05	3.92E+05	3.92E+05	3.92E+05	3.91E+05	3.90E+05	3.83E+05	3.74E+05	3.11E+05	2.47E+05
NB-93M	2.81E+04	3.39E+05	3.73E+05	3.92E+05	3.92E+05	3.92E+05	3.91E+05	3.83E+05	3.75E+05	3.11E+05	2.47E+05
TC-99	3.81E+05	3.04E+06	3.03E+06	3.03E+06	3.03E+06	2.99E+06	2.94E+06	2.47E+06	2.18E+06	5.83E+05	1.12E+05
RU-106+RH-106	4.93E+06	1.03E+04	1.05E+00	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	2.93E+03	2.31E+04	2.31E+04	2.31E+04	2.31E+04	2.31E+04	2.30E+04	2.30E+04	2.28E+04	2.20E+04	2.09E+04
AG-110M	8.90E+02	6.93E+01	1.43E-07	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	1.18E+05	3.11E+05	1.15E+05	2.18E-04	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	9.01E+06	3.88E+06	2.29E+04	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	4.24E+04	3.35E+05	3.35E+05	3.34E+05	3.33E+05	3.28E+05	3.13E+05	2.37E+05	1.68E+05	1.05E+04	3.30E+02
I-129	9.79E+02	7.78E+03	7.78E+03	7.78E+03	7.78E+03	7.78E+03	7.78E+03	7.77E+03	7.75E+03	7.63E+03	7.47E+03
CS-134	9.91E+07	1.91E+07	2.22E+04	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	7.64E+03	6.31E+04	6.31E+04	6.31E+04	6.31E+04	6.30E+04	6.30E+04	6.24E+04	6.17E+04	5.62E+04	5.01E+04
CS-137+BA-137	3.79E+09	1.71E+10	1.08E+10	9.16E+05	8.87E+00	0.	0.	0.	0.	0.	0.
CE-144+PR-144	1.06E+06	2.40E+05	4.39E-03	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	7.98E+07	3.99E+07	2.02E+05	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	3.09E+07	1.96E+08	1.67E+08	6.60E+06	1.23E+05	1.82E-09	0.	0.	0.	0.	0.
EU-152	1.57E+05	3.70E+05	1.17E+05	7.75E-06	0.	0.	0.	0.	0.	0.	0.
EU-154	8.65E+07	2.57E+08	1.08E+08	2.52E+00	1.00E-09	0.	0.	0.	0.	0.	0.
EU-155	1.19E+06	3.52E+05	1.67E+02	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	3.42E+01	7.46E+00	6.32E-09	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	6.94E+09	2.99E+10	1.85E+10	1.65E+07	5.42E+06	5.07E+06	4.92E+06	4.19E+06	3.52E+06	1.31E+06	6.85E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.2.3b. Radioactivity Inventory--Once-Through Cycle--Growth Case 3, Curies$^{(A)}$

Actinides

	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
RADIONUCLIDES (B)	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	8.84E+03	4.08E+04	4.08E+04	3.94E+04	3.78E+04	2.70E+04	1.78E+04	6.30E+02	9.36E+00	0.	0.
CM-244	2.03E+07	6.86E+07	3.19E+07	5.63E+00	2.72E-08	0.	0.	0.	0.	0.	0.
CM-243	7.95E+04	3.88E+05	2.52E+05	3.81E+01	7.43E-04	0.	0.	0.	0.	0.	0.
CM-242	2.11E+05	1.71E+06	1.56E+06	2.45E+05	2.51E+04	3.00E-04	0.	0.	0.	0.	0.
AM-243+NP-239	7.74E+05	6.39E+06	6.38E+06	6.15E+06	5.88E+06	4.09E+06	2.60E+06	5.93E+04	7.47E+02	0.	0.
AM-242M+AM-242	5.72E+05	4.17E+06	3.81E+06	5.98E+05	6.11E+04	7.30E-04	0.	0.	0.	0.	0.
AM-241	6.14E+07	7.37E+08	8.04E+08	4.51E+08	2.03E+08	3.64E+05	1.79E+04	6.21E+02	9.38E+00	0.	0.
PU-242	8.61E+04	3.72E+05	3.72E+05	3.72E+05	3.72E+05	3.69E+05	3.66E+05	3.40E+05	3.10E+05	1.49E+05	5.98E+04
PU-241	1.65E+09	4.39E+09	1.72E+09	3.95E+04	3.79E+04	2.71E+04	1.78E+04	6.21E+02	9.38E+00	0.	0.
PU-240	1.40E+07	1.06E+08	1.06E+08	1.02E+08	9.65E+07	6.42E+07	3.84E+07	4.36E+05	3.77E+03	0.	0.
PU-239	9.28E+06	6.90E+07	6.90E+07	6.82E+07	6.73E+07	6.04E+07	5.26E+07	1.71E+07	4.12E+06	4.78E+01	3.24E-05
PU-238	5.37E+07	3.63E+08	3.11E+08	1.36E+07	3.25E+05	7.24E-04	0.	0.	0.	0.	0.
PU-236	3.16E+02	1.35E+02	1.04E+00	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	1.83E+04	1.60E+05	1.79E+05	3.22E+05	4.34E+05	5.18E+05	5.18E+05	5.11E+05	5.03E+05	4.42E+05	3.76E+05
U-238+TH-234+ PA-234M	3.05E+04	2.27E+05	2.27E+05	2.27E+05	2.27E+05	2.27E+05	2.27E+05	2.27E+05	2.27E+05	2.27E+05	2.27E+05
U-236	6.60E+03	5.33E+04	5.34E+04	5.45E+04	5.60E+04	6.51E+04	7.25E+04	8.31E+04	8.32E+04	8.22E+04	8.10E+04
U-235+TH-231	1.07E+03	8.44E+03	8.45E+03	8.50E+03	8.57E+03	9.06E+03	9.61E+03	1.21E+04	1.30E+04	1.33E+04	1.32E+04
U-234	2.96E+04	2.80E+05	2.95E+05	3.95E+05	4.10E+05	4.07E+05	4.02E+05	3.47E+05	3.29E+05	1.58E+05	9.59E+04
U-233	2.60E+00	3.02E+01	3.73E+01	2.40E+02	6.71E+02	4.92E+03	1.03E+04	4.92E+04	8.86E+04	2.06E+05	1.99E+05
U-232	4.66E+02	3.12E+03	2.58E+03	5.17E+01	4.19E-01	0.	0.	0.	0.	0.	0.
PA-231	8.75E-01	9.83E+00	1.17E+01	4.52E+01	9.17E+01	4.43E+02	8.73E+02	3.60E+03	5.40E+03	6.63E+03	6.62E+03
TH-230	8.49E+00	9.84E+01	1.49E+02	1.34E+03	3.18E+03	1.69E+04	3.34E+04	1.36E+05	2.10E+05	1.90E+05	1.05E+05
TH-229+7 DAUGHTERS	7.35E-03	6.83E-01	1.19E+00	3.72E+01	2.08E+02	7.42E+03	2.84E+04	3.16E+05	6.47E+05	1.65E+06	1.60E+06
TH-228+6 DAUGHTERS	3.10E+03	2.23E+04	1.85E+04	3.72E+02	3.03E+00	1.01E-01	2.20E-01	1.33E+00	2.76E+00	1.41E+01	2.81E+01
AC-227+7 DAUGHTERS	7.48E-01	4.59E+01	6.55E+01	3.51E+02	7.34E+02	3.54E+03	6.08E+03	2.88E+04	4.32E+04	5.30E+04	5.30E+04
TH-232+2 DAUGHTERS	5.13E-06	2.12E-04	3.65E-04	3.38E-03	7.64E-03	4.33E-02	9.44E-02	5.69E-01	1.18E+00	6.05E+00	1.21E+01
RA-226+5 DAUGHTERS	1.13E-01	6.04E+00	1.24E+01	6.70E+02	3.32E+03	5.94E+04	1.56E+05	8.18E+05	1.27E+06	1.18E+06	6.53E+05
PB-210+2 DAUGHTERS	1.09E-02	1.17E+00	2.46E+00	3.17E+02	1.66E+03	2.97E+04	7.79E+04	4.09E+05	6.35E+05	5.71E+05	3.17E+05
TOTAL	1.81E+09	5.75E+09	3.06E+09	6.43E+08	3.75E+08	1.31E+08	9.56E+07	2.11E+07	8.49E+06	4.89E+06	3.77E+06

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.2.4a. Radioactivity Inventory--Once-Through Cycle--Growth Case 4, Curies(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	3.08E+04	2.35E+07	7.61E+06	8.94E-04	0.	0.	0.	0.	0.	0.	0.
C-14	9.68E+02	2.63E+05	2.63E+05	2.50E+05	2.35E+05	1.45E+05	7.83E+04	6.20E+02	1.49E+00	0.	0.
MN-54	3.57E-05	9.25E+02	5.17E-05	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	2.77E+03	1.23E+07	5.05E+04	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	6.11E+04	6.44E+07	4.63E+06	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	1.41E+03	9.52E+05	9.52E+05	9.49E+05	9.45E+05	9.13E+05	8.74E+05	6.18E+05	4.01E+05	1.26E+04	1.65E+02
NI-63	1.83E+05	1.16E+08	1.00E+08	4.70E+06	1.09E+05	9.07E-09	0.	0.	0.	0.	0.
SE-79	1.61E+02	1.08E+05	1.08E+05	1.08E+05	1.07E+05	1.03E+05	9.75E+04	6.37E+04	3.74E+04	5.26E+02	2.55E+00
KR-85	7.52E+05	4.59E+08	1.27E+08	6.25E-04	0.	0.	0.	0.	0.	0.	0.
RB-87	7.93E-03	5.35E+00	5.35E+00	5.35E+00	5.35E+00	5.35E+00	5.35E+00	5.35E+00	5.35E+00	5.35E+00	5.35E+00
SR-90+Y-90	3.12E+07	1.83E+10	1.12E+10	5.02E+05	2.23E+00	0.	0.	0.	0.	0.	0.
ZR-93	7.65E+02	5.15E+05	5.15E+05	5.14E+05	5.14E+05	5.13E+05	5.12E+05	5.03E+05	4.91E+05	4.08E+05	3.24E+05
NB-93M	5.80E+02	4.16E+05	4.79E+05	5.15E+05	5.15E+05	5.14E+05	5.13E+05	5.03E+05	4.92E+05	4.09E+05	3.25E+05
TC-99	5.99E+03	3.99E+06	3.99E+06	3.98E+06	3.98E+06	3.92E+06	3.86E+06	3.38E+06	2.87E+06	7.67E+05	1.47E+05
RU-106+RH-106	1.80E+00	8.28E+06	8.51E+00	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	4.52E+01	3.04E+04	3.04E+04	3.04E+04	3.04E+04	3.04E+04	3.04E+04	3.02E+04	3.01E+04	2.89E+04	2.75E+04
AG-110M	7.04E-07	7.64E+02	1.57E-06	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	7.90E+02	5.75E+05	2.14E+05	8.03E-04	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	3.69E+03	1.92E+07	1.14E+05	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	6.52E+02	4.41E+05	4.41E+05	4.40E+05	4.38E+05	4.26E+05	4.12E+05	3.12E+05	2.21E+05	1.38E+04	4.34E+02
I-129	1.53E+01	1.02E+04	1.02E+04	1.02E+04	1.02E+04	1.02E+04	1.02E+04	1.02E+04	1.02E+04	1.00E+04	9.82E+03
CS-134	5.36E+03	1.17E+08	1.36E+05	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	1.04E+02	8.25E+04	8.25E+04	8.25E+04	8.25E+04	8.24E+04	8.23E+04	8.15E+04	8.06E+04	7.35E+04	6.55E+04
CS-137+BA-137	4.43E+07	2.60E+10	1.64E+10	1.39E+06	1.35E+01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	1.43E-02	1.74E+06	3.19E-02	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	3.60E+04	1.73E+08	8.73E+05	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	4.89E+05	2.71E+08	2.31E+08	9.11E+06	1.90E+05	2.51E-09	0.	0.	0.	0.	0.
EU-152	1.05E+03	7.10E+05	2.24E+05	1.49E-05	0.	0.	0.	0.	0.	0.	0.
EU-154	6.46E+05	4.93E+08	1.91E+08	4.43E+00	1.76E-09	0.	0.	0.	0.	0.	0.
EU-155	5.38E+01	2.30E+06	1.09E+03	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	9.20E-08	5.51E+01	4.70E-08	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	7.77E+07	4.60E+10	2.82E+10	2.26E+07	7.13E+06	6.66E+06	6.47E+06	5.90E+06	4.63E+06	1.72E+06	8.99E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.2.4b. Radioactivity Inventory--Once-Through Cycle--Growth Case 4, Curies(A)

Actinides

RADIONUCLIDES (B)	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
CM-245	4.79E+01	5.35E+04	5.34E+04	5.16E+04	4.95E+04	3.54E+04	2.33E+04	8.12E+02	1.23E+01	0.	0.
CM-244	1.27E+05	1.16E+08	5.40E+07	9.54E+00	4.60E-08	0.	0.	0.	0.	0.	0.
CM-243	6.43E+02	5.82E+05	3.77E+05	5.71E+01	1.13E-03	0.	0.	0.	0.	0.	0.
CM-242	1.42E+03	2.30E+06	2.10E+06	3.30E+05	3.37E+04	4.04E-04	0.	0.	0.	0.	0.
AM-243+NP-239	8.78E+03	8.39E+06	8.38E+06	8.07E+06	7.72E+06	5.37E+06	3.41E+06	8.10E+04	9.80E+02	0.	0.
AM-242M+AM-242	6.42E+03	5.61E+06	5.12E+06	8.05E+05	8.23E+04	9.83E-04	0.	0.	0.	0.	0.
AM-241	1.34E+06	9.06E+08	1.04E+09	6.01E+08	2.70E+08	4.84E+05	2.35E+04	8.14E+02	1.23E+01	0.	0.
PU-242	5.96E+02	4.90E+05	4.90E+05	4.89E+05	4.89E+05	4.85E+05	4.81E+05	4.47E+05	4.08E+05	1.96E+05	7.87E+04
PU-241	1.42E+07	7.99E+09	3.13E+09	5.17E+04	4.06E+04	3.55E+04	2.33E+04	8.14E+02	1.23E+01	0.	0.
PU-240	2.53E+05	1.40E+08	1.40E+08	1.35E+08	1.28E+08	8.49E+07	5.08E+07	4.41E+05	4.99E+03	0.	0.
PU-239	1.92E+05	9.13E+07	9.13E+07	9.03E+07	8.81E+07	7.98E+07	6.96E+07	2.26E+07	5.45E+06	6.33E+01	4.29E-05
PU-238	5.85E+05	4.98E+08	4.26E+08	1.86E+07	4.43E+05	9.75E-04	0.	0.	0.	0.	0.
PU-236	1.15E-01	6.93E+02	5.35E+00	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	2.67E+02	2.07E+05	2.20E+05	4.18E+05	5.69E+05	6.82E+05	6.82E+05	6.74E+05	6.63E+05	5.82E+05	4.95E+05
U-238+TH-234+ PA-234M	6.73E+02	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05
U-236	1.05E+02	6.98E+04	6.99E+04	7.13E+04	7.33E+04	8.54E+04	9.51E+04	1.09E+05	1.09E+05	1.08E+05	1.06E+05
U-235+TH-231	2.47E+01	1.10E+04	1.10E+04	1.11E+04	1.11E+04	1.18E+04	1.25E+04	1.58E+04	1.70E+04	1.73E+04	1.73E+04
U-234	8.03E+02	3.55E+05	3.81E+05	5.16E+05	5.34E+05	5.30E+05	5.24E+05	4.79E+05	4.29E+05	2.07E+05	1.26E+05
U-233	4.64E-02	3.71E+01	4.62E+01	3.04E+02	8.72E+02	6.45E+03	1.36E+04	6.48E+04	1.17E+05	2.71E+05	2.63E+05
U-232	5.00E+00	4.30E+03	3.57E+03	7.16E+01	5.81E-01	0.	0.	0.	0.	0.	0.
PA-231	1.48E-02	1.22E+01	1.45E+01	5.79E+01	1.18E+02	5.75E+02	1.14E+03	4.70E+03	7.07E+03	8.67E+03	8.67E+03
TH-230	1.23E-01	1.12E+02	1.76E+02	1.69E+03	4.10E+03	2.20E+04	4.35E+04	1.77E+05	2.74E+05	2.48E+05	1.39E+05
TH-229+7 DAUGHTERS	3.54E-06	6.74E-01	1.30E+00	4.59E+01	2.48E+02	9.71E+03	3.74E+04	4.16E+05	8.52E+05	2.18E+06	2.11E+06
TH-228+6 DAUGHTERS	3.11E+01	3.06E+04	2.56E+04	5.15E+02	4.20E+00	1.32E-01	2.89E-01	1.74E+00	3.62E+00	1.86E+01	3.70E+01
AC-227+7 DAUGHTERS	3.76E-04	4.96E+01	7.72E+01	4.44E+02	9.48E+02	4.60E+03	9.09E+03	3.76E+04	5.65E+04	6.94E+04	6.93E+04
TH-232+2 DAUGHTERS	2.95E-07	1.93E-04	3.86E-04	4.26E-03	9.49E-03	5.66E-02	1.24E-01	7.48E-01	1.55E+00	7.95E+00	1.58E+01
RA-226+5 DAUGHTERS	4.69E-03	6.45E+00	1.38E+01	8.22E+02	4.24E+03	7.69E+04	2.03E+05	1.07E+06	1.66E+06	1.49E+06	8.32E+05
PB-210+2 DAUGHTERS	6.02E-04	1.21E+00	3.11E+00	3.84E+02	2.12E+03	3.85E+04	1.01E+05	5.33E+05	8.28E+05	7.46E+05	4.16E+05
TOTAL	1.67E+07	9.76E+09	4.90E+09	8.55E+08	4.07E+08	1.73E+08	1.26E+08	2.78E+07	1.12E+07	6.43E+06	4.97E+06

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.2.5a. Radioactivity Inventory--Once-Through Cycle--Growth Case 5, Curies(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	3.98E+04	3.78E+07	1.23E+07	1.44E-03	0.	0.	0.	0.	0.	0.	0.
C-14	3.68E+02	3.59E+05	3.58E+05	3.41E+05	3.21E+05	1.98E+05	1.08E+05	8.49E+02	2.04E+00	0.	0.
MN-54	3.57E-05	1.75E+03	9.40E-05	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	2.77E+03	2.26E+07	1.10E+05	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	6.11E+04	1.14E+08	8.20E+06	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	1.41E+03	1.30E+06	1.30E+06	1.29E+06	1.29E+06	1.24E+06	1.19E+06	8.41E+05	5.45E+05	1.71E+04	2.25E+02
NI-63	1.83E+05	1.63E+08	1.40E+08	6.58E+06	1.52E+05	1.27E-08	0.	0.	0.	0.	0.
SE-79	1.61E+02	1.47E+05	1.47E+05	1.47E+05	1.46E+05	1.40E+05	1.32E+05	9.45E+04	5.08E+04	7.15E+02	3.47E+00
KR-85	7.52E+05	7.50E+08	2.09E+08	1.02E-03	0.	0.	0.	0.	0.	0.	0.
RB-87	7.93E-03	7.26E+00	7.25E+00	7.26E+00	7.26E+00	7.26E+00	7.26E+00	7.26E+00	7.26E+00	7.26E+00	7.26E+00
SR-90+Y-90	3.12E+07	2.70E+10	1.65E+10	7.43E+05	3.30E+00	0.	0.	0.	0.	0.	0.
ZR-93	7.65E+02	6.99E+05	6.99E+05	6.99E+05	6.98E+05	6.97E+05	6.96E+05	6.83E+05	6.67E+05	5.55E+05	4.40E+05
NB-93M	5.80E+02	5.42E+05	6.83E+05	6.99E+05	6.99E+05	6.98E+05	6.96E+05	6.84E+05	6.68E+05	5.55E+05	4.41E+05
TC-99	5.99E+03	5.42E+06	5.48E+06	5.41E+06	5.40E+06	5.33E+06	5.24E+06	4.49E+06	3.90E+06	1.04E+06	2.00E+05
RU-106+RH-106	1.80E+00	1.58E+07	1.43E+01	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	4.52E+01	4.14E+04	4.14E+04	4.14E+04	4.14E+04	4.14E+04	4.13E+04	4.12E+04	4.10E+04	3.94E+04	3.75E+04
AG-110M	7.04E-07	1.48E+03	3.05E-06	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	7.90E+02	9.19E+05	3.42E+05	6.45E-04	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	3.69E+03	3.57E+07	2.11E+05	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	6.52E+02	6.00E+05	6.00E+05	5.98E+05	5.96E+05	5.80E+05	5.60E+05	4.25E+05	3.00E+05	1.88E+04	5.90E+02
I-129	1.53E+01	1.39E+04	1.39E+04	1.39E+04	1.39E+04	1.39E+04	1.39E+04	1.39E+04	1.38E+04	1.36E+04	1.33E+04
CS-134	5.36E+03	2.21E+08	2.57E+05	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	1.04E+02	1.12E+05	1.12E+05	1.12E+05	1.12E+05	1.12E+05	1.12E+05	1.11E+05	1.09E+05	9.97E+04	8.88E+04
CS-137+BA-137	4.43E+07	3.83E+10	2.41E+10	2.05E+06	1.44E+01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	1.43E-02	3.36E+06	6.14E-02	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	3.60E+04	3.16E+08	1.59E+06	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	4.49E+05	3.78E+08	3.23E+08	1.27E+07	2.38E+05	3.50E-09	0.	0.	0.	0.	0.
EU-152	1.05E+03	1.19E+06	3.61E+05	2.40E-05	0.	0.	0.	0.	0.	0.	0.
EU-154	6.46E+05	7.11E+08	2.49E+08	6.96E+00	2.76E-09	0.	0.	0.	0.	0.	0.
EU-155	5.38E+01	4.35E+06	2.06E+03	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	5.20E-08	1.09E+02	9.31E-08	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	7.77E+07	6.81E+10	4.16E+10	3.14E+07	9.70E+06	9.05E+06	8.79E+06	7.48E+06	6.29E+06	2.34E+06	1.22E+06

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.2.5b. Radioactivity Inventory--Once-Through Cycle--Growth Case 5, Curies(A)

Actinides

RADIONUCLIDES (B)	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
CM-245	8.79E+01	7.29E+04	7.28E+04	7.04E+04	6.95E+04	4.82E+04	3.17E+04	1.11E+03	1.67E+01	0.	0.
CM-244	1.27E+05	1.81E+08	8.40E+07	1.48E+01	7.16E-08	0.	0.	0.	0.	0.	0.
CM-243	6.43E+02	8.97E+05	5.55E+05	8.42E+01	1.66E-03	0.	0.	0.	0.	0.	0.
CM-242	1.42E+03	3.10E+06	2.91E+06	4.57E+05	4.47E+04	5.60E-04	0.	0.	0.	0.	0.
AM-243+NP-239	8.78E+03	1.14E+07	1.14E+07	1.10E+07	1.05E+07	7.32E+06	4.45E+06	1.24E+05	1.38E+03	0.	0.
AM-242M+AM-242	6.42E+03	7.77E+06	7.09E+06	1.11E+06	1.14E+05	1.36E-03	0.	0.	0.	0.	0.
AM-241	1.38E+06	1.18E+09	1.40E+09	8.23E+08	3.90E+08	6.63E+05	3.20E+04	1.11E+03	1.67E+01	0.	0.
PU-242	5.96E+02	6.67E+05	6.47E+05	6.67E+05	6.66E+05	6.61E+05	6.55E+05	6.09E+05	5.56E+05	2.67E+05	1.07E+05
PU-241	1.42E+07	1.27E+10	4.06E+09	7.04E+04	6.76E+04	4.83E+04	3.18E+04	1.11E+03	1.67E+01	0.	0.
PU-240	2.55E+05	1.91E+08	1.01E+08	1.83E+08	1.74E+08	1.16E+08	6.02E+07	1.14E+06	6.79E+03	0.	0.
PU-239	1.82E+05	1.24E+08	1.24E+08	1.23E+08	1.21E+08	1.08E+08	9.45E+07	3.86E+07	7.61E+06	8.60E+01	5.82E-05
PU-238	5.85E+05	6.97E+08	5.97E+08	2.60E+07	6.20E+05	1.35E-05	0.	0.	0.	0.	0.
PU-236	1.15E-01	1.30E+03	1.00E+01	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	2.67E+02	2.78E+05	2.95E+05	5.65E+05	7.73E+05	9.28E+05	9.29E+05	8.17E+05	8.03E+05	7.93E+05	6.74E+05
U-238+TH-234+PA-234M	6.73E+02	4.06E+05	4.06E+05	4.06E+05	4.06E+05	4.06E+05	4.06E+05	4.06E+05	4.06E+05	4.06E+05	4.06E+05
U-236	1.05E+02	9.46E+04	9.47E+04	9.67E+04	9.84E+04	1.16E+05	1.29E+05	1.48E+05	1.48E+05	1.47E+05	1.45E+05
U-235+TH-231	2.47E+01	1.47E+04	1.47E+04	1.48E+04	1.49E+04	1.58E+04	1.68E+04	2.12E+04	2.29E+04	2.34E+04	2.33E+04
U-234	9.05E+02	4.71E+05	5.07E+05	6.95E+05	7.22E+05	7.16E+05	7.08E+05	6.47E+05	5.80E+05	2.80E+05	1.71E+05
U-233	8.64E-02	4.80E+01	6.03E+01	4.06E+02	1.18E+03	8.77E+03	1.45E+04	6.62E+04	1.59E+05	3.69E+05	3.56E+05
U-232	9.00E+00	6.08E+03	5.15E+03	1.01E+02	6.19E-01	0.	0.	0.	0.	0.	0.
PA-231	1.49E-02	1.59E+01	1.91E+01	7.64E+01	1.48E+02	7.69E+02	1.42E+03	6.31E+03	9.91E+03	1.17E+04	1.17E+04
TH-230	1.25E-01	1.36E+02	2.21E+02	2.29E+03	5.42E+03	2.96E+04	9.87E+04	2.79E+05	3.70E+05	3.36E+05	1.86E+05
TH-229+7 DAUGHTERS	3.54E-06	7.97E-01	1.62E+00	6.07E+01	3.60E+02	1.37E+04	5.09E+04	5.46E+05	1.16E+06	2.97E+06	2.88E+06
TH-228+6 DAUGHTERS	3.11E+01	4.28E+04	3.62E+04	7.26E+02	5.02E+00	1.79E-01	3.92E-01	2.37E+00	4.92E+00	2.52E+01	5.02E+01
AC-227+7 DAUGHTERS	3.76E-04	6.05E+01	9.47E+01	5.89E+02	1.27E+03	6.15E+03	1.22E+04	5.45E+04	7.61E+04	9.34E+04	9.34E+04
TH-232+2 DAUGHTERS	2.95E-07	2.27E-04	4.84E-04	5.70E-03	1.34E-02	7.66E-02	1.68E-01	1.61E+00	2.11E+00	1.08E+01	2.15E+01
RA-226+5 DAUGHTERS	4.69E-05	7.33E+00	1.65E+01	1.08E+03	5.67E+03	1.04E+05	3.73E+05	1.64E+06	2.24E+06	2.02E+06	1.13E+06
PB-210+2 DAUGHTERS	6.02E-06	1.33E+00	3.60E+00	5.02E+02	2.44E+03	5.19E+04	1.37E+05	7.50E+05	1.12E+06	1.01E+06	5.63E+05
TOTAL	1.67E+07	1.51E+10	7.38E+09	1.17E+09	6.79E+08	2.35E+08	1.72E+08	5.78E+07	1.52E+07	8.72E+06	6.75E+06

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.
B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.2.6a. Radioactivity Inventory--Reprocessing Cycle--Growth Case 3 - 1990 Reprocessing Startup, Curies(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2170	500	1000	5000	10000	50000	100000	500000	1000000
H-3	7.44E+05	1.97E+06	6.37E+05	7.49E-05	0.	0.	0.	0.	0.	0.	0.
C-14	2.73E+04	1.90E+05	1.89E+05	1.80E+05	1.69E+05	1.04E+05	5.71E+04	4.53E+02	1.08E+00	0.	0.
MN-54	4.22E+02	1.27E+02	7.04E-06	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	5.15E+06	2.10E+06	1.02E+04	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	2.10E+07	1.94E+07	1.39E+06	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	8.89E+04	6.28E+05	6.25E+05	6.25E+05	6.23E+05	6.01E+05	5.76E+05	4.07E+05	2.64E+05	8.28E+03	1.09E+02
NI-63	1.26E+07	7.28E+07	6.26E+07	2.95E+06	6.83E+04	5.49E-09	0.	0.	0.	0.	0.
SE-79	3.25E+03	7.88E+04	7.84E+04	7.81E+04	7.77E+04	7.44E+04	7.06E+04	4.61E+04	2.70E+04	3.81E+02	1.85E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	1.60E-01	3.62E+00	3.62E+00	3.62E+00	3.62E+00	3.62E+00	3.62E+00	3.62E+00	3.62E+00	3.62E+00	3.62E+00
SR-90+Y-90	7.39E+08	1.04E+10	6.35E+09	2.86E+05	1.27E+00	0.	0.	0.	0.	0.	0.
ZR-93	1.82E+04	3.88E+05	3.84E+05	3.88E+05	3.88E+05	3.87E+05	3.87E+05	3.79E+05	3.71E+05	3.08E+05	2.45E+05
NB-93M	1.23E+04	3.37E+05	3.70E+05	3.88E+05	3.89E+05	3.89E+05	3.87E+05	3.80E+05	3.71E+05	3.09E+05	2.45E+05
TC-99	1.20E+05	3.01E+06	3.01E+06	3.00E+06	3.00E+06	2.96E+06	2.91E+06	2.55E+06	2.16E+06	5.78E+05	1.11E+05
RU-106+RH-106	1.69E+04	1.19E+06	1.22E+00	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	9.24E+02	2.88E+04	2.88E+04	2.88E+04	2.88E+04	2.87E+04	2.87E+04	2.86E+04	2.85E+04	2.74E+04	2.61E+04
AG-110M	2.67E-01	1.00E+02	2.07E-07	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	6.64E+04	6.31E+05	2.35E+05	4.43E-04	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	5.46E+05	4.69E+06	2.77E+04	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	1.33E+04	3.91E+05	3.91E+05	3.90E+05	3.88E+05	3.78E+05	3.65E+05	2.77E+05	1.96E+05	1.23E+04	3.84E+02
I-129	9.32E+02	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.29E+03	8.26E+03	8.13E+03	7.96E+03
CS-134	1.74E+06	1.91E+07	2.22E+04	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	2.37E+03	7.94E+04	7.94E+04	7.94E+04	7.94E+04	7.93E+04	7.92E+04	7.85E+04	7.76E+04	7.07E+04	6.30E+04
CS-137+BA-137	1.04E+09	1.71E+10	1.08E+10	9.13E+05	8.84E+00	0.	0.	0.	0.	0.	0.
CE-144+PR-144	8.62E+02	2.34E+05	8.24E-03	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	4.24E+06	3.88E+07	1.96E+05	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	9.45E+06	2.09E+08	1.79E+08	7.04E+06	1.31E+05	1.94E-09	0.	0.	0.	0.	0.
EU-152	3.46E+04	6.44E+05	2.03E+05	1.35E-05	0.	0.	0.	0.	0.	0.	0.
EU-154	2.05E+07	3.11E+08	1.31E+08	3.04E+00	1.21E-09	0.	0.	0.	0.	0.	0.
EU-155	2.53E+04	4.19E+05	1.08E+02	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	2.40E+00	6.72E+00	5.70E-09	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	1.86E+09	2.82E+10	1.79E+10	1.64E+07	5.35E+06	5.01E+06	4.87E+06	4.16E+06	3.91E+06	1.32E+06	6.98E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.2.6b. Radioactivity Inventory--Reprocessing Cycle--Growth Case 3 - 1990 Reprocessing Startup, Curies(A)

Actinides

RADIONUCLIDES (B)	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	1.43E+03	7.19E+05	7.18E+05	6.94E+05	6.65E+05	4.76E+05	3.13E+05	1.09E+04	1.65E+02	0.	0.
CM-244	4.81E+06	7.72E+08	3.59E+08	6.34E+01	3.06E-07	0.	0.	0.	0.	0.	0.
CM-243	2.11E+04	1.01E+06	6.56E+05	9.94E+01	1.06E-03	0.	0.	0.	0.	0.	0.
CM-242	7.02E+04	1.24E+07	1.13E+07	1.77E+06	1.81E+05	2.17E-03	0.	0.	0.	0.	0.
AM-243+NP-239	2.34E+05	2.99E+07	2.98E+07	2.87E+07	2.75E+07	1.91E+07	1.21E+07	3.24E+05	3.49E+03	0.	0.
AM-242M+AM-242	1.71E+05	3.02E+07	2.75E+07	4.32E+06	4.42E+05	5.28E-03	0.	0.	0.	0.	0.
AM-241	1.85E+07	4.04E+08	4.15E+08	2.25E+08	1.02E+08	6.65E+05	3.14E+05	1.09E+04	1.65E+02	0.	0.
PU-242	3.09E+02	1.30E+05	1.30E+05	1.30E+05	1.31E+05	1.30E+05	1.28E+05	1.19E+05	1.09E+05	5.24E+04	2.10E+04
PU-241	1.15E+07	1.18E+09	4.63E+08	6.94E+05	6.66E+05	4.77E+05	3.13E+05	1.09E+04	1.65E+02	0.	0.
PU-240	9.72E+04	1.61E+07	1.71E+07	1.73E+07	1.65E+07	1.09E+07	6.55E+06	1.08E+05	6.43E+02	0.	0.
PU-239	6.17E+04	3.59E+06	3.57E+06	3.71E+06	3.86E+06	4.67E+06	5.07E+06	2.44E+06	6.08E+05	7.06E+00	4.78E-06
PU-238	3.61E+05	1.13E+08	9.81E+07	7.03E+06	4.04E+05	5.24E-03	0.	0.	0.	0.	0.
PU-236	6.26E+00	6.45E+04	4.90E+02	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	5.74E+03	2.72E+05	2.74E+05	3.54E+05	4.09E+05	4.53E+05	4.84E+05	4.80E+05	4.43E+05	3.89E+05	3.31E+05
U-238+TH-234+PA-234M	1.46E+02	1.87E+03	1.87E+03	1.87E+03	1.87E+03	1.87E+03	1.87E+03	1.87E+03	1.88E+03	1.89E+03	1.90E+03
U-236	2.95E+01	6.45E+02	6.59E+02	8.42E+02	1.10E+03	2.66E+03	3.01E+03	5.73E+03	5.76E+03	5.69E+03	5.61E+03
U-235+TH-231	5.10E+00	6.65E+01	6.60E+01	6.93E+01	7.31E+01	1.07E+02	1.35E+02	4.63E+02	5.03E+02	6.34E+02	6.34E+02
U-234	1.35E+02	1.09E+04	1.60E+04	5.16E+04	5.09E+04	5.83E+04	5.75E+04	5.15E+04	4.48E+04	1.50E+04	4.16E+03
U-233	9.78E-02	2.02E+01	3.21E+01	2.86E+02	7.14E+02	4.46E+03	9.19E+03	4.33E+04	7.80E+04	1.81E+05	1.76E+05
U-232	2.25E+01	4.73E+05	3.92E+05	7.87E+03	6.38E+01	0.	0.	0.	0.	0.	0.
PA-231	2.63E-01	7.92E+00	7.93E+00	8.13E+00	8.04E+00	1.14E+01	1.69E+01	1.07E+02	2.18E+02	3.17E+02	3.17E+02
TH-230	1.30E+00	1.86E+01	2.11E+01	1.50E+02	4.13E+02	2.38E+03	4.75E+03	1.02E+04	2.93E+04	2.07E+04	5.84E+03
TH-229+7 DAUGHTERS	2.67E-04	2.99E-01	6.84E-01	4.37E+01	2.34E+02	6.92E+03	2.56E+04	2.78E+05	5.70E+05	1.46E+06	1.41E+06
TH-228+6 DAUGHTERS	9.04E+01	3.37E+06	2.92E+06	5.66E+04	4.89E+02	2.28E-03	6.03E-03	5.71E-02	1.25E-01	6.68E-01	1.34E+00
AC-227+7 DAUGHTERS	4.30E-01	4.18E+01	5.21E+01	6.48E+01	6.75E+01	9.11E+01	1.35E+02	8.40E+02	1.75E+03	2.54E+03	2.54E+03
TH-232+2 DAUGHTERS	1.20E-06	3.04E-06	4.32E-06	4.37E-05	1.10E-04	9.77E-04	2.75E-03	2.45E-02	5.37E-02	2.86E-01	5.73E-01
RA-226+5 DAUGHTERS	5.30E-02	1.99E+00	3.00E+00	7.20E+01	4.08E+02	8.27E+03	2.21E+04	1.16E+05	1.77E+05	1.25E+05	3.50E+04
PB-210+2 DAUGHTERS	6.33E-03	4.87E-01	8.65E-01	3.36E+01	2.04E+02	4.14E+03	1.10E+04	5.79E+04	8.86E+04	6.23E+04	1.75E+04
TOTAL	3.59E+07	2.57E+09	1.43E+09	2.90E+08	1.53E+08	3.70E+07	2.54E+07	4.05E+06	2.16E+06	2.31E+06	2.01E+06

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.2.7a. Radioactivity Inventory--Reprocessing Cycle--Growth Case 3 - 2010 Reprocessing Startup, Curies(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	1.90E+06	6.16E+05	7.25E-05	0.	0.	0.	0.	0.	0.	0.
C-14	0.	2.12E+05	2.11E+05	2.01E+05	1.89E+05	1.17E+05	6.38E+04	5.07E+02	1.20E+00	0.	0.
MN-54	0.	1.24E+02	6.92E-06	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	2.18E+06	1.06E+04	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	2.03E+07	1.46E+06	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	7.00E+05	7.00E+05	6.97E+05	6.94E+05	6.71E+05	6.42E+05	4.44E+05	2.95E+05	9.23E+03	1.22E+02
NI-63	0.	8.13E+07	7.00E+07	3.29E+06	7.63E+04	6.35E-09	0.	0.	0.	0.	0.
SE-79	0.	8.08E+04	8.05E+04	8.04E+04	8.00E+04	7.67E+04	7.27E+04	4.79E+04	2.79E+04	3.92E+02	1.90E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	3.91E+00	3.91E+00	3.91E+00	3.91E+00	3.91E+00	3.91E+00	3.91E+00	3.91E+00	3.91E+00	3.91E+00
SR-90+Y-90	0.	1.13E+10	6.89E+09	3.10E+05	1.78E+00	0.	0.	0.	0.	0.	0.
ZR-93	0.	4.05E+05	4.05E+05	4.05E+05	4.05E+05	4.04E+05	4.03E+05	3.96E+05	3.87E+05	3.21E+05	2.55E+05
NB-93M	0.	3.51E+05	3.86E+05	4.05E+05	4.05E+05	4.04E+05	4.03E+05	3.96E+05	3.87E+05	3.22E+05	2.55E+05
TC-99	0.	3.01E+06	3.01E+06	3.00E+06	3.00E+06	2.96E+06	2.91E+06	2.55E+06	2.16E+06	5.78E+05	1.11E+05
RU-106+RH-106	0.	1.18E+06	1.22E+00	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	2.46E+04	2.46E+04	2.46E+04	2.46E+04	2.46E+04	2.46E+04	2.45E+04	2.43E+04	2.34E+04	2.23E+04
AG-110M	0.	9.66E+01	1.89E-07	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	5.25E+05	1.95E+05	3.69E-04	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	4.67E+06	2.76E+04	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	3.49E+05	3.49E+05	3.48E+05	3.47E+05	3.38E+05	3.26E+05	2.47E+05	1.75E+05	1.10E+04	3.43E+02
I-129	0.	7.92E+03	7.92E+03	7.92E+03	7.92E+03	7.92E+03	7.92E+03	7.91E+03	7.89E+03	7.76E+03	7.61E+03
CS-134	0.	1.94E+07	2.26E+04	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	6.70E+04	6.70E+04	6.70E+04	6.70E+04	6.70E+04	6.69E+04	6.63E+04	6.55E+04	5.97E+04	5.32E+04
CS-137+BA-137	0.	1.70E+10	1.07E+10	9.09E+05	8.81E+00	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	2.27E+05	8.16E-03	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	3.87E+07	1.96E+05	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	1.99E+08	1.69E+08	6.68E+06	1.25E+05	1.84E-09	0.	0.	0.	0.	0.
EU-152	0.	4.88E+05	1.54E+05	1.02E-05	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	2.82E+08	1.19E+08	2.76E+00	1.10E-09	0.	0.	0.	0.	0.	0.
EU-155	0.	4.21E+05	2.00E+02	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	6.42E+00	5.49E-09	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	2.89E+10	1.80E+10	1.64E+07	5.42E+06	5.07E+06	4.92E+06	4.19E+06	3.53E+06	1.33E+06	7.05E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.2.7b. Radioactivity Inventory--Reprocessing Cycle--Growth Case 3 - 2010 Reprocessing Startup, Curies(A)

Actinides

RADIONUCLIDES (B)	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	1.89E+05	1.89E+05	1.83E+05	1.75E+05	1.25E+05	8.24E+04	2.88E+03	4.30E+01	0.	0.
CM-244	0.	2.76E+08	1.28E+08	2.27E+01	1.09E-07	0.	0.	0.	0.	0.	0.
CM-243	0.	5.80E+05	3.76E+05	5.70E+01	1.13E-03	0.	0.	0.	0.	0.	0.
CM-242	0.	4.06E+06	3.70E+06	5.81E+05	5.04E+04	7.12E-04	0.	0.	0.	0.	0.
AM-243+NP-239	0.	1.12E+07	1.12E+07	1.08E+07	1.03E+07	7.16E+06	4.55E+06	1.21E+05	1.31E+03	0.	0.
AM-242M+AM-242	0.	9.88E+06	9.02E+06	1.42E+06	1.45E+05	1.73E-03	0.	0.	0.	0.	0.
AM-241	0.	6.93E+08	6.94E+08	3.31E+08	1.49E+08	3.77E+05	8.27E+04	2.88E+03	4.35E+01	0.	0.
PU-242	0.	5.15E+03	5.18E+03	5.42E+03	5.49E+03	5.45E+03	5.40E+03	5.02E+03	4.58E+03	2.21E+03	8.84E+02
PU-241	0.	6.63E+07	2.61E+07	1.83E+05	1.76E+05	1.26E+05	8.25E+04	2.88E+03	4.35E+01	0.	0.
PU-240	0.	1.77E+06	2.16E+06	2.40E+06	2.28E+06	1.51E+06	9.07E+05	1.30E+04	8.90E+01	0.	0.
PU-239	0.	7.41E+05	7.44E+05	7.92E+05	8.59E+05	1.22E+06	1.45E+06	7.70E+05	1.03E+05	2.24E+00	1.52E-06
PU-238	0.	6.37E+06	6.01E+06	1.17E+06	1.39E+05	1.72E-03	0.	0.	0.	0.	0.
PU-236	0.	3.62E+00	2.79E-02	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	1.89E+05	1.97E+05	3.07E+05	3.40E+05	4.53E+05	4.53E+05	4.48E+05	4.41E+05	3.87E+05	3.29E+05
U-238+TH-234+ PA-234M	0.	1.84E+03	1.84E+03	1.84E+03	1.84E+03	1.84E+03	1.84E+03	1.84E+03	1.84E+03	1.84E+03	1.84E+03
U-236	0.	4.79E+02	4.80E+02	5.05E+02	5.42E+02	7.57E+02	9.31E+02	1.18E+03	1.19E+03	1.17E+03	1.15E+03
U-235+TH-231	0.	6.70E+01	6.70E+01	6.76E+01	6.84E+01	7.66E+01	8.09E+01	1.84E+02	2.25E+02	2.38E+02	2.38E+02
U-234	0.	2.55E+03	2.90E+03	6.01E+03	7.19E+03	7.26E+03	7.17E+03	6.47E+03	5.70E+03	2.27E+03	1.02E+03
U-233	0.	7.75E+00	1.60E+01	2.15E+02	6.15E+02	4.33E+03	9.08E+03	4.31E+04	7.76E+04	1.80E+05	1.75E+05
U-232	0.	3.56E+01	2.95E+01	5.92E-01	4.80E-03	0.	0.	0.	0.	0.	0.
PA-231	0.	8.22E+00	8.23E+00	8.42E+00	8.71E+00	1.09E+01	1.41E+01	4.87E+01	8.65E+01	1.19E+02	1.19E+02
TH-230	0.	5.26E+01	5.31E+01	6.80E+01	9.45E+01	3.42E+02	6.36E+02	2.44E+03	3.71E+03	2.92E+03	1.21E+03
TH-229+7 DAUGHTERS	0.	6.54E-02	2.45E-01	2.98E+01	1.88E+02	6.56E+03	2.51E+04	2.77E+05	5.67E+05	1.45E+06	1.41E+06
TH-228+6 DAUGHTERS	0.	4.59E+02	2.12E+02	4.26E+00	3.47E-02	9.35E-04	2.09E-03	1.32E-02	2.76E-02	1.42E-01	2.84E-01
AC-227+7 DAUGHTERS	0.	3.09E+01	4.74E+01	6.70E+01	6.97E+01	8.75E+01	1.13E+02	3.89E+02	6.92E+02	9.54E+02	9.53E+02
TH-232+2 DAUGHTERS	0.	1.61E-05	4.06E-06	2.84E-05	6.77E-05	4.01E-04	8.97E-04	5.66E-03	1.18E-02	6.10E-02	1.22E-01
RA-226+5 DAUGHTERS	0.	4.70E+00	7.39E+00	5.82E+01	1.49E+02	1.27E+03	3.02E+03	1.47E+04	2.24E+04	1.76E+04	7.28E+03
PB-210+2 DAUGHTERS	0.	1.01E+00	2.02E+00	2.77E+01	7.47E+01	6.37E+02	1.51E+03	7.34E+03	1.12E+04	8.78E+03	3.64E+03
TOTAL	0.	1.03E+09	8.22E+08	3.49E+08	1.43E+08	1.10E+07	7.46E+06	1.72E+06	1.33E+06	2.06E+06	1.93E+06

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.2.8a. Radioactivity Inventory--Reprocessing Cycle--Growth Case 4 - 2000 Reprocessing Startup, Curies(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	6.00E+03	3.75E+06	1.22E+06	1.43E-04	0.	0.	0.	0.	0.	0.	0.
C-14	4.75E+02	2.61E+05	2.60E+05	2.48E+05	2.33E+05	1.44E+05	7.86E+04	6.24E+02	1.48E+00	0.	0.
MN-54	3.57E-05	1.06E+03	5.90E-05	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	2.77E+03	1.01E+07	4.89E+04	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	6.11E+04	6.05E+07	4.34E+06	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	1.41E+03	8.64E+05	8.64E+05	8.61E+05	8.57E+05	8.28E+05	7.93E+05	5.61E+05	3.64E+05	1.14E+04	1.50E+02
NI-63	1.63E+05	1.05E+08	9.03E+07	4.23E+06	9.41E+04	8.17E-09	0.	0.	0.	0.	0.
SE-79	8.56E-02	1.04E+05	1.04E+05	1.04E+05	1.03E+05	9.88E+04	9.37E+04	6.12E+04	3.59E+04	5.06E+02	2.45E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	4.22E-06	4.90E+00	4.90E+00	4.90E+00	4.90E+00	4.90E+00	4.90E+00	4.90E+00	4.90E+00	4.90E+00	4.90E+00
SR-90+Y-90	1.66E+04	1.63E+10	9.98E+09	4.49E+05	1.09E+00	0.	0.	0.	0.	0.	0.
ZR-93	4.32E+01	5.18E+05	5.18E+05	5.18E+05	5.18E+05	5.17E+05	5.16E+05	5.06E+05	4.95E+05	4.11E+05	3.26E+05
NB-93M	3.54E+01	4.22E+05	4.84E+05	5.18E+05	5.18E+05	5.17E+05	5.16E+05	5.07E+05	4.95E+05	4.12E+05	3.27E+05
TC-99	5.80E+00	3.95E+06	3.95E+06	3.95E+06	3.94E+06	3.89E+06	3.82E+06	3.35E+06	2.84E+06	7.60E+05	1.46E+05
RU-106+RH-106	3.11E-03	1.06E+07	1.09E+01	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	2.41E-02	3.58E+04	3.58E+04	3.58E+04	3.58E+04	3.58E+04	3.57E+04	3.56E+04	3.54E+04	3.40E+04	3.24E+04
AG-110M	3.75E-10	1.30E+03	2.65E-06	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	2.76E+02	1.12E+06	4.17E+05	7.88E-04	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	2.42E+01	2.36E+07	1.40E+05	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	3.47E-01	4.93E+05	4.93E+05	4.92E+05	4.90E+05	4.77E+05	4.61E+05	3.49E+05	2.47E+05	1.55E+04	4.85E+02
I-129	1.51E+01	1.07E+04	1.07E+04	1.07E+04	1.07E+04	1.07E+04	1.07E+04	1.07E+04	1.07E+04	1.05E+04	1.03E+04
CS-134	2.85E+00	1.20E+08	1.39E+05	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	5.56E-02	9.77E+04	9.77E+04	9.77E+04	9.76E+04	9.76E+04	9.74E+04	9.65E+04	9.54E+04	8.70E+04	7.75E+04
CS-137+BA-137	2.36E+04	2.59E+10	1.63E+10	1.38E+06	1.34E+01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	7.59E-06	1.81E+06	3.31E-02	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	1.92E+01	1.68E+08	8.49E+05	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	2.60E+02	2.83E+08	2.41E+08	9.53E+06	1.78E+05	2.62E-09	0.	0.	0.	0.	0.
EU-152	5.61E-01	1.15E+06	3.62E+05	2.41E-05	0.	0.	0.	0.	0.	0.	0.
EU-154	3.44E+02	5.36E+08	2.29E+08	5.24E+00	2.08E-09	0.	0.	0.	0.	0.	0.
EU-155	2.87E-02	2.85E+06	1.35E+03	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	2.39E-09	4.81E+01	4.14E-08	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	2.96E+05	4.35E+10	2.69E+10	2.24E+07	7.08E+06	6.61E+06	6.43E+06	5.48E+06	4.62E+06	1.74E+06	9.20E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.2.8b. Radioactivity Inventory--Reprocessing Cycle--Growth Case 4 - 2000 Reprocessing Startup, Curies(A)

Actinides

	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
RADIONUCLIDES (B)	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	2.55E-02	6.03E+05	6.02E+05	5.82E+05	5.58E+05	3.99E+05	2.62E+05	9.16E+03	1.38E+02	0.	0.
CM-244	6.76E+01	9.23E+08	4.29E+08	7.58E+01	3.46E-07	0.	0.	0.	0.	0.	0.
CM-243	3.43E-01	1.25E+06	8.12E+05	1.23E+02	2.03E-03	0.	0.	0.	0.	0.	0.
CM-242	7.58E-01	1.10E+07	1.01E+07	1.58E+06	1.62E+05	1.94E-03	0.	0.	0.	0.	0.
AM-243+NP-239	4.68E+00	2.63E+07	2.63E+07	2.53E+07	2.02E+07	1.68E+07	1.07E+07	2.49E+05	3.07E+03	0.	0.
AM-242M+AM-242	3.42E+00	2.69E+07	2.46E+07	3.86E+06	3.94E+05	4.71E-03	0.	0.	0.	0.	0.
AM-241	7.29E+02	6.09E+08	5.94E+08	3.11E+08	1.40E+08	6.49E+05	2.63E+05	9.16E+03	1.39E+02	0.	0.
PU-242	3.07E+00	1.13E+04	1.14E+04	1.20E+04	1.22E+04	1.21E+04	1.20E+04	1.12E+04	1.02E+04	4.91E+03	1.97E+03
PU-241	9.68E+04	1.76E+08	6.94E+07	5.83E+05	5.59E+05	4.00E+05	2.63E+05	9.16E+03	1.39E+02	0.	0.
PU-240	1.22E+03	4.77E+06	6.08E+06	6.93E+06	6.59E+06	4.37E+06	2.62E+06	4.33E+04	2.57E+02	0.	0.
PU-239	9.02E+02	1.20E+06	1.21E+06	1.33E+06	1.50E+06	2.01E+06	2.09E+06	1.68E+06	4.21E+05	4.90E+00	3.32E-06
PU-238	3.14E+03	2.06E+07	1.91E+07	3.33E+06	3.51E+05	4.67E-03	0.	0.	0.	0.	0.
PU-236	9.80E-02	2.73E+01	2.10E-01	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	1.42E-01	3.41E+05	3.49E+05	4.53E+05	5.31E+05	5.90E+05	5.91E+05	5.86E+05	5.76E+05	5.06E+05	4.31E+05
U-238+TH-234+ PA-234M	2.11E+00	2.46E+03	2.46E+03	2.46E+03	2.46E+03	2.46E+03	2.46E+03	2.46E+03	2.46E+03	2.47E+03	2.47E+03
U-236	3.18E-01	8.13E+02	8.17E+02	8.49E+02	9.04E+02	1.62E+03	2.12E+03	2.89E+03	2.85E+03	2.82E+03	2.78E+03
U-235+TH-231	7.70E-02	8.78E+01	8.78E+01	8.87E+01	9.02E+01	1.06E+02	1.33E+02	3.35E+02	4.25E+02	4.54E+02	4.54E+02
U-234	1.52E+00	4.38E+03	5.49E+03	1.49E+04	1.42E+04	1.64E+04	1.61E+04	1.63E+04	1.43E+04	5.19E+03	1.90E+03
U-233	1.40E-04	1.66E+01	3.14E+01	3.49E+02	9.07E+02	5.78E+03	1.20E+04	5.64E+04	1.01E+05	2.36E+05	2.28E+05
U-232	1.52E-02	8.20E+01	6.86E+01	1.38E+00	1.12E-02	0.	0.	0.	0.	0.	0.
PA-231	7.96E-06	1.09E+01	1.09E+01	1.11E+01	1.15E+01	1.45E+01	1.91E+01	8.23E+01	1.59E+02	2.27E+02	2.27E+02
TH-230	6.68E-05	3.81E+01	3.90E+01	7.46E+01	1.55E+02	7.72E+02	1.82E+03	6.09E+03	9.28E+03	6.93E+03	2.41E+03
TH-229+7 DAUGHTERS	1.06E-08	1.69E-01	5.33E-01	5.07E+01	2.90E+02	8.92E+03	3.33E+04	3.62E+05	7.41E+05	1.89E+06	1.84E+06
TH-228+6 DAUGHTERS	1.94E-02	6.70E+02	4.93E+02	9.90E+00	8.06E-02	1.60E-03	3.61E-03	2.30E-02	4.82E-02	2.49E-01	4.96E-01
AC-227+7 DAUGHTERS	2.10E-07	4.65E+01	6.57E+01	8.85E+01	9.21E+01	1.16E+02	1.53E+02	6.59E+02	1.27E+03	1.82E+03	1.81E+03
TH-232+2 DAUGHTERS	1.58E-10	5.79E-06	4.58E-06	4.90E-05	1.16E-04	6.87E-04	1.55E-03	4.85E-03	2.07E-02	1.07E-01	2.12E-01
RA-226+5 DAUGHTERS	2.50E-06	3.68E+00	5.65E+00	5.29E+01	1.84E+02	2.73E+03	7.09E+03	3.66E+04	5.62E+04	4.16E+04	1.44E+04
PB-210+2 DAUGHTERS	3.21E-07	8.34E-01	1.58E+00	2.52E+01	9.18E+01	1.36E+03	3.54E+03	1.83E+04	2.81E+04	2.08E+04	7.22E+03
TOTAL	1.03E+05	1.80E+09	1.18E+09	3.55E+08	1.75E+08	2.57E+07	1.78E+07	3.14E+06	1.97E+06	2.72E+06	2.53E+06

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.2.9a. Radioactivity Inventory--Reprocessing Cycle--Growth Case 5 - 2000 Reprocessing Startup, Curies(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	6.00E+03	6.06E+06	1.96E+06	2.31E-04	0.	0.	0.	0.	0.	0.	0.
C-14	4.75E+02	3.53E+05	3.52E+05	3.35E+05	3.15E+05	1.94E+05	1.06E+05	9.43E+02	2.00E+00	0.	0.
MN-54	3.57E-05	1.88E+03	1.05E-04	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	2.77E+03	1.79E+07	8.68E+04	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	6.11E+04	1.05E+08	7.97E+06	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	1.41E+03	1.17E+06	1.16E+06	1.16E+06	1.16E+06	1.12E+06	1.07E+06	7.96E+05	4.90E+05	1.54E+04	2.02E+02
NI-63	1.83E+05	1.45E+08	1.25E+08	5.87E+06	1.36E+05	1.13E-08	0.	0.	0.	0.	0.
SE-79	8.56E-02	1.41E+05	1.41E+05	1.40E+05	1.40E+05	1.34E+05	1.27E+05	8.28E+04	4.86E+04	6.85E+02	3.32E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	4.22E-06	6.59E+00	6.59E+00	6.59E+00	6.59E+00	6.59E+00	6.59E+00	6.59E+00	6.59E+00	6.59E+00	6.59E+00
SR-90+Y-90	1.66E+04	2.40E+10	1.46E+10	6.59E+05	2.03E+00	0.	0.	0.	0.	0.	0.
ZR-93	4.32E+01	7.00E+05	7.00E+05	7.00E+05	7.00E+05	6.99E+05	6.97E+05	6.84E+05	6.69E+05	5.56E+05	4.41E+05
NB-93M	3.54E+01	5.47E+05	6.45E+05	7.00E+05	7.01E+05	6.99E+05	6.98E+05	6.85E+05	6.69E+05	5.56E+05	4.42E+05
TC-99	5.80E+00	5.37E+06	5.37E+06	5.36E+06	5.35E+06	5.28E+06	5.19E+06	4.55E+06	3.86E+06	1.03E+06	1.98E+05
RU-106+RH-106	3.11E-03	2.03E+07	2.09E+01	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	2.41E-02	4.94E+04	4.94E+04	4.94E+04	4.94E+04	4.94E+04	4.94E+04	4.92E+04	4.90E+04	4.71E+04	4.48E+04
AG-110M	3.75E-10	2.45E+03	5.05E-06	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	2.76E+02	1.78E+06	6.61E+05	1.25E-03	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	2.42E+01	4.83E+07	2.62E+05	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	3.47E-01	6.79E+05	6.79E+05	6.77E+05	6.74E+05	6.56E+05	6.34E+05	4.80E+05	3.40E+05	2.13E+04	6.67E+02
I-129	1.51E+01	1.46E+04	1.46E+04	1.46E+04	1.46E+04	1.46E+04	1.46E+04	1.46E+04	1.46E+04	1.43E+04	1.40E+04
CS-134	2.85E+00	2.20E+08	2.55E+05	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	5.56E-02	1.34E+05	1.34E+05	1.34E+05	1.34E+05	1.34E+05	1.34E+05	1.33E+05	1.31E+05	1.20E+05	1.07E+05
CS-137+BA-137	2.36E+04	3.81E+10	2.40E+10	2.04E+06	1.07E+01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	7.59E-06	3.34E+06	6.11E-02	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	1.92E+01	3.08E+08	1.96E+06	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	2.60E+02	3.98E+08	3.39E+08	1.34E+07	2.40E+05	3.69E-09	0.	0.	0.	0.	0.
EU-152	5.61E-01	1.89E+06	5.06E+05	3.95E-05	0.	0.	0.	0.	0.	0.	0.
EU-154	3.44E+02	8.36E+08	3.52E+08	8.18E+00	3.25E-09	0.	0.	0.	0.	0.	0.
EU-155	2.87E-02	5.34E+06	2.53E+03	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	2.39E-09	8.71E+01	7.49E-08	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	2.96E+05	6.42E+10	3.95E+10	3.12E+07	9.62E+06	8.98E+06	8.72E+06	7.64E+06	6.27E+06	2.36E+06	1.25E+06

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.2.9b. Radioactivity Inventory--Reprocessing Cycle--Growth Case 5 - 2000 Reprocessing Startup, Curies(A)

Actinides

	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
RADIONUCLIDES (B)	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	2.55E-02	9.57E+05	9.55E+05	9.23E+05	8.85E+05	6.33E+05	4.16E+05	1.45E+04	2.19E+02	0.	0.
CM-244	6.76E+01	1.59E+09	7.39E+08	1.30E+02	6.29E-07	0.	0.	0.	0.	0.	0.
CM-243	3.43E-01	1.96E+06	1.27E+06	1.92E+02	3.40E-03	0.	0.	0.	0.	0.	0.
CM-242	7.58E-01	1.76E+07	1.61E+07	2.52E+06	2.68E+05	3.09E-03	0.	0.	0.	0.	0.
AM-243+NP-239	4.68E+00	4.08E+07	4.07E+07	3.93E+07	3.75E+07	2.61E+07	1.66E+07	4.42E+05	4.77E+03	0.	0.
AM-242M+AM-242	3.42E+00	4.29E+07	3.91E+07	6.14E+06	6.28E+05	7.51E-03	0.	0.	0.	0.	0.
AM-241	7.29E+02	8.37E+08	8.18E+08	4.30E+08	1.04E+08	9.82E+05	4.17E+05	1.46E+04	2.20E+02	0.	0.
PU-242	3.07E+00	2.29E+04	2.31E+04	2.41E+04	2.44E+04	2.43E+04	2.40E+04	2.23E+04	2.04E+04	9.81E+03	3.93E+03
PU-241	9.68E+04	3.92E+08	1.34E+08	9.24E+05	8.87E+05	6.34E+05	4.17E+05	1.46E+04	2.20E+02	0.	0.
PU-240	1.22E+03	7.35E+06	9.61E+06	1.11E+07	1.06E+07	7.01E+06	4.20E+06	6.44E+04	4.12E+02	0.	0.
PU-239	9.02E+02	1.80E+06	1.81E+06	2.00E+06	2.25E+06	3.68E+06	4.39E+06	2.49E+06	6.09E+05	7.55E+00	5.11E-06
PU-238	3.14E+03	3.22E+07	3.00E+07	5.27E+06	6.07E+05	7.44E-03	0.	0.	0.	0.	0.
PU-236	9.80E-02	8.11E+04	6.26E+02	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	1.42E-01	4.22E+05	4.33E+05	5.76E+05	6.44E+05	7.66E+05	7.67E+05	7.61E+05	7.49E+05	6.58E+05	5.39E+05
U-238+TH-234+ PA-234M	2.11E+00	3.35E+03	3.35E+03	3.35E+03	3.35E+03	3.35E+03	3.35E+03	3.35E+03	3.35E+03	3.36E+03	3.36E+03
U-236	3.18E-01	1.01E+03	1.02E+03	1.13E+03	1.30E+03	2.30E+03	3.10E+03	4.27E+03	4.28E+03	4.23E+03	4.17E+03
U-235+TH-231	7.70E-02	1.15E+02	1.15E+02	1.17E+02	1.19E+02	1.42E+02	1.84E+02	4.05E+02	6.34E+02	6.79E+02	6.78E+02
U-234	1.52E+00	5.55E+03	7.30E+03	2.20E+04	2.73E+04	2.76E+04	2.73E+04	2.45E+04	2.14E+04	7.73E+03	2.74E+03
U-233	1.40E-04	1.92E+01	3.74E+01	4.35E+02	1.15E+03	7.46E+03	1.55E+04	7.32E+04	1.32E+05	3.06E+05	2.97E+05
U-232	1.52E-02	2.16E+04	2.06E+04	4.13E+02	3.36E+00	0.	0.	0.	0.	0.	0.
PA-231	7.96E-06	1.36E+01	1.35E+01	1.39E+01	1.44E+01	1.85E+01	2.49E+01	1.19E+02	2.35E+02	3.39E+02	3.39E+02
TH-230	6.68E-05	4.66E+01	4.77E+01	9.93E+01	2.19E+02	1.15E+03	2.27E+03	9.15E+03	1.40E+04	1.04E+04	3.51E+03
TH-229+7 DAUGHTERS	1.06E-08	1.88E-01	6.13E-01	6.26E+01	3.46E+02	1.15E+04	4.30E+04	4.70E+05	9.62E+05	2.46E+06	2.39E+06
TH-228+6 DAUGHTERS	1.94E-02	1.41E+05	1.43E+05	2.97E+03	2.01E+01	2.08E-03	4.81E-03	3.21E-02	6.78E-02	3.52E-01	7.02E-01
AC-227+7 DAUGHTERS	2.10E-07	5.51E+01	8.04E+01	1.11E+02	1.15E+02	1.48E+02	1.99E+02	9.52E+02	1.88E+03	2.71E+03	2.71E+03
TH-232+2 DAUGHTERS	1.58E-10	7.94E-06	5.58E-06	6.08E-05	1.05E-04	8.93E-04	2.06E-03	1.38E-02	2.91E-02	1.51E-01	3.01E-01
RA-226+5 DAUGHTERS	2.50E-06	4.21E+00	6.61E+00	6.71E+01	2.51E+02	4.03E+03	1.06E+04	5.51E+04	8.45E+04	6.22E+04	2.11E+04
PB-210+2 DAUGHTERS	3.21E-07	9.20E-01	1.81E+00	3.17E+01	1.25E+02	2.02E+03	5.30E+03	2.75E+04	4.22E+04	3.11E+04	1.05E+04
TOTAL	1.03E+05	2.96E+09	1.85E+09	4.99E+08	2.48E+08	3.99E+07	2.75E+07	4.80E+06	2.69E+06	3.56E+06	3.30E+06

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-231 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

A.3 HEAT GENERATION RATE TABLES

The tables of heat generation rates (A.3.1a through A.3.9b) appear in the same format as those for radioactivity inventory.

TABLE A.3.1a. Heat Generation Rates--Once-Through Cycle--Growth Case 1, Watts$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR			GEOLOGIC TIME (YEARS BEYOND 1978)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
H-3	3.61E+01	2.16E+00	7.00E-01	0.	0.	0.	0.	0.	0.	0.	0.
C-14	1.83E+00	1.82E+00	1.81E+00	1.73E+00	1.68E+00	1.00E+00	5.67E-01	4.35E-03	1.03E-05	0.	0.
MN-54	1.25E+00	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	1.20E+03	1.96E-03	9.52E-06	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	6.08E+04	8.34E+01	5.09E+00	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	1.10E+00	1.10E+00	1.10E+00	1.10E+00	1.09E+00	1.05E+00	1.01E+00	7.13E-01	4.63E-01	1.45E-02	1.91E-04
NI-63	5.08E+02	3.49E+02	3.00E+02	1.41E+01	3.27E-01	0.	0.	0.	0.	0.	0.
SE-79	9.96E-01	9.96E-01	9.95E-01	9.91E-01	9.86E-01	9.45E-01	8.96E-01	5.85E-01	3.43E-01	4.83E-03	2.35E-05
KR-85	3.53E+04	1.43E+03	3.96E+02	1.04E-09	0.	0.	0.	0.	0.	0.	0.
RB-87	8.52E-05	8.52E-05	8.52E-05	8.52E-05	8.52E-05	8.52E-05	8.52E-05	8.52E-05	8.52E-05	8.52E-05	8.52E-05
SR-90+Y-90	2.26E+06	6.58E+05	4.02E+05	1.81E+01	8.03E-05	0.	0.	0.	0.	0.	0.
ZR-93	1.48E+00	1.48E+00	1.48E+00	1.48E+00	1.48E+00	1.48E+00	1.48E+00	1.45E+00	1.42E+00	1.18E+00	9.34E-01
NB-93M	2.89E+00	4.28E+00	4.34E+00	4.38E+00	4.38E+00	4.37E+00	4.36E+00	4.28E+00	4.18E+00	3.48E+00	2.76E+00
TC-99	1.67E+02	1.66E+02	1.66E+02	1.66E+02	1.66E+02	1.64E+02	1.61E+02	1.41E+02	1.20E+02	3.20E+01	6.15E+00
RU-106+RH-106	8.77E+03	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	5.85E-02	5.85E-02	5.85E-02	5.85E-02	5.85E-02	5.85E-02	5.85E-02	5.83E-02	5.80E-02	5.57E-02	5.30E-02
AG-110M	9.76E-01	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	2.50E+01	2.10E+00	7.83E-01	1.48E-09	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	3.74E+03	1.00E-02	5.93E-05	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	1.13E+02	1.13E+02	1.13E+02	1.13E+02	1.12E+02	1.09E+02	1.05E+02	7.99E+01	5.65E+01	3.54E+00	1.11E-01
I-129	1.61E-01	1.61E-01	1.61E-01	1.61E-01	1.61E-01	1.61E-01	1.61E-01	1.61E-01	1.61E-01	1.58E-01	1.55E-01
CS-134	5.84E+04	2.68E-03	3.12E-06	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	9.33E-01	9.33E-01	9.33E-01	9.33E-01	9.33E-01	9.32E-01	9.31E-01	9.22E-01	9.12E-01	8.31E-01	7.41E-01
CS-137+BA-137	2.36E+06	7.43E+05	4.68E+05	3.97E+01	3.85E-04	0.	0.	0.	0.	0.	0.
CE-144+PR-144	1.55E+03	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	9.17E+03	1.66E-02	8.41E-05	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	1.40E+04	9.43E+03	8.04E+03	3.17E+02	5.02E+00	0.	0.	0.	0.	0.	0.
EU-152	5.77E+02	3.22E+01	1.01E+01	6.73E-10	0.	0.	0.	0.	0.	0.	0.
EU-154	1.23E+05	1.41E+04	5.95E+03	1.38E-04	0.	0.	0.	0.	0.	0.	0.
EU-155	1.03E+02	5.05E-07	2.39E-10	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	2.40E-02	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	4.93E+06	1.43E+06	8.85E+05	6.79E+02	2.85E+02	2.83E+02	2.76E+02	2.29E+02	1.84E+02	4.15E+01	1.09E+01

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.3.1b. Heat Generation Rates--Once-Through Cycle, Growth Case 1, Watts(A)

Actinides

RADIONUCLIDES (B)	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	2.85E+01	2.84E+01	2.83E+01	2.74E+01	2.63E+01	1.88E+01	1.24E+01	4.91E-01	6.51E-03	0.	0.
CM-244	1.05E+05	1.54E+04	7.18E+03	1.27E-03	0.	0.	0.	0.	0.	0.	0.
CM-243	5.11E+02	1.73E+02	1.12E+02	1.70E-02	3.36E-07	0.	0.	0.	0.	0.	0.
CM-242	1.84E+03	1.47E+03	1.34E+03	2.10E+02	2.15E+01	2.57E-07	0.	0.	0.	0.	0.
AM-243+NP-239	2.96E+03	2.95E+03	2.94E+03	2.84E+03	2.71E+03	1.89E+03	1.20E+03	3.30E+01	3.44E-01	0.	0.
AM-242M+AM-242	9.86E+01	7.85E+01	7.16E+01	1.12E+01	1.15E+00	1.37E-08	0.	0.	0.	0.	0.
AM-241	5.93E+05	8.49E+05	8.42E+05	4.47E+05	2.01E+05	3.53E+02	1.33E+01	4.59E-01	6.93E-03	0.	0.
PU-242	2.95E+02	2.95E+02	2.95E+02	2.94E+02	2.94E+02	2.92E+02	2.89E+02	2.69E+02	2.45E+02	1.18E+02	4.73E+01
PU-241	1.28E+04	1.23E+03	4.83E+02	3.63E-02	3.48E-02	2.49E-02	1.64E-02	5.71E-04	8.62E-06	0.	0.
PU-240	1.15E+05	1.14E+05	1.14E+05	1.09E+05	1.04E+05	6.90E+04	4.13E+04	6.83E+02	4.05E+00	0.	0.
PU-239	8.46E+04	8.44E+04	8.44E+04	8.35E+04	8.23E+04	7.37E+04	6.41E+04	2.07E+04	5.00E+03	5.81E-02	3.93E-08
PU-238	3.62E+05	2.46E+05	2.10E+05	9.23E+03	2.25E+02	5.58E-07	0.	0.	0.	0.	0.
PU-236	8.01E-01	4.19E-06	3.24E-08	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	6.73E+01	7.89E+01	8.39E+01	1.57E+02	2.05E+02	2.43E+02	2.43E+02	2.40E+02	2.36E+02	2.07E+02	1.76E+02
U-238+TH-234+ PA-234M	9.77E+01	9.77E+01	9.77E+01	9.77E+01	9.77E+01	9.77E+01	9.77E+01	9.78E+01	9.78E+01	9.78E+01	9.78E+01
U-236	4.78E+01	4.79E+01	4.80E+01	4.91E+01	5.05E+01	5.91E+01	6.59E+01	7.48E+01	7.59E+01	7.50E+01	7.39E+01
U-235+TH-231	6.13E+00	6.13E+00	6.13E+00	6.16E+00	6.20E+00	6.48E+00	6.79E+00	8.17E+00	8.66E+00	8.82E+00	8.81E+00
U-234	2.83E+02	3.19E+02	3.30E+02	3.91E+02	3.06E+02	3.93E+02	3.89E+02	3.57E+02	3.22E+02	1.66E+02	1.10E+02
U-233	2.20E-02	3.67E-02	4.33E-02	2.40E-01	6.21E-01	4.41E+00	9.20E+00	4.37E+01	7.86E+01	1.83E+02	1.77E+02
U-232	3.08E+00	1.92E+00	1.58E+00	3.18E-02	2.48E-04	0.	0.	0.	0.	0.	0.
PA-231	7.28E-03	1.44E-02	1.72E-02	7.16E-02	1.62E-01	6.84E-01	1.33E+00	5.29E+00	7.79E+00	9.43E+00	9.42E+00
TH-230	4.72E-02	1.76E-01	2.31E-01	1.47E+00	3.18E+00	1.62E+01	3.18E+01	1.59E+02	2.01E+02	1.92E+02	1.16E+02
TH-229+7 DAUGHTERS	1.03E-04	1.05E-03	1.57E-03	3.47E-02	1.71E-01	5.79E+00	2.19E+01	2.42E+02	4.04E+02	1.26E+03	1.23E+03
TH-228+6 DAUGHTERS	2.00E+01	1.27E+01	1.05E+01	2.10E-01	1.93E-03	1.00E-04	2.18E-04	1.32E-03	2.74E-03	1.41E-02	2.80E-02
AC-227+7 DAUGHTERS	9.52E-03	6.32E-02	8.26E-02	4.61E-01	9.30E-01	4.47E+00	8.72E+00	3.46E+01	5.09E+01	6.16E+01	6.16E+01
TH-232+2 DAUGHTERS	1.40E-08	1.23E-07	1.74E-07	1.21E-06	2.98E-06	1.44E-05	3.12E-05	1.89E-04	3.92E-04	2.01E-03	4.00E-03
RA-226+5 DAUGHTERS	1.28E-03	1.46E-02	2.43E-02	7.66E-01	3.24E+00	5.39E+01	1.39E+02	7.30E+02	1.14E+03	1.08E+03	6.55E+02
PB-210+2 DAUGHTERS	6.05E-05	1.48E-03	2.82E-03	1.61E-01	6.07E-01	1.16E+01	3.00E+01	1.47E+02	2.45E+02	2.32E+02	1.41E+02
TOTAL	1.28E+06	1.32E+06	1.26E+06	6.53E+05	3.01E+05	1.46E+05	1.08E+05	2.38E+04	8.21E+03	3.69E+03	2.90E+03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.3.2a. Heat Generation Rates--Once-Through Cycle--Growth Case 2, Watts$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	1.18E+02	3.76E+01	1.22E+01	1.43E-09	0.	0.	0.	0.	0.	0.	0.
C-14	4.76E+00	1.18E+01	1.13E+01	1.08E+01	1.02E+01	6.26E+00	3.42E+00	2.72E-02	6.44E-05	0.	0.
MN-54	2.82E+00	4.51E-09	0.	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	3.98E+03	4.43E+00	2.15E-02	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	2.05E+05	7.32E+03	5.26E+02	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	2.83E+00	4.77E+00	6.74E+00	6.74E+00	6.71E+00	6.48E+00	6.21E+00	4.39E+00	2.89E+00	3.92E-02	1.18E-03
NI-63	1.34E+03	2.41E+03	2.77E+03	9.76E+01	2.26E+00	0.	0.	0.	0.	0.	0.
SE-79	2.58E+00	6.24E+00	6.24E+00	6.21E+00	6.18E+00	5.92E+00	5.61E+00	3.47E+00	2.15E+00	3.03E-02	1.47E-04
KR-85	1.08E+05	2.82E+04	7.41E+03	3.43E-08	0.	0.	0.	0.	0.	0.	0.
RB-87	2.18E-04	5.30E-04	5.30E-04	5.30E-04	5.30E-04	5.30E-04	5.30E-04	5.30E-04	5.30E-04	5.30E-04	5.30E-04
SR-90+Y-90	6.23E+06	4.09E+06	3.72E+06	1.68E+02	7.03E-04	0.	0.	0.	0.	0.	0.
ZR-93	3.83E+00	9.26E+00	9.24E+00	9.26E+00	9.26E+00	9.24E+00	9.22E+00	9.05E+00	8.84E+00	7.35E+00	5.83E+00
NB-93M	6.81E+00	2.56E+01	2.47E+01	2.73E+01	2.73E+01	2.73E+01	2.72E+01	2.67E+01	2.61E+01	2.17E+01	1.72E+01
TC-99	4.31E+02	1.04E+03	1.04E+03	1.04E+03	1.04E+03	1.02E+03	1.01E+03	8.82E+02	7.48E+02	2.00E+02	3.88E+01
RU-106+RH-106	1.62E+04	4.62E-04	6.81E-10	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	1.60E-01	3.42E-01	3.42E-01	3.42E-01	3.41E-01	3.41E-01	3.41E-01	3.40E-01	3.38E-01	3.23E-01	3.06E-01
AG-110M	6.56E+00	1.53E-10	0.	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	9.86E+01	3.98E+01	1.48E+01	2.79E-08	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	1.64E+04	2.24E+01	1.32E-01	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	3.05E+02	7.30E+02	7.30E+02	7.28E+02	7.25E+02	7.05E+02	6.81E+02	5.17E+02	3.65E+02	2.29E+01	7.19E-01
I-129	4.28E-01	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.02E+00	1.00E+00	9.80E-01
CS-134	3.51E+05	5.96E+01	6.92E-02	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	2.51E+00	6.13E+00	6.13E+00	6.13E+00	6.13E+00	6.13E+00	6.12E+00	6.06E+00	5.99E+00	5.46E+00	4.87E+00
CS-137+BA-137	6.64E+06	6.82E+06	4.30E+06	3.65E+02	3.53E-03	0.	0.	0.	0.	0.	0.
CE-144+PR-144	3.18E+03	1.45E-06	0.	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	2.13E+04	2.93E+01	1.48E-01	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	3.48E+04	6.13E+04	5.23E+04	2.06E+03	3.45E+01	0.	0.	0.	0.	0.	0.
EU-152	1.76E+03	5.45E+02	1.78E+02	1.18E-08	0.	0.	0.	0.	0.	0.	0.
EU-154	4.50E+05	2.26E+05	9.49E+04	2.21E-03	0.	0.	0.	0.	0.	0.	0.
EU-155	5.71E+02	3.28E-02	1.54E-05	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	5.70E-02	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	1.41E+07	1.32E+07	8.18E+06	4.53E+03	1.87E+03	1.79E+03	1.75E+03	1.45E+03	1.16E+03	2.59E+02	6.88E+01

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.3.2b. Heat Generation Rates--Once-Through Cycle--Growth Case 2, Watts$^{(A)}$

Actinides

RADIONUCLIDES (B)	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
CM-245	1.04E+02	2.52E+02	2.52E+02	2.43E+02	2.33E+02	1.67E+02	1.10E+02	3.43E+00	5.78E-02	0.	0.
CM-244	4.68E+05	2.76E+05	1.28E+05	2.27E-02	1.09E-10	0.	0.	0.	0.	0.	0.
CM-243	1.98E+03	2.11E+03	1.37E+03	2.08E-01	4.11E-06	0.	0.	0.	0.	0.	0.
CM-242	3.52E+03	1.19E+04	1.08E+04	1.70E+03	1.74E+02	2.08E-06	0.	0.	0.	0.	0.
AM-243+NP-239	9.97E+03	2.40E+04	2.39E+04	2.31E+04	2.20E+04	1.53E+04	9.75E+03	2.60E+02	2.80E+00	0.	0.
AM-242M+AM-242	3.14E+02	6.34E+02	5.79E+02	9.09E+01	9.29E+00	1.11E-07	0.	0.	0.	0.	0.
AM-241	1.41E+06	5.28E+06	5.42E+06	2.93E+06	1.32E+06	2.37E+03	1.18E+02	4.08E+00	6.15E-02	0.	0.
PU-242	9.13E+02	2.19E+03	2.19E+03	2.19E+03	2.18E+03	2.17E+03	2.15E+03	2.00E+03	1.82E+03	8.77E+02	3.51E+02
PU-241	4.18E+04	1.84E+04	7.22E+03	3.22E-01	3.09E-01	2.21E-01	1.45E-01	5.07E-03	7.65E-05	0.	0.
PU-240	2.79E+05	6.60E+05	6.59E+05	6.33E+05	6.01E+05	3.99E+05	2.39E+05	3.49E+03	2.34E+01	0.	0.
PU-239	1.80E+05	4.28E+05	4.28E+05	4.23E+05	4.17E+05	3.74E+05	3.26E+05	1.06E+05	2.55E+04	2.96E-01	2.01E-07
PU-238	1.20E+06	2.16E+06	1.45E+06	8.07E+04	1.04E+03	4.51E-06	0.	0.	0.	0.	0.
PU-236	6.27E+00	1.08E-02	8.32E-05	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	1.88E+02	5.09E+02	5.41E+02	1.01E+03	1.33E+03	1.58E+03	1.58E+03	1.66E+03	1.54E+03	1.35E+03	1.15E+03
U-238+TH-234+ PA-234M	1.95E+02	4.66E+02	4.66E+02	4.66E+02	4.66E+02	4.66E+02	4.66E+02	4.66E+02	4.66E+02	4.66E+02	4.66E+02
U-236	1.18E+02	2.88E+02	2.88E+02	2.95E+02	3.03E+02	3.52E+02	3.92E+02	4.49E+02	4.49E+02	4.44E+02	4.38E+02
U-235+TH-231	9.38E+00	2.40E+01	2.40E+01	2.42E+01	2.44E+01	2.58E+01	2.74E+01	3.64E+01	3.69E+01	3.77E+01	3.77E+01
U-234	3.65E+02	1.68E+03	1.78E+03	2.30E+03	2.35E+03	2.33E+03	2.31E+03	2.11E+03	1.89E+03	9.05E+02	5.52E+02
U-233	3.09E-02	2.01E-01	2.43E-01	1.47E+00	3.07E+00	2.86E+01	3.09E+01	2.85E+02	3.13E+02	1.19E+03	1.15E+03
U-232	1.01E+01	1.75E+01	1.44E+01	2.89E-01	2.35E-03	0.	0.	0.	0.	0.	0.
PA-231	1.86E-02	6.71E-02	7.82E-02	2.87E-01	5.67E-01	2.71E+00	5.32E+00	2.19E+01	3.29E+01	4.03E+01	4.03E+01
TH-230	9.07E-02	7.38E-01	1.03E+00	7.98E+00	1.43E+01	9.56E+01	1.88E+02	7.45E+02	1.18E+03	1.07E+03	5.96E+02
TH-229+7 DAUGHTERS	1.54E-04	4.78E-03	7.67E-03	2.04E-01	1.08E+00	3.74E+01	1.42E+02	1.38E+03	3.22E+03	8.24E+03	8.00E+03
TH-228+6 DAUGHTERS	6.31E+01	1.16E+02	9.55E+01	1.92E+00	1.37E-02	5.98E-04	1.30E-03	7.83E-03	1.63E-02	8.32E-02	1.66E-01
AC-227+7 DAUGHTERS	1.59E-02	2.90E-01	3.80E-01	1.83E+00	3.71E+00	1.77E+01	3.48E+01	1.43E+02	2.15E+02	2.64E+02	2.63E+02
TH-232+2 DAUGHTERS	3.42E-08	5.74E-07	8.81E-07	6.95E-06	1.32E-05	8.55E-05	1.86E-04	1.12E-03	2.32E-03	1.10E-02	2.37E-02
RA-226+5 DAUGHTERS	2.30E-03	5.10E-02	9.33E-02	3.91E+00	1.81E+01	3.16E+02	8.24E+02	4.32E+03	6.71E+03	6.04E+03	3.35E+03
PB-210+2 DAUGHTERS	1.01E-04	4.70E-03	1.00E-02	8.08E-01	3.00E+00	6.80E+01	1.77E+02	9.29E+02	1.84E+03	1.30E+03	7.21E+02
TOTAL	3.59E+06	8.86E+06	8.53E+06	4.10E+06	2.37E+06	7.98E+05	5.83E+05	1.25E+05	4.51E+04	2.22E+04	1.71E+04

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-231 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.3.3a. Heat Generation Rates--Once-Through Cycle--Growth Case 3, Watts$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	1.86E+02	4.33E+02	1.40E+02	1.65E-08	0.	0.	0.	0.	0.	0.	0.
C-14	7.68E+00	5.89E+01	5.85E+01	5.60E+01	5.27E+01	3.25E+01	1.78E+01	1.41E-01	3.38E-04	0.	0.
MN-54	8.68E+00	9.34E-01	5.22E-08	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	7.62E+03	3.29E+03	1.60E+01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	3.57E+05	3.30E+05	2.37E+04	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	4.40E+00	3.43E+01	3.42E+01	3.41E+01	3.40E+01	3.28E+01	3.14E+01	2.22E+01	1.44E+01	4.52E-01	5.95E-03
NI-63	2.11E+03	1.35E+04	1.16E+04	5.46E+02	1.26E+01	0.	0.	0.	0.	0.	0.
SE-79	3.92E+00	3.13E+01	3.13E+01	3.12E+01	3.10E+01	2.97E+01	2.82E+01	1.88E+01	1.08E+01	1.52E-01	7.38E-04
KR-85	1.77E+05	3.69E+05	1.02E+05	5.03E-07	0.	0.	0.	0.	0.	0.	0.
RB-87	3.31E-04	2.66E-03	2.66E-03	2.66E-03	2.66E-03	2.66E-03	2.66E-03	2.66E-03	2.66E-03	2.66E-03	2.66E-03
SR-90+Y-90	9.77E+06	4.29E+07	2.62E+07	1.18E+03	5.24E-03	0.	0.	0.	0.	0.	0.
ZR-93	5.81E+00	4.65E+01	4.65E+01	4.65E+01	4.64E+01	4.64E+01	4.63E+01	4.54E+01	4.44E+01	3.69E+01	2.93E+01
NB-93M	9.82E+00	1.19E+02	1.30E+02	1.37E+02	1.37E+02	1.37E+02	1.37E+02	1.34E+02	1.31E+02	1.09E+02	8.65E+01
TC-99	6.95E+02	5.22E+03	5.22E+03	5.21E+03	5.20E+03	5.13E+03	5.05E+03	4.43E+03	3.75E+03	1.00E+03	1.93E+02
RU-106+RH-106	2.61E+04	5.42E+03	5.57E-03	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	2.43E-01	1.91E+00	1.91E+00	1.91E+00	1.91E+00	1.91E+00	1.91E+00	1.91E+00	1.90E+00	1.82E+00	1.73E+00
AG-110M	8.28E+00	1.17E+00	2.01E-09	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	1.56E+02	4.11E+02	1.93E+02	2.68E-07	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	3.05E+04	1.31E+04	7.76E+01	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	4.63E+02	3.66E+03	3.66E+03	3.65E+03	3.64E+03	3.54E+03	3.42E+03	2.59E+03	1.83E+03	1.15E+02	3.60E+00
I-129	6.04E-01	5.12E+00	5.12E+00	5.12E+00	5.12E+00	5.12E+00	5.12E+00	5.11E+00	5.10E+00	5.02E+00	4.92E+00
CS-134	6.26E+05	2.02E+05	2.35E+02	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	3.71E+00	3.07E+01	3.07E+01	3.07E+01	3.07E+01	3.06E+01	3.06E+01	3.03E+01	3.00E+01	2.73E+01	2.43E+01
CS-137+BA-137	1.04E+07	4.70E+07	2.96E+07	2.51E+03	2.63E-02	0.	0.	0.	0.	0.	0.
CE-144+PR-144	4.55E+03	1.03E+03	1.45E-05	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	8.11E+04	2.06E+04	1.04E+02	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	5.39E+04	3.42E+05	2.92E+05	1.15E+04	2.15E+02	0.	0.	0.	0.	0.	0.
EU-152	2.81E+03	6.64E+03	2.09E+03	1.39E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	7.10E+05	2.11E+06	8.89E+05	2.07E-02	0.	0.	0.	0.	0.	0.	0.
EU-155	1.00E+03	2.96E+02	1.40E-01	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	7.21E-02	1.41E-02	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	2.22E+07	9.34E+07	5.72E+07	2.50E+04	9.41E+03	8.99E+03	8.77E+03	7.28E+03	5.82E+03	1.30E+03	3.43E+02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.3.3b. Heat Generation Rates--Once-Through Cycle--Growth Case 3, Watts(A)

Actinides

	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
RADIONUCLIDES (B)	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	1.52E+02	1.28E+03	1.28E+03	1.24E+03	1.19E+03	8.48E+02	5.58E+02	1.45E+01	2.94E-01	0.	0.
CM-244	7.10E+05	2.40E+06	1.12E+06	1.97E-01	9.51E-10	0.	0.	0.	0.	0.	0.
CM-243	2.92E+03	1.03E+04	9.25E+03	1.40E+00	2.77E-05	0.	0.	0.	0.	0.	0.
CM-242	7.77E+03	6.31E+04	5.76E+04	9.03E+03	9.23E+02	1.11E-05	0.	0.	0.	0.	0.
AM-243+NP-239	1.47E+04	1.21E+05	1.21E+05	1.16E+05	1.11E+05	7.75E+04	4.02E+04	1.31E+03	1.41E+01	0.	0.
AM-242M+AM-242	4.63E+02	3.37E+03	3.08E+03	4.84E+02	4.04E+01	5.91E-07	0.	0.	0.	0.	0.
AM-241	2.05E+06	2.46E+07	2.48E+07	1.50E+07	6.77E+06	1.21E+04	5.08E+02	2.07E+01	3.13E-01	0.	0.
PU-242	1.36E+03	1.10E+04	1.10E+04	1.10E+04	1.10E+04	1.09E+04	1.08E+04	1.00E+04	9.16E+03	4.41E+03	1.77E+03
PU-241	6.83E+04	1.82E+05	7.14E+04	1.64E+00	1.57E+00	1.12E+00	7.39E-01	2.58E-02	3.89E-04	0.	0.
PU-240	4.35E+05	3.31E+06	3.30E+06	3.17E+06	3.01E+06	2.00E+06	1.20E+06	1.08E+04	1.18E+02	0.	0.
PU-239	2.80E+05	2.15E+06	2.14E+06	2.12E+06	2.09E+06	1.88E+06	1.63E+06	5.30E+05	1.28E+05	1.40E+00	1.01E-06
PU-238	1.78E+06	1.20E+07	1.03E+07	4.49E+05	1.07E+04	2.40E-05	0.	0.	0.	0.	0.
PU-236	1.10E+01	4.71E+00	3.63E-02	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	2.81E+02	2.46E+03	2.62E+03	4.94E+03	6.66E+03	7.96E+03	7.96E+03	7.86E+03	7.73E+03	6.79E+03	5.78E+03
U-238+TH-234+ PA-234M	3.13E+02	2.33E+03	2.33E+03	2.33E+03	2.33E+03	2.33E+03	2.33E+03	2.33E+03	2.33E+03	2.33E+03	2.33E+03
U-236	1.79E+02	1.44E+03	1.45E+03	1.48E+03	1.52E+03	1.77E+03	1.96E+03	2.25E+03	2.25E+03	2.23E+03	2.20E+03
U-235+TH-231	1.52E+01	1.20E+02	1.21E+02	1.21E+02	1.22E+02	1.29E+02	1.37E+02	1.72E+02	1.85E+02	1.89E+02	1.89E+02
U-234	8.52E+02	8.05E+03	8.59E+03	1.15E+04	1.18E+04	1.17E+04	1.16E+04	1.06E+04	9.48E+03	4.55E+03	2.76E+03
U-233	7.57E-02	8.79E-01	1.06E+00	6.98E+00	1.05E+01	1.43E+02	3.01E+02	1.43E+03	2.59E+03	5.99E+03	5.81E+03
U-232	1.50E+01	1.00E+02	8.26E+01	1.66E+00	1.35E-02	0.	0.	0.	0.	0.	0.
PA-231	2.67E-02	3.00E-01	3.56E-01	1.38E+00	2.80E+00	1.35E+01	2.66E+01	1.10E+02	1.65E+02	2.02E+02	2.02E+02
TH-230	1.27E-01	2.78E+00	4.20E+00	3.79E+01	8.09E+01	4.78E+02	9.44E+02	3.84E+03	5.93E+03	5.37E+03	2.98E+03
TH-229+7 DAUGHTERS	1.84E-04	1.71E-02	2.99E-02	9.32E-01	5.21E+00	1.86E+02	7.13E+02	7.92E+03	1.62E+04	4.15E+04	4.02E+04
TH-228+6 DAUGHTERS	9.15E+01	6.60E+02	5.47E+02	1.10E+01	8.06E-02	2.99E-03	6.51E-03	3.03E-02	8.15E-02	4.17E-01	8.31E-01
AC-227+7 DAUGHTERS	1.86E-02	1.14E+00	1.63E+00	8.75E+00	1.83E+01	8.82E+01	1.74E+02	7.17E+02	1.08E+03	1.32E+03	1.32E+03
TH-232+2 DAUGHTERS	5.06E-08	2.09E-06	3.60E-06	3.33E-05	7.53E-05	4.27E-04	9.31E-04	5.61E-03	1.16E-02	5.96E-02	1.19E-01
RA-226+5 DAUGHTERS	3.00E-03	1.60E-01	3.28E-01	1.78E+01	8.79E+01	1.57E+03	4.13E+03	2.17E+04	3.37E+04	3.03E+04	1.68E+04
PB-210+2 DAUGHTERS	1.24E-04	1.33E-02	3.26E-02	3.62E+00	1.89E+01	3.38E+02	8.87E+02	4.46E+03	7.24E+03	6.51E+03	3.61E+03
TOTAL	5.36E+06	4.49E+07	4.40E+07	2.10E+07	1.20E+07	4.00E+06	2.02E+06	6.35E+05	2.26E+05	1.12E+05	8.99E+04

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.3.4a. Heat Generation Rates--Once-Through Cycle--Growth Case 4, Watts(A)

Fission and Activiation Products

MAJOR RADIONUCLIDES	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	1.41E+00	8.35E+02	2.71E+02	3.18E-08	0.	0.	0.	0.	0.	0.	0.
C-14	1.09E-01	7.80E+01	7.78E+01	7.41E+01	6.97E+01	4.30E+01	2.35E+01	1.87E-01	4.82E-04	0.	0.
MN-54	2.89E-07	7.49E+00	4.18E-07	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	3.62E+00	1.60E+04	7.78E+01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	8.55E+02	1.01E+06	7.23E+04	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	6.68E-02	4.52E+01	4.52E+01	4.50E+01	4.48E+01	4.33E+01	4.14E+01	2.83E+01	1.80E+01	5.95E-01	7.85E-03
NI-63	2.92E+01	1.86E+04	1.60E+04	7.92E+02	1.74E+01	0.	0.	0.	0.	0.	0.
SE-79	6.10E-02	4.11E+01	4.11E+01	4.09E+01	4.07E+01	3.90E+01	3.70E+01	2.82E+01	1.42E+01	2.00E-01	9.69E-04
KR-85	1.22E+05	7.46E+05	2.07E+05	1.01E-06	0.	0.	0.	0.	0.	0.	0.
RB-87	5.17E-06	3.49E-03	3.49E-03	3.49E-03	3.49E-03	3.49E-03	3.49E-03	3.49E-03	3.49E-03	3.49E-03	3.49E-03
SR-90+Y-90	1.12E+05	6.97E+07	8.01E+07	1.81E+03	8.02E-03	0.	0.	0.	0.	0.	0.
ZR-93	9.07E-02	6.10E+01	6.10E+01	6.10E+01	6.10E+01	6.09E+01	6.07E+01	5.96E+01	5.82E+01	4.84E+01	3.84E+01
NB-93M	2.03E-01	1.46E+02	1.68E+02	1.80E+02	1.80E+02	1.80E+02	1.79E+02	1.76E+02	1.72E+02	1.43E+02	1.14E+02
TC-99	1.03E+01	6.85E+03	6.85E+03	6.84E+03	6.83E+03	6.74E+03	6.63E+03	5.81E+03	4.93E+03	1.32E+03	2.53E+02
RU-106+RH-106	9.50E-03	4.38E+04	4.90E-02	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	3.75E-03	2.52E+00	2.52E+00	2.52E+00	2.52E+00	2.52E+00	2.52E+00	2.51E+00	2.50E+00	2.40E+00	2.28E+00
AG-110M	1.19E-08	1.29E+01	2.64E-08	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	1.04E+00	7.60E+02	2.83E+02	5.33E-07	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	1.25E+01	6.51E+04	3.85E+02	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	7.13E+00	4.82E+03	4.82E+03	4.81E+03	4.79E+03	4.66E+03	4.50E+03	3.61E+03	2.61E+03	1.51E+02	4.74E+00
I-129	1.00E-02	6.73E+00	6.73E+00	6.73E+00	6.73E+00	6.73E+00	6.73E+00	6.72E+00	6.70E+00	6.60E+00	6.46E+00
CS-134	9.67E+01	1.24E+06	1.44E+03	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	5.07E-02	4.01E+01	4.01E+01	4.01E+01	4.01E+01	4.00E+01	4.00E+01	3.96E+01	3.92E+01	3.57E+01	3.18E+01
CS-137+BA-137	1.22E+05	7.13E+07	8.69E+07	3.81E+03	3.49E-02	0.	0.	0.	0.	0.	0.
CE-144+PR-144	6.12E-05	7.88E+03	1.37E-04	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	1.88E+01	8.91E+04	8.90E+02	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	8.52E+02	4.72E+05	4.02E+05	1.59E+04	2.06E+02	0.	0.	0.	0.	0.	0.
EU-152	1.89E+01	1.27E+04	4.01E+03	2.66E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	5.30E+03	3.72E+06	1.56E+06	3.64E-02	0.	0.	0.	0.	0.	0.	0.
EU-155	4.53E-02	1.93E+03	9.17E-01	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	1.15E-01	1.05E-10	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	2.42E+05	1.44E+08	8.73E+07	3.43E+04	1.24E+04	1.18E+04	1.15E+04	9.56E+03	7.65E+03	1.71E+03	4.51E+02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.3.4b. Heat Generation Rates--Once Through Cycle--Growth Case 4, Watts(A)

Actinides

RADIONUCLIDES (B)	YEAR 2000	 2050	 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	 1000	 5000	 10000	 50000	 100000	 500000	 1000000
CM-245	1.50E+00	1.68E+03	1.68E+03	1.62E+03	1.55E+03	1.11E+03	7.30E+02	2.55E+01	3.85E-01	0.	0.
CM-244	4.43E+03	4.07E+06	1.89E+06	3.34E-01	1.61E-09	0.	0.	0.	0.	0.	0.
CM-243	2.36E+01	2.14E+04	1.39E+04	2.10E+00	4.15E-05	0.	0.	0.	0.	0.	0.
CM-242	5.24E+01	8.49E+04	7.75E+04	1.22E+04	1.24E+03	1.49E-05	0.	0.	0.	0.	0.
AM-243+NP-239	1.66E+02	1.59E+05	1.59E+05	1.53E+05	1.46E+05	1.02E+05	6.46E+04	1.72E+03	1.86E+01	0.	0.
AM-242M+AM-242	5.19E+00	4.84E+03	4.15E+03	6.51E+02	6.86E+01	7.95E-07	0.	0.	0.	0.	0.
AM-241	4.47E+04	3.02E+07	3.47E+07	2.00E+07	9.01E+06	1.62E+04	7.84E+02	2.72E+01	4.10E-01	0.	0.
PU-242	1.76E+01	1.45E+04	1.45E+04	1.44E+04	1.44E+04	1.43E+04	1.42E+04	1.32E+04	1.20E+04	5.79E+03	2.32E+03
PU-241	5.88E+02	3.32E+05	1.30E+05	2.14E+00	2.06E+00	1.47E+00	9.87E-01	3.38E-02	5.10E-04	0.	0.
PU-240	7.87E+03	4.37E+06	4.37E+06	4.20E+06	3.99E+06	2.64E+06	1.58E+06	2.62E+04	1.55E+02	0.	0.
PU-239	5.95E+03	2.84E+06	2.84E+06	2.81E+06	2.77E+06	2.48E+06	2.16E+06	7.01E+05	1.70E+05	1.97E+00	1.33E-06
PU-238	1.94E+04	1.65E+07	1.41E+07	6.15E+05	1.07E+04	3.23E-05	0.	0.	0.	0.	0.
PU-236	8.00E-03	2.41E+01	1.86E-01	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	4.10E+00	3.18E+03	3.38E+03	6.42E+03	8.74E+03	1.05E+04	1.05E+04	1.04E+04	1.02E+04	8.95E+03	7.61E+03
U-238+TH-234+ PA-234M	6.91E+00	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03
U-236	2.65E+00	1.89E+03	1.89E+03	1.93E+03	1.99E+03	2.32E+03	2.58E+03	2.96E+03	2.96E+03	2.93E+03	2.89E+03
U-235+TH-231	3.52E-01	1.57E+02	1.57E+02	1.58E+02	1.59E+02	1.68E+02	1.79E+02	2.35E+02	2.42E+02	2.47E+02	2.47E+02
U-234	1.45E+01	1.02E+04	1.10E+04	1.48E+04	1.54E+04	1.52E+04	1.51E+04	1.38E+04	1.24E+04	5.96E+03	3.63E+03
U-233	1.35E-03	1.08E+00	1.34E+00	8.84E+00	2.54E+01	1.88E+02	3.06E+02	1.48E+03	3.40E+03	7.90E+03	7.65E+03
U-232	1.60E-01	1.38E+02	1.14E+02	2.30E+00	1.86E-02	0.	0.	0.	0.	0.	0.
PA-231	4.51E-04	3.71E-01	4.44E-01	1.76E+00	3.61E+00	1.75E+01	3.47E+01	1.43E+02	2.16E+02	2.65E+02	2.65E+02
TH-230	3.48E-03	3.16E+00	4.06E+00	4.77E+01	1.16E+02	6.20E+02	1.23E+03	5.60E+03	7.73E+03	7.02E+03	3.42E+03
TH-229+7 DAUGHTERS	8.87E-08	1.69E-02	3.27E-02	1.15E+00	6.72E+00	2.43E+02	9.38E+02	1.04E+04	2.14E+04	5.46E+04	5.30E+04
TH-228+6 DAUGHTERS	9.19E-01	9.03E+02	7.58E+02	1.52E+01	1.24E-01	3.90E-03	8.54E-03	5.16E-02	1.07E-01	5.48E-01	1.09E+00
AC-227+7 DAUGHTERS	9.38E-06	1.24E+00	1.92E+00	1.11E+01	2.36E+01	1.15E+02	2.27E+02	9.36E+02	1.41E+03	1.73E+03	1.73E+03
TH-232+2 DAUGHTERS	2.91E-09	1.90E-06	3.80E-06	4.20E-05	9.74E-05	5.58E-04	1.22E-03	7.37E-03	1.53E-02	7.84E-02	1.56E-01
RA-226+5 DAUGHTERS	1.24E-04	1.71E-01	3.66E-01	2.18E+01	1.12E+02	2.04E+03	5.37E+03	2.82E+04	4.39E+04	3.95E+04	2.21E+04
PB-210+2 DAUGHTERS	6.87E-06	1.38E-02	3.54E-02	4.38E+00	2.42E+01	4.38E+02	1.15E+03	6.07E+03	9.43E+03	8.50E+03	4.74E+03
TOTAL	8.32E+04	5.86E+07	5.84E+07	2.79E+07	1.60E+07	5.29E+06	3.87E+06	8.35E+05	2.98E+05	1.47E+05	1.13E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-231 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.3.5a. Heat Generation Rates--Once-Through Cycle--Growth Case 5, Watts$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	1.41E+00	1.35E+03	8.36E+02	5.13E-08	0.	0.	0.	0.	0.	0.	0.
C-14	1.09E-01	1.06E+02	1.06E+02	1.01E+02	9.81E+01	5.86E+01	3.20E+01	2.54E-01	6.03E-04	0.	0.
MN-54	2.89E-07	1.42E+01	7.93E-07	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	3.62E+00	2.95E+04	1.43E+02	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	9.55E+02	1.78E+06	1.28E+05	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	6.68E-02	6.14E+01	6.14E+01	6.12E+01	6.10E+01	5.89E+01	5.64E+01	4.09E+01	2.59E+01	8.10E-01	1.07E-02
NI-63	2.92E+01	2.60E+04	2.24E+04	1.05E+03	2.44E+01	0.	0.	0.	0.	0.	0.
SE-79	6.10E-02	5.59E+01	5.58E+01	5.56E+01	5.43E+01	5.30E+01	5.03E+01	3.28E+01	1.93E+01	2.71E-01	1.32E-03
KR-85	1.22E+03	1.22E+06	3.35E+05	1.66E-06	0.	0.	0.	0.	0.	0.	0.
RB-87	8.17E-06	4.73E-03	4.73E-03	4.73E-03	4.73E-03	4.73E-03	4.73E-03	4.73E-03	4.73E-03	4.73E-03	4.73E-03
SR-90+Y-90	1.12E+05	9.72E+07	5.93E+07	2.67E+03	1.19E-02	0.	0.	0.	0.	0.	0.
ZR-93	9.07E-02	8.28E+01	8.28E+01	8.28E+01	8.28E+01	8.26E+01	8.25E+01	8.09E+01	7.91E+01	6.58E+01	5.22E+01
NB-93M	2.03E-01	1.90E+02	2.25E+02	2.44E+02	2.45E+02	2.44E+02	2.44E+02	2.39E+02	2.34E+02	1.94E+02	1.54E+02
TC-99	1.03E+01	9.31E+03	9.31E+03	9.30E+03	9.28E+03	9.16E+03	9.01E+03	7.90E+03	6.70E+03	1.79E+03	3.44E+02
RU-106+RH-106	9.53E-03	8.35E+04	8.59E-02	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	3.75E-03	3.43E+00	3.43E+00	3.43E+00	3.43E+00	3.43E+00	3.43E+00	3.42E+00	3.40E+00	3.27E+00	3.11E+00
AG-110M	1.19E-08	2.50E+01	5.16E-08	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	1.04E+00	1.22E+03	4.92E+02	8.53E-07	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	1.25E+01	1.21E+05	7.14E+02	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	7.13E+00	6.56E+03	6.56E+03	6.54E+03	6.52E+03	6.34E+03	6.12E+03	4.64E+03	3.28E+03	2.06E+02	6.45E+00
I-129	1.00E-02	9.15E+00	9.15E+00	9.15E+00	9.15E+00	9.15E+00	9.14E+00	9.13E+00	9.11E+00	8.96E+00	8.78E+00
CS-134	5.67E+01	2.34E+06	2.72E+03	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	5.07E-02	5.44E+01	5.44E+01	5.44E+01	5.44E+01	5.43E+01	5.43E+01	5.38E+01	5.31E+01	4.85E+01	4.32E+01
CS-137+BA-137	1.22E+05	1.05E+08	6.52E+07	5.62E+03	5.44E-02	0.	0.	0.	0.	0.	0.
CE-144+PR-144	6.12E-05	1.44E+04	2.63E-04	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	1.86E+01	1.63E+05	8.22E+02	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	8.52E+02	6.99E+05	5.62E+05	2.22E+04	4.14E+02	0.	0.	0.	0.	0.	0.
EU-152	1.59E+01	2.05E+04	6.47E+03	4.29E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	8.30E+03	5.88E+06	2.86E+06	5.71E-02	0.	0.	0.	0.	0.	0.	0.
EU-155	8.53E-02	3.66E+03	1.74E+00	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	2.29E-01	2.07E-10	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	2.42E+05	2.15E+08	1.29E+08	4.80E+04	1.68E+04	1.61E+04	1.47E+04	1.30E+04	1.08E+04	2.32E+03	6.12E+02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.3.5b. Heat Generation Rates--Once Through Cycle--Growth Case 5, Watts(A)

Actinides

RADIONUCLIDES (B)	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2040	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	1.50E+00	2.29E+03	2.29E+03	2.21E+03	2.12E+03	1.51E+03	9.96E+02	3.68E+01	5.25E-01	0.	0.
CM-244	8.43E+03	6.32E+06	2.94E+06	5.19E-01	2.81E-09	0.	0.	0.	0.	0.	0.
CM-243	2.36E+01	3.15E+04	2.04E+04	3.09E+00	6.12E-05	0.	0.	0.	0.	0.	0.
CM-242	5.24E+01	1.18E+05	1.07E+05	1.68E+04	1.72E+03	2.06E-05	0.	0.	0.	0.	0.
AM-243+NP-239	1.66E+02	2.16E+05	2.16E+05	2.08E+05	1.89E+05	1.39E+05	8.80E+04	2.35E+03	2.53E+01	0.	0.
AM-242M+AM-242	5.19E+00	6.29E+03	5.74E+03	9.01E+02	9.22E+01	1.10E-06	0.	0.	0.	0.	0.
AM-241	8.47E+04	3.94E+07	4.48E+07	2.75E+07	1.24E+07	2.21E+04	1.07E+03	3.70E+01	5.59E-01	0.	0.
PU-242	1.76E+01	1.97E+04	1.97E+04	1.97E+04	1.97E+04	1.95E+04	1.93E+04	1.80E+04	1.64E+04	7.89E+03	3.16E+03
PU-241	5.88E+02	5.25E+05	2.06E+05	2.92E+00	2.81E+00	2.01E+00	1.32E+00	4.60E-02	6.95E-04	0.	0.
PU-240	7.87E+03	5.95E+06	5.95E+06	5.71E+06	5.63E+06	3.60E+06	2.16E+06	3.47E+04	2.12E+02	0.	0.
PU-239	5.95E+03	3.86E+06	3.85E+06	3.81E+06	3.76E+06	3.37E+06	2.94E+06	8.92E+05	2.30E+05	2.67E+00	1.81E-06
PU-238	1.94E+04	2.31E+07	1.98E+07	8.61E+05	2.05E+04	4.47E-05	0.	0.	0.	0.	0.
PU-236	8.00E-03	4.52E+01	3.49E-01	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	4.10E+00	4.28E+03	4.54E+03	8.67E+03	1.19E+04	1.43E+04	1.43E+04	1.41E+04	1.39E+04	1.22E+04	1.04E+04
U-238+TH-234+ PA-234M	6.91E+00	4.17E+03	4.17E+03	4.17E+03	4.17E+03	4.17E+03	4.17E+03	4.17E+03	4.17E+03	4.17E+03	4.17E+03
U-236	2.25E+00	2.56E+03	2.57E+03	2.62E+03	2.70E+03	3.14E+03	3.50E+03	4.02E+03	4.02E+03	3.98E+03	3.92E+03
U-235+TH-231	3.92E-01	2.10E+02	2.10E+02	2.11E+02	2.13E+02	2.26E+02	2.40E+02	3.03E+02	3.26E+02	3.33E+02	3.33E+02
U-234	1.45E+01	1.35E+04	1.46E+04	2.00E+04	2.08E+04	2.06E+04	2.04E+04	1.86E+04	1.67E+04	8.06E+03	4.92E+03
U-233	1.35E-03	1.40E+00	1.75E+00	1.18E+01	3.03E+01	2.55E+02	9.99E+02	2.87E+03	4.62E+03	1.08E+04	1.04E+04
U-232	1.60E-01	1.94E+02	1.61E+02	3.24E+00	2.63E-02	0.	0.	0.	0.	0.	0.
PA-231	4.51E-04	4.85E-01	5.42E-01	2.33E+00	4.82E+00	2.35E+01	4.45E+01	1.03E+02	2.90E+02	3.56E+02	3.56E+02
TH-230	3.48E-03	3.84E+00	6.24E+00	6.35E+01	1.56E+02	8.37E+02	1.46E+03	4.76E+03	1.04E+04	9.50E+03	5.31E+03
TH-229+7 DAUGHTERS	8.87E-08	2.00E-02	4.05E-02	1.52E+00	9.03E+00	5.30E+02	1.28E+03	1.42E+04	2.91E+04	7.44E+04	7.22E+04
TH-228+6 DAUGHTERS	9.19E-01	1.27E+03	1.07E+03	2.14E+01	1.75E-01	5.28E-03	1.16E-02	7.00E-02	1.45E-01	7.44E-01	1.48E+00
AC-227+7 DAUGHTERS	9.38E-06	1.51E+00	2.46E+00	1.47E+01	3.15E+01	1.53E+02	3.04E+02	1.26E+03	1.90E+03	2.33E+03	2.33E+03
TH-232+2 DAUGHTERS	2.91E-09	2.24E-06	4.77E-06	5.62E-05	1.32E-04	7.55E-04	1.65E-03	1.60E-02	2.08E-02	1.06E-01	2.12E-01
RA-226+5 DAUGHTERS	1.24E-04	1.94E-01	4.37E-01	2.86E+01	1.50E+02	2.75E+03	7.95E+03	3.41E+04	5.03E+04	5.35E+04	2.99E+04
PB-210+2 DAUGHTERS	6.87E-06	1.52E-02	4.10E-02	5.72E+00	3.23E+01	5.91E+02	1.56E+03	8.30E+03	1.27E+04	1.15E+04	6.42E+03
TOTAL	8.32E+04	7.96E+07	7.09E+07	3.81E+07	2.18E+07	7.20E+06	5.26E+06	1.12E+06	4.04E+05	1.99E+05	1.54E+05

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.3.6a. Heat Generation Rates--Reprocessing Cycle--Growth Case 3--1990 Reprocessing Startup, Watts(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	2.65E+01	6.99E+01	2.27E+01	2.66E-09	0.	0.	0.	0.	0.	0.	0.
C-14	8.09E+00	9.62E+01	5.60E+01	5.34E+01	5.02E+01	3.10E+01	1.69E+01	1.34E-01	3.19E-04	0.	0.
MN-54	3.42E+00	1.03E+00	5.73E-08	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	6.72E+03	2.73E+03	1.33E+01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	3.29E+05	3.03E+05	2.14E+04	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	8.21E+00	2.98E+01	2.98E+01	2.97E+01	2.95E+01	2.85E+01	2.73E+01	1.93E+01	1.25E+01	3.92E-01	5.17E-03
NI-63	2.02E+03	1.17E+04	1.00E+04	4.71E+02	1.49E+01	0.	0.	0.	0.	0.	0.
SE-79	1.23E+00	2.98E+01	2.97E+01	2.96E+01	2.95E+01	2.82E+01	2.68E+01	1.75E+01	1.03E+01	1.44E-01	7.01E-04
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	1.04E-04	2.36E-03	2.36E-03	2.36E-03	2.36E-03	2.36E-03	2.36E-03	2.36E-03	2.36E-03	2.36E-03	2.36E-03
SR-90+Y-90	2.66E+06	3.74E+07	2.28E+07	1.03E+03	4.96E-03	0.	0.	0.	0.	0.	0.
ZR-93	2.16E+00	4.60E+01	4.60E+01	4.60E+01	4.60E+01	4.59E+01	4.58E+01	4.50E+01	4.40E+01	3.65E+01	2.90E+01
NB-93M	4.31E+00	1.18E+02	1.29E+02	1.36E+02	1.36E+02	1.36E+02	1.35E+02	1.33E+02	1.30E+02	1.08E+02	8.57E+01
TC-99	2.07E+02	5.17E+03	5.17E+03	5.16E+03	5.15E+03	5.09E+03	5.00E+03	4.39E+03	3.72E+03	9.94E+02	1.91E+02
RU-106+RH-106	8.68E+01	6.28E+03	6.45E-03	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	7.67E-02	2.39E+00	2.39E+00	2.39E+00	2.39E+00	2.39E+00	2.39E+00	2.38E+00	2.36E+00	2.27E+00	2.16E+00
AG-110M	4.50E-03	1.70E+00	3.09E-09	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	8.78E+01	8.34E+02	3.10E+02	5.95E-07	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	1.85E+03	1.59E+04	9.34E+01	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	1.46E+02	4.27E+03	4.27E+03	4.26E+03	4.24E+03	4.13E+03	3.99E+03	3.02E+03	2.14E+03	1.34E+02	4.20E+00
I-129	6.13E-01	5.46E+00	5.46E+00	5.46E+00	5.46E+00	5.46E+00	5.45E+00	5.44E+00	5.43E+00	5.35E+00	5.24E+00
CS-134	1.85E+04	2.03E+05	2.35E+02	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	1.15E+00	3.86E+01	3.86E+01	3.86E+01	3.86E+01	3.85E+01	3.85E+01	3.81E+01	3.77E+01	3.44E+01	3.06E+01
CS-137+BA-137	2.86E+06	4.69E+07	2.09E+07	2.51E+03	2.03E-02	0.	0.	0.	0.	0.	0.
CE-144+PR-144	3.70E+00	1.01E+03	1.84E-05	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	2.19E+03	2.00E+04	1.01E+02	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	1.65E+04	3.65E+05	3.11E+05	1.23E+04	2.29E+02	0.	0.	0.	0.	0.	0.
EU-152	6.21E+02	1.15E+04	3.64E+03	2.41E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	1.68E+05	2.55E+06	1.07E+06	2.50E-02	0.	0.	0.	0.	0.	0.	0.
EU-155	2.13E+01	3.52E+02	1.67E-01	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	1.89E-02	1.31E-02	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	6.07E+06	8.78E+07	5.39E+07	2.60E+04	9.08E+03	9.53E+03	9.29E+03	7.67E+03	6.10E+03	1.31E+03	3.48E+02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.3.6b. Heat Generation Rates, Reprocessing Cycle--Growth Case 3, 1990 Reprocessing Startup, Watts(A)

Actinides

	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
RADIONUCLIDES (B)	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	4.48E+01	2.26E+04	2.25E+04	2.18E+04	2.09E+04	1.49E+04	9.82E+03	3.43E+02	5.17E+00	0.	0.
CM-244	1.68E+05	2.70E+07	1.26E+07	2.22E+00	1.07E-08	0.	0.	0.	0.	0.	0.
CM-243	7.76E+02	3.72E+04	2.41E+04	3.65E+00	7.22E-05	0.	0.	0.	0.	0.	0.
CM-242	2.59E+03	4.56E+05	4.16E+05	6.53E+04	6.68E+03	8.00E-05	0.	0.	0.	0.	0.
AM-243+NP-239	4.42E+03	5.65E+05	5.44E+05	5.44E+05	5.20E+05	3.62E+05	2.30E+05	6.13E+03	6.60E+01	0.	0.
AM-242M+AM-242	1.38E+02	2.44E+04	2.23E+04	3.50E+03	3.38E+02	4.27E-06	0.	0.	0.	0.	0.
AM-241	6.19E+05	1.35E+07	1.39E+07	7.52E+06	3.39E+06	2.22E+04	1.05E+04	3.65E+02	5.51E+00	0.	0.
PU-242	9.13E+00	3.83E+03	3.83E+03	3.85E+03	3.85E+03	3.83E+03	3.79E+03	3.42E+03	3.22E+03	1.55E+03	6.20E+02
PU-241	4.78E+02	4.93E+04	1.92E+04	2.88E+01	2.77E+01	1.98E+01	1.30E+01	4.34E-01	6.85E-03	0.	0.
PU-240	3.03E+03	5.00E+05	5.34E+05	5.40E+05	5.14E+05	3.41E+05	2.04E+05	3.38E+03	2.00E+01	0.	0.
PU-239	1.92E+03	1.11E+05	1.12E+05	1.15E+05	1.20E+05	1.45E+05	1.38E+05	7.60E+04	1.89E+04	2.19E-01	1.49E-07
PU-238	1.19E+04	3.73E+06	3.25E+06	2.33E+05	1.64E+04	1.73E-04	0.	0.	0.	0.	0.
PU-236	2.18E-01	2.24E+03	1.73E+01	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	6.82E+01	4.19E+03	6.27E+03	5.43E+03	6.29E+03	6.96E+03	6.97E+03	6.92E+03	6.81E+03	5.98E+03	5.09E+03
U-238+TH-234+ PA-234M	1.50E+00	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.92E+01	1.93E+01	1.94E+01	1.95E+01
U-236	8.01E-01	1.75E+01	1.76E+01	2.28E+01	2.08E+01	7.21E+01	1.06E+02	1.45E+02	1.56E+02	1.54E+02	1.52E+02
U-235+TH-231	7.27E-02	9.49E-01	9.51E-01	9.88E-01	1.04E+00	1.52E+00	2.21E+00	6.60E+00	8.46E+00	9.05E+00	9.05E+00
U-234	3.90E+00	3.14E+02	4.44E+02	1.48E+03	1.68E+03	1.68E+03	1.66E+03	1.48E+03	1.29E+03	4.32E+02	1.20E+02
U-233	2.25E-03	5.89E-01	9.31E-01	8.33E+00	2.08E+01	1.30E+02	2.68E+02	1.36E+03	2.27E+03	5.28E+03	5.11E+03
U-232	7.23E-02	1.52E+04	1.26E+04	2.52E+02	2.05E+00	0.	0.	0.	0.	0.	0.
PA-231	8.01E-03	2.42E-01	2.42E-01	2.48E-01	2.87E-01	3.47E-01	5.15E-01	3.28E+00	6.66E+00	9.68E+00	9.68E+00
TH-230	3.67E-02	5.24E-01	5.02E-01	4.23E+00	1.17E+01	6.72E+01	1.34E+02	5.44E+02	8.28E+02	5.86E+02	1.65E+02
TH-229+7 DAUGHTERS	7.19E-06	7.24E-03	1.72E-02	1.09E+00	5.26E+00	1.74E+02	6.42E+02	6.08E+03	1.43E+04	3.65E+04	3.54E+04
TH-228+6 DAUGHTERS	2.79E+00	9.95E+04	8.35E+04	1.67E+03	1.36E+01	6.74E-05	1.00E-04	1.49E-03	3.71E-03	1.97E-02	3.95E-02
AC-227+7 DAUGHTERS	1.07E-02	1.04E+00	1.30E+00	1.61E+00	1.68E+00	2.27E+00	3.37E+00	2.14E+01	4.35E+01	6.32E+01	6.32E+01
TH-232+2 DAUGHTERS	1.18E-08	3.00E-08	4.26E-08	4.30E-07	1.08E-06	9.63E-06	2.72E-05	2.41E-04	5.30E-04	2.82E-03	5.65E-03
RA-226+5 DAUGHTERS	1.40E-03	5.29E-02	7.94E-02	1.91E+00	1.08E+01	2.19E+02	5.85E+02	3.07E+03	4.70E+03	3.30E+03	9.29E+02
PB-210+2 DAUGHTERS	7.21E-05	5.56E-03	9.86E-03	3.82E-01	2.32E+00	4.71E+01	1.26E+02	6.60E+02	1.01E+03	7.10E+02	2.00E+02
TOTAL	8.12E+05	4.61E+07	3.13E+07	9.06E+06	4.40E+06	8.98E+05	6.26E+05	1.31E+05	5.36E+04	5.46E+04	4.79E+04

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.3.7a. Heat Generation Rates, Reprocessing Cycle, Growth Case 3, 2010 Reprocessing Startup, Watts$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	6.76E+01	2.19E+01	2.58E-09	0.	0.	0.	0.	0.	0.	0.
C-14	0.	6.28E+01	6.26E+01	5.96E+01	5.41E+01	3.46E+01	1.49E+01	1.40E-01	3.56E-04	0.	0.
MN-54	0.	1.00E+00	5.61E-08	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	2.85E+03	1.38E+01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	3.18E+05	2.29E+04	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	3.32E+01	3.32E+01	3.31E+01	3.29E+01	3.18E+01	3.05E+01	2.15E+01	1.40E+01	4.38E-01	5.77E-03
NI-63	0.	1.30E+04	1.12E+04	5.27E+02	1.22E+01	0.	0.	0.	0.	0.	0.
SE-79	0.	3.07E+01	3.06E+01	3.05E+01	3.04E+01	2.91E+01	2.76E+01	1.80E+01	1.06E+01	1.49E-01	7.22E-04
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	2.55E-03	2.55E-03	2.55E-03	2.55E-03	2.55E-03	2.55E-03	2.55E-03	2.55E-03	2.55E-03	2.55E-03
SR-90+Y-90	0.	4.06E+07	2.48E+07	1.12E+03	4.06E-03	0.	0.	0.	0.	0.	0.
ZR-93	0.	4.80E+01	4.80E+01	4.80E+01	4.80E+01	4.79E+01	4.78E+01	4.69E+01	4.58E+01	3.81E+01	3.02E+01
NB-93M	0.	1.23E+02	1.35E+02	1.42E+02	1.42E+02	1.41E+02	1.41E+02	1.38E+02	1.35E+02	1.12E+02	8.93E+01
TC-99	0.	5.17E+03	5.17E+03	5.16E+03	5.15E+03	5.09E+03	5.00E+03	4.39E+03	3.72E+03	9.94E+02	1.91E+02
RU-106+RH-106	0.	6.25E+03	6.02E-03	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	2.04E+00	2.04E+00	2.04E+00	2.04E+00	2.04E+00	2.04E+00	2.03E+00	2.02E+00	1.94E+00	1.85E+00
AG-110M	0.	1.63E+00	3.36E-09	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	6.94E+02	2.58E+02	4.87E-07	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	1.58E+04	9.34E+01	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	3.82E+03	3.82E+03	3.81E+03	3.79E+03	3.69E+03	3.56E+03	2.70E+03	1.91E+03	1.20E+02	3.75E+00
I-129	0.	5.21E+00	5.21E+00	5.21E+00	5.21E+00	5.21E+00	5.21E+00	5.20E+00	5.19E+00	5.11E+00	5.00E+00
CS-134	0.	2.06E+05	2.39E+02	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	3.26E+01	3.26E+01	3.26E+01	3.26E+01	3.25E+01	3.25E+01	3.22E+01	3.18E+01	2.90E+01	2.59E+01
CS-137+BA-137	0.	4.67E+07	2.94E+07	2.50E+03	2.42E-02	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	9.76E+02	1.78E-05	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	2.00E+04	1.01E+02	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	3.46E+05	2.95E+05	1.16E+04	2.17E+02	0.	0.	0.	0.	0.	0.
EU-152	0.	8.74E+03	2.76E+03	1.83E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	2.32E+06	9.75E+05	2.27E-02	0.	0.	0.	0.	0.	0.	0.
EU-155	0.	3.55E+02	1.68E-01	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	1.25E-02	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	9.05E+07	5.55E+07	2.51E+04	9.53E+03	9.10E+03	8.87E+03	7.35E+03	5.87E+03	1.30E+03	3.47E+02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.3.7b. Heat Generation Rates--Reprocessing Cycle--Growth Case 3 - 2010 Reprocessing Startup, Watts(A)

Actinides

RADIONUCLIDES (B)	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	5.95E+03	5.94E+03	5.74E+03	5.50E+03	3.93E+03	2.59E+03	9.03E+01	1.36E+00	0.	0.
CM-244	0.	9.66E+06	4.49E+06	7.93E-01	3.43E-09	0.	0.	0.	0.	0.	0.
CM-243	0.	2.13E+04	1.38E+04	2.09E+00	4.14E-05	0.	0.	0.	0.	0.	0.
CM-242	0.	1.49E+05	1.36E+05	2.14E+04	2.19E+03	2.62E-05	0.	0.	0.	0.	0.
AM-243+NP-239	0.	2.12E+05	2.11E+05	2.04E+05	1.95E+05	1.36E+05	8.62E+04	2.30E+03	2.47E+01	0.	0.
AM-242M+AM-242	0.	8.00E+03	7.30E+03	1.15E+03	1.17E+02	1.40E-06	0.	0.	0.	0.	0.
AM-241	0.	2.18E+07	2.12E+07	1.11E+07	4.97E+06	1.26E+04	2.76E+03	9.62E+01	1.45E+00	0.	0.
PU-242	0.	1.52E+02	1.53E+02	1.60E+02	1.62E+02	1.61E+02	1.60E+02	1.48E+02	1.35E+02	6.51E+01	2.61E+01
PU-241	0.	2.79E+03	1.08E+03	7.59E+00	7.29E+00	5.21E+00	3.42E+00	1.20E-01	1.80E-03	0.	0.
PU-240	0.	5.51E+04	6.73E+04	7.47E+04	7.11E+04	4.72E+04	2.83E+04	4.67E+02	2.77E+00	0.	0.
PU-239	0.	2.30E+04	2.31E+04	2.46E+04	2.67E+04	3.80E+04	4.49E+04	2.39E+04	5.98E+03	6.95E-02	4.71E-08
PU-238	0.	2.11E+05	1.99E+05	3.89E+04	4.61E+03	5.68E-05	0.	0.	0.	0.	0.
PU-236	0.	1.26E-01	9.72E-04	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	2.90E+03	3.03E+03	4.71E+03	5.49E+03	6.96E+03	6.97E+03	6.89E+03	6.78E+03	5.95E+03	5.06E+03
U-238+TH-234+PA-234M	0.	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.88E+01	1.89E+01
U-236	0.	1.30E+01	1.30E+01	1.37E+01	1.47E+01	2.05E+01	2.42E+01	3.21E+01	3.21E+01	3.18E+01	3.13E+01
U-235+TH-231	0.	9.56E-01	9.56E-01	9.64E-01	9.76E-01	1.09E+00	1.28E+00	2.63E+00	3.21E+00	3.40E+00	3.40E+00
U-234	0.	7.35E+01	8.35E+01	1.73E+02	2.07E+02	2.09E+02	2.06E+02	1.86E+02	1.64E+02	6.53E+01	2.93E+01
U-233	0.	2.25E-01	4.66E-01	6.27E+00	1.79E+01	1.26E+02	2.64E+02	1.35E+03	2.26E+03	5.25E+03	5.09E+03
U-232	0.	1.14E+00	9.47E-01	1.90E-02	1.54E-04	0.	0.	0.	0.	0.	0.
PA-231	0.	2.51E-01	2.51E-01	2.57E-01	2.66E-01	3.34E-01	4.29E-01	1.49E+00	2.64E+00	3.64E+00	3.64E+00
TH-230	0.	1.49E+00	1.50E+00	1.92E+00	2.81E+00	9.67E+00	1.80E+01	6.89E+01	1.05E+02	8.26E+01	3.43E+01
TH-229+7 DAUGHTERS	0.	1.64E-03	6.14E-03	7.46E-01	4.71E+00	1.65E+02	6.28E+02	6.94E+03	1.42E+04	3.63E+04	3.53E+04
TH-228+6 DAUGHTERS	0.	1.36E+01	6.27E+00	1.26E-01	1.03E-03	2.76E-05	6.19E-05	3.90E-04	8.17E-04	4.20E-03	8.38E-03
AC-227+7 DAUGHTERS	0.	7.69E-01	1.18E+00	1.67E+00	1.74E+00	2.18E+00	2.80E+00	9.71E+00	1.73E+01	2.38E+01	2.38E+01
TH-232+2 DAUGHTERS	0.	1.59E-07	4.00E-08	2.80E-07	6.67E-07	3.95E-06	8.64E-06	5.48E-05	1.17E-04	6.01E-04	1.20E-03
RA-226+5 DAUGHTERS	0.	1.25E-01	1.96E-01	1.54E+00	3.96E+00	3.38E+01	8.00E+01	3.89E+02	5.95E+02	4.65E+02	1.93E+02
PB-210+2 DAUGHTERS	0.	1.15E-02	2.30E-02	3.16E-01	8.41E-01	7.26E+00	1.72E+01	8.36E+01	1.28E+02	1.00E+02	4.15E+01
TOTAL	0.	3.21E+07	2.63E+07	1.14E+07	5.28E+06	2.45E+05	1.73E+05	4.29E+04	3.05E+04	4.84E+04	4.58E+04

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-231 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.3.8a. Heat Generation Rates--Reprocessing Cycle--Growth Case 4 - 2000 Reprocessing Startup, Watts$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	2.19E-01	1.33E+02	4.32E+01	5.08E-09	0.	0.	0.	0.	0.	0.	0.
C-14	1.41E-01	7.73E+01	7.72E+01	7.35E+01	6.02E+01	4.26E+01	2.33E+01	1.85E-01	4.39E-04	0.	0.
MN-54	2.89E-07	8.28E+00	4.63E-07	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	3.62E+00	1.29E+04	6.25E+01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	9.55E+02	9.39E+05	6.74E+04	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	6.68E-02	4.10E+01	4.10E+01	4.09E+01	4.07E+01	3.93E+01	3.76E+01	2.66E+01	1.73E+01	5.41E-01	7.13E-03
NI-63	2.93E+01	1.68E+04	1.44E+04	6.79E+02	1.57E+01	0.	0.	0.	0.	0.	0.
SE-79	3.25E-05	3.95E+01	3.95E+01	3.93E+01	3.91E+01	3.75E+01	3.56E+01	2.32E+01	1.36E+01	1.92E-01	9.31E-04
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	2.75E-09	3.19E-03	3.19E-03	3.19E-03	3.19E-03	3.19E-03	3.19E-03	3.19E-03	3.19E-03	3.19E-03	3.19E-03
SR-90+Y-90	5.98E+01	5.88E+07	3.59E+07	1.62E+03	7.18E-03	0.	0.	0.	0.	0.	0.
ZR-93	5.12E-03	6.14E+01	6.14E+01	6.14E+01	6.14E+01	6.13E+01	6.11E+01	6.02E+01	5.87E+01	4.84E+01	3.87E+01
NB-93M	1.24E-02	1.48E+02	1.69E+02	1.81E+02	1.81E+02	1.81E+02	1.81E+02	1.77E+02	1.73E+02	1.44E+02	1.14E+02
TC-99	9.98E-03	6.79E+03	6.79E+03	6.78E+03	6.77E+03	6.68E+03	6.57E+03	5.76E+03	4.88E+03	1.31E+03	2.51E+02
RU-106+RH-106	1.65E-05	5.59E+04	5.75E-02	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	2.00E-06	2.96E+00	2.96E+00	2.96E+00	2.96E+00	2.96E+00	2.96E+00	2.95E+00	2.93E+00	2.82E+00	2.68E+00
AG-110M	0.	2.15E+01	4.44E-08	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	3.65E-01	1.49E+03	5.52E+02	1.04E-06	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	8.20E-02	7.98E+00	4.71E-02	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	3.80E-03	5.38E+03	5.38E+03	5.37E+03	5.35E+03	5.20E+03	5.03E+03	3.81E+03	2.70E+03	1.69E+02	5.29E+00
I-129	9.97E-03	7.05E+00	7.05E+00	7.04E+00	7.04E+00	7.04E+00	7.04E+00	7.03E+00	7.02E+00	6.90E+00	6.76E+00
CS-134	3.02E-02	1.26E+06	1.46E+03	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	2.70E-05	4.74E+01	4.74E+01	4.74E+01	4.74E+01	4.73E+01	4.73E+01	4.68E+01	4.63E+01	4.22E+01	3.76E+01
CS-137+BA-137	6.47E+01	7.10E+07	4.47E+07	3.80E+03	3.68E-02	0.	0.	0.	0.	0.	0.
CE-144+PR-144	3.26E-08	7.75E+03	1.42E-04	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	9.89E-03	8.72E+04	4.40E+02	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	4.54E-01	4.93E+05	4.20E+05	1.66E+04	3.10E+02	0.	0.	0.	0.	0.	0.
EU-152	1.00E-02	2.06E+04	6.49E+03	4.31E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	2.82E+00	4.41E+06	1.85E+06	4.31E-02	0.	0.	0.	0.	0.	0.	0.
EU-155	2.41E-05	2.38E+03	1.13E+00	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	1.06E-01	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	1.12E+03	1.37E+08	8.31E+07	3.53E+04	1.29E+04	1.23E+04	1.20E+04	9.01E+03	7.90E+03	1.72E+03	4.56E+02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.3.8b. Heat Generation Rates--Reprocessing Cycle--Growth Case 4 - 2000 Reprocessing Startup, Watts$^{(A)}$

Actinides

	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
RADIONUCLIDES (B)	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	8.02E-04	1.89E+04	1.89E+04	1.83E+04	1.75E+04	1.25E+04	8.24E+03	2.88E+02	4.34E+00	0.	0.
CM-244	2.36E+00	3.23E+07	1.50E+07	2.65E+00	1.28E-08	0.	0.	0.	0.	0.	0.
CM-243	1.26E-02	4.60E+04	2.99E+04	4.52E+00	8.04E-05	0.	0.	0.	0.	0.	0.
CM-242	2.79E-02	4.07E+05	3.72E+05	5.83E+04	5.06E+03	7.14E-05	0.	0.	0.	0.	0.
AM-243+NP-239	8.86E-02	4.98E+05	4.97E+05	4.79E+05	4.58E+05	3.19E+05	2.03E+05	5.40E+03	5.82E+01	0.	0.
AM-242M+AM-242	2.77E-03	2.18E+04	1.99E+04	3.12E+03	3.19E+02	3.81E-06	0.	0.	0.	0.	0.
AM-241	2.43E+01	2.03E+07	1.98E+07	1.04E+07	4.68E+06	2.17E+04	8.79E+03	3.06E+02	4.62E+00	0.	0.
PU-242	9.06E-02	3.33E+02	3.35E+02	3.55E+02	3.60E+02	3.58E+02	3.55E+02	3.30E+02	3.01E+02	1.45E+02	5.80E+01
PU-241	4.02E+00	7.31E+03	2.86E+03	2.42E+01	2.32E+01	1.66E+01	1.09E+01	3.81E-01	5.75E-03	0.	0.
PU-240	3.79E+01	1.49E+05	1.49E+05	2.16E+05	2.05E+05	1.36E+05	8.16E+04	1.35E+03	8.01E+00	0.	0.
PU-239	2.80E+01	3.74E+04	3.76E+04	4.14E+04	4.65E+04	7.90E+04	9.30E+04	5.22E+04	1.31E+04	1.52E-01	1.03E-07
PU-238	1.04E+02	6.81E+05	6.33E+05	1.10E+05	1.26E+04	1.55E-04	0.	0.	0.	0.	0.
PU-236	3.41E-03	9.49E-01	7.32E-03	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	2.19E-03	5.25E+03	5.37E+03	6.97E+03	8.16E+03	9.07E+03	9.08E+03	9.00E+03	8.85E+03	7.78E+03	6.61E+03
U-238+TH-234+ PA-234M	2.17E-02	2.53E+01	2.53E+01	2.53E+01	2.53E+01	2.53E+01	2.53E+01	2.53E+01	2.53E+01	2.53E+01	2.53E+01
U-236	8.61E-03	2.20E+01	2.21E+01	2.41E+01	2.69E+01	4.38E+01	5.74E+01	7.71E+01	7.74E+01	7.65E+01	7.54E+01
U-235+TH-231	1.10E-03	1.25E+00	1.25E+00	1.27E+00	1.29E+00	1.51E+00	1.89E+00	4.78E+00	6.06E+00	6.48E+00	6.47E+00
U-234	6.37E-02	1.26E+02	1.58E+02	4.28E+02	5.23E+02	5.28E+02	5.21E+02	4.69E+02	4.10E+02	1.49E+02	5.46E+01
U-233	4.08E-06	4.84E-01	9.14E-01	1.02E+01	2.64E+01	1.68E+02	3.48E+02	1.64E+03	2.95E+03	6.86E+03	6.65E+03
U-232	4.87E-04	2.63E+00	2.20E+00	4.42E-02	3.58E-04	0.	0.	0.	0.	0.	0.
PA-231	2.43E-07	3.32E-01	3.32E-01	3.40E-01	3.51E-01	4.43E-01	5.83E-01	2.51E+00	4.84E+00	6.93E+00	6.92E+00
TH-230	1.89E-06	1.08E+00	1.10E+00	2.11E+00	4.37E+00	2.18E+01	4.29E+01	1.72E+02	2.62E+02	1.96E+02	6.80E+01
TH-229+7 DAUGHTERS	2.67E-10	4.23E-03	1.34E-02	1.27E+00	7.28E+00	2.28E+02	8.34E+02	9.08E+03	1.86E+04	4.75E+04	4.61E+04
TH-228+6 DAUGHTERS	5.72E-04	1.98E+01	1.46E+01	2.92E-01	2.38E-03	4.74E-05	1.07E-04	6.80E-04	1.42E-03	7.35E-03	1.47E-02
AC-227+7 DAUGHTERS	5.22E-09	1.16E+00	1.64E+00	2.21E+00	2.30E+00	2.90E+00	3.81E+00	1.64E+01	3.17E+01	4.53E+01	4.52E+01
TH-232+2 DAUGHTERS	0.	5.70E-08	4.52E-08	4.83E-07	1.14E-06	6.77E-06	1.52E-05	9.71E-05	2.04E-04	1.05E-03	2.09E-03
RA-226+5 DAUGHTERS	6.63E-08	9.77E-02	1.50E-01	1.40E+00	4.87E+00	7.23E+01	1.88E+02	9.71E+02	1.49E+03	1.10E+03	3.83E+02
PB-210+2 DAUGHTERS	3.66E-09	9.50E-03	1.80E-02	2.87E-01	1.05E+00	1.55E+01	4.04E+01	2.09E+02	3.20E+02	2.37E+02	8.23E+01
TOTAL	2.01E+02	5.49E+07	3.66E+07	1.13E+07	5.03E+06	5.75E+05	4.06E+05	8.15E+04	4.65E+04	6.41E+04	6.01E+04

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.3.9a. Heat Generation Rates--Reprocessing Cycle--Growth Case 5 - 2000 Reprocessing Startup, Watts(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
H-3	2.14E-01	2.16E+02	6.94E+01	8.21E-09	0.	0.	0.	0.	0.	0.	0.
C-14	1.41E-01	1.05E+02	1.04E+02	9.93E+01	9.35E+01	5.76E+01	3.15E+01	2.50E-01	5.03E-04	0.	0.
MN-54	2.89E-07	1.56E+01	8.73E-07	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	3.62E+00	2.37E+04	1.15E+02	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	9.55E+02	1.67E+06	1.20E+05	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	6.68E-02	5.53E+01	5.53E+01	5.51E+01	5.49E+01	5.30E+01	5.08E+01	3.59E+01	2.33E+01	7.29E-01	9.61E-03
NI-63	2.93E+01	2.33E+04	2.10E+04	9.42E+02	2.18E+01	0.	0.	0.	0.	0.	0.
SE-79	3.25E-05	5.35E+01	5.35E+01	5.32E+01	5.30E+01	5.07E+01	4.81E+01	3.14E+01	1.84E+01	2.60E-01	1.26E-03
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	2.75E-09	4.30E-03	4.30E-03	4.30E-03	4.30E-03	4.30E-03	4.30E-03	4.30E-03	4.30E-03	4.30E-03	4.30E-03
SR-90+Y-90	3.98E+01	8.62E+07	5.27E+07	2.37E+03	1.05E-02	0.	0.	0.	0.	0.	0.
ZR-93	5.12E-03	8.30E+01	8.30E+01	8.30E+01	8.30E+01	8.28E+01	8.26E+01	8.11E+01	7.93E+01	6.59E+01	5.23E+01
NB-93M	1.24E-02	1.91E+02	2.29E+02	2.45E+02	2.45E+02	2.45E+02	2.44E+02	2.40E+02	2.34E+02	1.95E+02	1.54E+02
TC-99	9.08E-03	9.22E+03	9.22E+03	9.21E+03	9.20E+03	9.05E+03	8.93E+03	7.82E+03	6.63E+03	1.77E+03	3.41E+02
RU-106+RH-106	1.65E-05	1.07E+09	1.10E-01	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	2.00E-06	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.08E+00	4.06E+00	3.90E+00	3.72E+00
AG-110M	0.	4.20E+01	5.66E-08	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	3.65E-01	2.39E+03	8.87E+02	1.07E-06	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	8.20E-02	1.50E+05	8.84E+02	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	3.80E-03	7.42E+03	7.41E+03	7.39E+03	7.37E+03	7.17E+03	6.92E+03	5.25E+03	3.71E+03	2.33E+02	7.29E+00
I-129	9.97E-03	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.62E+00	9.60E+00	9.58E+00	9.43E+00	9.24E+00
CS-134	3.02E-02	2.37E+06	2.75E+03	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	2.70E-05	6.52E+01	6.52E+01	6.51E+01	6.51E+01	6.51E+01	6.50E+01	6.44E+01	6.37E+01	5.81E+01	5.17E+01
CS-137+BA-137	6.47E+01	1.05E+08	6.54E+07	5.59E+03	5.42E-02	0.	0.	0.	0.	0.	0.
CE-144+PR-144	3.26E-08	1.44E+04	2.63E-04	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	9.89E-03	1.57E+05	7.05E+02	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	4.54E-01	6.92E+05	5.97E+05	2.33E+04	4.35E+02	0.	0.	0.	0.	0.	0.
EU-152	1.00E-02	3.35E+04	1.06E+04	7.00E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	2.82E+00	6.93E+06	2.92E+06	5.78E-02	0.	0.	0.	0.	0.	0.	0.
EU-155	2.41E-05	4.53E+03	2.15E+00	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	2.00E-01	1.88E-10	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	1.12E+03	2.03E+08	1.22E+08	4.94E+04	1.76E+04	1.68E+04	1.64E+04	1.35E+04	1.08E+04	2.34E+03	6.20E+02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.3.9b. Heat Generation Rates--Reprocessing Cycle--Growth Case 5 - 2000 Reprocessing Startup, Watts(A)

Actinides

RADIONUCLIDES (B)	YEAR 2000	 2050	 2100	GEOLOGIC TIME (YEARS BEYOND 1975) 500	 1000	 5000	 10000	 50000	 100000	 500000	 1000000
CM-245	8.02E-04	3.00E+04	3.00E+04	2.91E+04	2.78E+04	1.99E+04	1.31E+04	4.56E+02	6.88E+00	0.	0.
CM-244	2.36E+00	5.55E+07	2.55E+07	4.56E+00	2.20E-08	0.	0.	0.	0.	0.	0.
CM-243	1.26E-02	7.20E+04	4.67E+04	7.07E+00	1.10E-04	0.	0.	0.	0.	0.	0.
CM-242	2.79E-02	6.48E+05	5.92E+05	9.28E+04	9.49E+03	1.14E-04	0.	0.	0.	0.	0.
AM-243+NP-239	8.86E-02	7.72E+05	7.71E+05	7.13E+05	7.10E+05	4.94E+05	3.14E+05	8.37E+03	2.02E+01	0.	0.
AM-242M+AM-242	2.77E-03	3.47E+04	3.17E+04	4.97E+03	5.08E+02	6.07E-06	0.	0.	0.	0.	0.
AM-241	2.43E+01	2.79E+07	2.74E+07	1.44E+07	6.47E+06	3.28E+04	1.39E+04	4.46E+02	7.33E+00	0.	0.
PU-242	9.06E-02	6.77E+02	6.81E+02	7.12E+02	7.20E+02	7.16E+02	7.10E+02	6.60E+02	6.02E+02	2.90E+02	1.16E+02
PU-241	4.02E+00	1.63E+04	6.4 E+03	3.83E+01	3.68E+01	2.63E+01	1.73E+01	6.04E-01	9.11E-03	0.	0.
PU-240	3.79E+01	2.29E+05	2.94E+05	3.45E+05	3.29E+05	2.15E+05	1.31E+05	2.16E+03	1.28E+01	0.	0.
PU-239	2.80E+01	5.60E+04	5.63E+04	6.21E+04	7.01E+04	1.14E+05	1.03E+05	8.05E+04	2.02E+04	2.35E-01	1.59E-07
PU-238	1.04E+02	1.07E+06	9.02E+05	1.74E+05	2.01E+04	2.46E-04	0.	0.	0.	0.	0.
PU-236	3.41E-03	2.82E+03	2.18E+01	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	2.19E-03	6.48E+03	6.65E+03	8.84E+03	1.05E+04	1.19E+04	1.18E+04	1.17E+04	1.15E+04	1.01E+04	8.59E+03
U-238+TH-234+PA-234M	2.17E-02	3.44E+01	3.44E+01	3.44E+01	3.44E+01	3.44E+01	3.44E+01	3.44E+01	3.44E+01	3.45E+01	3.45E+01
U-236	8.61E-03	2.74E+01	2.75E+01	3.07E+01	3.52E+01	6.22E+01	8.40E+01	1.16E+02	1.16E+02	1.15E+02	1.13E+02
U-235+TH-231	1.10E-03	1.65E+00	1.65E+00	1.67E+00	1.70E+00	2.03E+00	2.62E+00	7.07E+00	9.05E+00	9.68E+00	9.68E+00
U-234	4.37E-02	1.60E+02	2.10E+02	6.35E+02	7.87E+02	7.96E+02	7.85E+02	7.05E+02	6.17E+02	2.22E+02	7.90E+01
U-233	4.08E-06	5.58E-01	1.09E+00	1.27E+01	3.35E+01	2.17E+02	4.51E+02	2.13E+03	3.84E+03	8.92E+03	8.64E+03
U-232	4.87E-04	6.94E+02	6.61E+02	1.33E+01	1.08E-01	0.	0.	0.	0.	0.	0.
PA-231	2.43E-07	4.14E-01	4.14E-01	4.25E-01	4.40E-01	5.65E-01	7.60E-01	3.63E+00	7.17E+00	1.04E+01	1.03E+01
TH-230	1.89E-06	1.32E+00	1.35E+00	2.81E+00	6.20E+00	3.25E+01	6.42E+01	2.59E+02	3.04E+02	2.93E+02	9.93E+01
TH-229+7 DAUGHTERS	2.67E-10	4.61E-03	1.54E-02	1.57E+00	9.17E+00	2.88E+02	1.08E+03	1.18E+04	2.41E+04	6.17E+04	5.99E+04
TH-228+6 DAUGHTERS	3.72E-04	4.17E+03	4.36E+03	8.79E+01	7.13E-01	6.16E-05	1.02E-04	9.49E-04	2.01E-03	1.00E-02	2.07E-02
AC-227+7 DAUGHTERS	3.22E-09	1.37E+00	2.00E+00	2.76E+00	2.88E+00	3.69E+00	4.07E+00	2.37E+01	4.69E+01	6.77E+01	6.76E+01
TH-232+2 DAUGHTERS	0.	7.83E-08	5.90E-08	5.09E-07	1.43E-06	8.80E-06	2.03E-05	1.36E-04	2.87E-04	1.49E-03	2.97E-03
RA-226+8 DAUGHTERS	6.63E-08	1.12E-01	1.75E-01	1.78E+00	6.44E+00	1.07E+02	2.81E+02	1.46E+03	2.24E+03	1.65E+03	5.59E+02
PB-210+2 DAUGHTERS	3.66E-09	1.05E-02	2.07E-02	3.62E-01	1.43E+00	2.30E+01	6.04E+01	3.14E+02	4.81E+02	3.54E+02	1.20E+02
TOTAL	2.01E+02	8.64E+07	5.60E+07	1.58E+07	7.65E+06	8.94E+05	6.30E+05	1.21E+05	6.43E+04	8.37E+04	7.83E+04

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

A.4 HAZARD INDEX TABLES

The tables of hazard indices (A.4.1a through A.4.9b) appear in the same format as those for the radioactivity inventory (A.2) and heat generation rates (A.3).

The hazard index employed here is the amount of water (m^3) required to dilute the quantity of a radionuclide present in one metric ton of spent fuel (MTHM) to drinking water standards. Following the summation at the bottom of each table, a uranium ore index is also shown. This is the ratio of the hazard index for the spent fuel to the hazard index (8.7×10^7 m^3) for the quantity of 0.2% U_3O_8 uranium ore required to produce one metric ton of 3% ^{235}U fuel (see Section 3.4 for further discussion of these indices).

The total index for the fission products and activation products must be added to the total index for the actinides to obtain the total spent fuel index.

TABLE A.4.1a. Hazard Index--Once-Through Cycle--Growth Case 1, m^3 water/MTHM$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975). 500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	0.	6.55E+02	7.70E-08	0.	0.	0.	0.	0.	0.	0.
C-14	0.	0.	7.64E+02	7.28E+02	6.85E+02	4.22E+02	2.31E+02	1.83E+00	4.35E-03	0.	0.
MN-54	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	0.	9.13E-04	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	0.	7.67E+02	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	0.	1.16E+04	1.15E+04	1.15E+04	1.11E+04	1.06E+04	7.52E+03	4.88E+03	1.53E+02	2.01E+00
NI-63	0.	0.	6.25E+06	2.94E+05	6.81E+03	5.67E-10	0.	0.	0.	0.	0.
SE-79	0.	0.	8.74E+04	8.70E+04	8.65E+04	8.29E+04	7.86E+04	5.13E+04	3.01E+04	4.24E+02	2.06E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	0.	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01	1.31E-01
SR-90+Y-90	0.	0.	1.87E+10	8.40E+05	3.73E+00	0.	0.	0.	0.	0.	0.
ZR-93	0.	0.	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.56E+03	1.53E+03	1.49E+03	1.24E+03	9.85E+02
NB-93M	0.	0.	3.10E+03	3.13E+03	3.13E+03	3.12E+03	3.12E+03	3.06E+03	2.99E+03	2.49E+03	1.97E+03
TC-99	0.	0.	3.22E+04	3.22E+04	3.22E+04	3.17E+04	3.12E+04	2.74E+04	2.32E+04	6.20E+03	1.19E+03
RU-106+RH-106	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	0.	2.35E+04	2.35E+04	2.35E+04	2.35E+04	2.35E+04	2.34E+04	2.33E+04	2.24E+04	2.13E+04
AG-110M	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	0.	1.97E+05	3.72E-04	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	0.	1.31E-02	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	0.	3.44E+05	3.43E+05	3.42E+05	3.33E+05	3.21E+05	2.43E+05	1.72E+05	1.08E+04	3.38E+02
I-129	0.	0.	4.09E+05	4.09E+05	4.09E+05	4.09E+05	4.09E+05	4.09E+05	4.08E+05	4.01E+05	3.93E+05
CS-134	0.	0.	3.27E-01	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	0.	1.92E+03	1.92E+03	1.92E+03	1.92E+03	1.91E+03	1.90E+03	1.88E+03	1.71E+03	1.52E+03
CS-137+BA-137	0.	0.	4.26E+08	3.62E+04	3.51E-01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	0.	8.16E-02	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	0.	1.15E+06	4.55E+04	8.49E+02	0.	0.	0.	0.	0.	0.
EU-152	0.	0.	7.07E+02	4.69E-08	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	0.	3.62E+06	8.42E-02	0.	0.	0.	0.	0.	0.	0.
EU-155	0.	0.	1.42E-06	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	1.91E+10	2.13E+06	9.20E+05	8.98E+05	8.81E+05	7.68E+05	6.68E+05	4.46E+05	4.20E+05
URANIUM ORE INDEX	0.	0.	2.19E+02	2.45E-02	1.06E-02	1.03E-02	1.01E-02	8.83E-03	7.68E-03	5.13E-03	4.83E-03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.4.1b. Hazard Index--Once-Through Cycle--Growth Case 1, m^3 water/MTHM$^{(A)}$

Actinides

RADIONUCLIDES (B)	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	0.	2.26E+04	2.18E+04	2.09E+04	1.50E+04	9.84E+03	3.43E+02	5.18E+00	0.	0.
CM-244	0.	0.	2.93E+06	5.18E-01	2.50E-09	0.	0.	0.	0.	0.	0.
CM-243	0.	0.	6.10E+04	9.24E+00	1.83E-04	0.	0.	0.	0.	0.	0.
CM-242	0.	0.	1.82E+05	2.85E+04	2.91E+03	3.49E-05	0.	0.	0.	0.	0.
AM-243+NP-239	0.	0.	2.02E+06	1.95E+06	1.86E+06	1.30E+06	8.24E+05	2.20E+04	2.36E+02	0.	0.
AM-242M+AM-242	0.	0.	1.15E+06	1.81E+05	1.85E+04	2.21E-04	0.	0.	0.	0.	0.
AM-241	0.	0.	6.31E+08	3.35E+08	1.50E+08	2.65E+05	9.04E+03	3.44E+02	5.19E+00	0.	0.
PU-242	0.	0.	2.00E+05	1.99E+05	1.99E+05	1.98E+05	1.96E+05	1.82E+05	1.66E+05	8.00E+04	3.21E+04
PU-241	0.	0.	5.82E+06	4.37E+02	4.19E+02	3.00E+02	1.97E+02	6.88E+00	1.04E-01	0.	0.
PU-240	0.	0.	7.32E+07	7.02E+07	6.67E+07	4.43E+07	2.65E+07	4.39E+05	2.60E+03	0.	0.
PU-239	0.	0.	5.43E+07	5.37E+07	5.30E+07	4.74E+07	4.12E+07	1.33E+07	3.22E+06	3.74E+01	2.53E-05
PU-238	0.	0.	1.27E+08	5.57E+06	1.36E+05	3.37E-04	0.	0.	0.	0.	0.
PU-236	0.	0.	3.10E-05	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	0.	9.40E+04	1.76E+05	2.30E+05	2.72E+05	2.72E+05	2.68E+05	2.64E+05	2.32E+05	1.97E+05
U-238+TH-234+ PA-234M	0.	0.	2.38E+04	2.38E+04	2.38E+04	2.38E+04	2.38E+04	2.38E+04	2.38E+04	2.38E+04	2.38E+04
U-236	0.	0.	5.90E+03	6.03E+03	6.20E+03	7.25E+03	8.09E+03	9.31E+03	9.32E+03	9.21E+03	9.08E+03
U-235+TH-231	0.	0.	8.25E+02	8.29E+02	8.34E+02	8.72E+02	9.13E+02	1.10E+03	1.17E+03	1.19E+03	1.19E+03
U-234	0.	0.	3.82E+04	4.52E+04	4.58E+04	4.54E+04	4.50E+04	4.13E+04	3.73E+04	1.93E+04	1.27E+04
U-233	0.	0.	4.95E+00	2.74E+01	7.10E+01	5.05E+02	1.05E+03	5.60E+03	8.99E+03	2.09E+04	2.03E+04
U-232	0.	0.	1.64E+03	3.30E+01	2.87E-01	0.	0.	0.	0.	0.	0.
PA-231	0.	0.	6.26E+01	2.60E+02	5.18E+02	2.49E+03	4.85E+03	1.92E+04	2.83E+04	3.43E+04	3.43E+04
TH-230	0.	0.	4.09E+02	2.60E+03	5.62E+03	2.87E+04	9.63E+04	2.39E+05	3.55E+05	3.39E+05	2.06E+05
TH-229+7 DAUGHTERS	0.	0.	7.85E-01	1.73E+01	8.54E+01	2.88E+03	1.09E+04	1.21E+05	2.47E+05	6.30E+05	6.12E+05
TH-228+6 DAUGHTERS	0.	0.	3.52E+03	7.07E+01	5.80E-01	3.37E-02	7.34E-02	4.64E-01	9.22E-01	4.72E+00	9.41E+00
AC-227+7 DAUGHTERS	0.	0.	8.22E+01	4.59E+02	9.25E+02	4.45E+03	8.68E+03	3.44E+04	5.07E+04	6.13E+04	6.13E+04
TH-232+2 DAUGHTERS	0.	0.	2.00E-02	1.39E-01	2.95E-01	1.65E+00	3.58E+00	2.16E+01	4.50E+01	2.30E+02	4.59E+02
RA-226+5 DAUGHTERS	0.	0.	5.15E+02	1.62E+04	6.86E+04	1.14E+06	2.05E+06	1.55E+07	2.41E+07	2.29E+07	1.39E+07
PB-210+2 DAUGHTERS	0.	0.	9.44E+01	5.39E+03	2.34E+04	3.89E+05	1.00E+06	5.36E+06	8.20E+06	7.78E+06	4.72E+06
TOTAL	0.	0.	8.98E+08	4.67E+08	2.73E+08	9.54E+07	7.32E+07	3.54E+07	3.67E+07	3.21E+07	1.98E+07
URANIUM ORE INDEX	0.	0.	1.03E+01	5.37E+00	3.13E+00	1.10E+00	8.41E-01	4.67E-01	4.22E-01	3.69E-01	2.28E-01

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.
B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-231 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.4.2a. Hazard Index--Once-Through Cycle--Growth Case 2, m^3 water/MTHM(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	0.	2.38E+03	2.80E-07	0.	0.	0.	0.	0.	0.	0.
C-14	0.	0.	9.96E+02	9.48E+02	8.92E+02	5.50E+02	3.01E+02	2.39E+00	5.66E-03	0.	0.
MN-54	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	0.	4.29E-01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	0.	1.40E+04	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	0.	1.49E+04	1.48E+04	1.47E+04	1.42E+04	1.36E+04	9.45E+03	6.26E+03	1.96E+02	2.58E+00
NI-63	0.	0.	8.99E+06	4.23E+05	9.80E+03	8.16E-10	0.	0.	0.	0.	0.
SE-79	0.	0.	1.14E+05	1.14E+05	1.13E+05	1.08E+05	1.03E+05	6.70E+04	3.94E+04	5.54E+02	2.69E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	0.	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01
SR-90+Y-90	0.	0.	3.60E+10	1.62E+06	7.19E+00	0.	0.	0.	0.	0.	0.
ZR-93	0.	0.	2.03E+03	2.03E+03	2.03E+03	2.03E+03	2.03E+03	1.99E+03	1.94E+03	1.61E+03	1.28E+03
NB-93M	0.	0.	3.98E+03	4.07E+03	4.07E+03	4.06E+03	4.05E+03	3.98E+03	3.89E+03	3.23E+03	2.57E+03
TC-99	0.	0.	4.20E+04	4.19E+04	4.18E+04	4.13E+04	4.06E+04	3.56E+04	3.02E+04	8.07E+03	1.55E+03
RU-106+RH-106	0.	0.	1.34E-07	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	0.	3.19E+04	3.19E+04	3.19E+04	3.19E+04	3.19E+04	3.17E+04	3.16E+04	3.04E+04	2.89E+04
AG-110M	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	0.	7.76E+05	1.46E-03	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	0.	6.10E+00	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	0.	4.63E+05	4.62E+05	4.60E+05	4.48E+05	4.33E+05	3.35E+05	2.32E+05	1.45E+04	4.56E+02
I-129	0.	0.	5.40E+05	5.40E+05	5.40E+05	5.40E+05	5.39E+05	5.39E+05	5.37E+05	5.29E+05	5.18E+05
CS-134	0.	0.	1.51E+03	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	0.	2.63E+03	2.63E+03	2.63E+03	2.63E+03	2.62E+03	2.60E+03	2.57E+03	2.34E+03	2.09E+03
CS-137+BA-137	0.	0.	8.15E+08	6.92E+04	6.70E-01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	0.	2.09E+01	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	0.	1.86E+06	6.17E+04	1.15E+03	1.70E-11	0.	0.	0.	0.	0.
EU-152	0.	0.	2.59E+03	1.72E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	0.	1.20E+07	2.80E-01	1.11E-10	0.	0.	0.	0.	0.	0.
EU-155	0.	0.	1.90E-02	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	3.68E+10	3.39E+06	1.22E+06	1.19E+06	1.17E+06	1.02E+06	8.45E+05	5.90E+05	5.55E+05
URANIUM ORE INDEX	0.	0.	4.23E+02	3.89E-02	1.40E-02	1.37E-02	1.34E-02	1.17E-02	1.02E-02	6.78E-03	6.38E-03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.4.2b. Hazard Index--Once-Through Cycle--Growth Case 2, m^3 water/MTHM$^{(A)}$

Actinides

RADIONUCLIDES (B)	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	0.	4.18E+04	4.04E+04	3.47E+04	2.77E+04	1.42E+04	4.35E+02	9.49E+00	0.	0.
CM-244	0.	0.	1.09E+07	1.93E+00	9.32E-09	0.	0.	0.	0.	0.	0.
CM-243	0.	0.	1.55E+05	2.35E+01	4.45E-04	0.	0.	0.	0.	0.	0.
CM-242	0.	0.	3.06E+05	4.80E+04	4.01E+03	5.88E-05	0.	0.	0.	0.	0.
AM-243+NP-239	0.	0.	3.42E+06	3.30E+06	3.15E+06	2.20E+06	1.40E+06	3.72E+04	4.01E+02	0.	0.
AM-242M+AM-242	0.	0.	1.94E+06	3.04E+05	3.11E+04	3.72E-04	0.	0.	0.	0.	0.
AM-241	0.	0.	8.45E+08	4.58E+08	2.06E+08	3.69E+05	1.84E+04	6.36E+02	9.60E+00	0.	0.
PU-242	0.	0.	3.09E+05	3.09E+05	3.08E+05	3.06E+05	3.03E+05	2.82E+05	2.57E+05	1.24E+05	4.96E+04
PU-241	0.	0.	1.81E+07	9.08E+02	7.76E+02	5.54E+02	3.45E+02	1.27E+01	1.92E-01	0.	0.
PU-240	0.	0.	8.82E+07	8.47E+07	8.04E+07	5.34E+07	3.20E+07	5.59E+05	3.14E+03	0.	0.
PU-239	0.	0.	5.73E+07	5.67E+07	5.59E+07	5.01E+07	4.37E+07	1.42E+07	3.42E+06	3.97E+01	2.69E-05
PU-238	0.	0.	2.32E+08	1.02E+07	2.45E+05	5.67E-04	0.	0.	0.	0.	0.
PU-236	0.	0.	1.66E-02	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	0.	1.26E+05	2.35E+05	3.11E+05	3.69E+05	3.69E+05	3.64E+05	3.59E+05	3.15E+05	2.68E+05
U-238+TH-234+ PA-234M	0.	0.	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04
U-236	0.	0.	7.38E+03	7.54E+03	7.74E+03	9.01E+03	1.00E+04	1.15E+04	1.15E+04	1.14E+04	1.12E+04
U-235+TH-231	0.	0.	6.74E+02	6.78E+02	6.84E+02	7.23E+02	7.67E+02	9.44E+02	1.04E+03	1.06E+03	1.06E+03
U-234	0.	0.	4.28E+04	5.54E+04	5.67E+04	5.62E+04	5.56E+04	5.08E+04	4.55E+04	2.19E+04	1.53E+04
U-233	0.	0.	5.80E+00	3.52E+01	9.07E+01	6.82E+02	1.43E+03	6.79E+03	1.22E+04	2.84E+04	2.75E+04
U-232	0.	0.	3.12E+03	6.25E+01	5.08E-01	0.	0.	0.	0.	0.	0.
PA-231	0.	0.	5.93E+01	2.17E+02	4.30E+02	2.05E+03	4.03E+03	1.46E+04	2.49E+04	3.06E+04	3.05E+04
TH-230	0.	0.	3.79E+02	2.94E+03	6.73E+03	3.53E+04	6.95E+04	2.82E+05	4.36E+05	3.95E+05	2.20E+05
TH-229+7 DAUGHTERS	0.	0.	7.97E-01	2.12E+01	1.12E+02	3.88E+03	1.48E+04	1.64E+05	3.35E+05	8.56E+05	8.31E+05
TH-228+6 DAUGHTERS	0.	0.	6.69E+03	1.34E+02	1.10E+00	4.19E-02	4.10E-02	5.48E-01	1.14E+00	5.82E+00	1.16E+01
AC-227+7 DAUGHTERS	0.	0.	7.87E+01	3.80E+02	7.49E+02	3.67E+03	7.21E+03	2.97E+04	4.46E+04	5.46E+04	5.46E+04
TH-232+2 DAUGHTERS	0.	0.	2.10E-02	1.66E-01	3.44E-01	2.04E+00	4.44E+00	2.47E+01	5.55E+01	2.84E+02	5.66E+02
RA-226+5 DAUGHTERS	0.	0.	4.11E+02	1.72E+04	7.99E+04	1.39E+06	3.43E+06	1.91E+07	2.96E+07	2.66E+07	1.48E+07
PB-210+2 DAUGHTERS	0.	0.	7.01E+01	5.64E+03	2.72E+04	4.75E+05	1.24E+06	6.49E+06	1.01E+07	9.06E+06	5.04E+06
TOTAL	0.	0.	1.26E+09	6.14E+08	3.06E+08	1.09E+08	8.29E+07	4.15E+07	4.46E+07	3.75E+07	2.14E+07
URANIUM ORE INDEX	0.	0.	1.05E+01	7.05E+00	3.08E+00	1.25E+00	9.52E-01	4.77E-01	5.13E-01	4.31E-01	2.46E-01

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.4.3a. *Hazard Index--Once-Through Cycle--Growth Case 3, m³ water/MTHM*[A]

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	0.	5.50E+03	6.47E-07	0.	0.	0.	0.	0.	0.	0.
C-14	0.	0.	1.04E+03	9.88E+02	9.30E+02	5.73E+02	3.13E+02	2.49E+00	5.90E-03	0.	0.
MN-54	0.	0.	2.70E-07	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	0.	6.41E+01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	0.	1.27E+05	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	0.	1.51E+04	1.51E+04	1.50E+04	1.45E+04	1.39E+04	9.81E+03	6.36E+03	1.99E+02	2.63E+00
NI-63	0.	0.	1.01E+07	4.75E+05	1.10E+04	9.17E-10	0.	0.	0.	0.	0.
SE-79	0.	0.	1.15E+05	1.15E+05	1.14E+05	1.09E+05	1.03E+05	6.76E+04	3.97E+04	5.59E+02	2.71E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	0.	1.71E-01	1.71E-01	1.71E-01	1.71E-01	1.71E-01	1.71E-01	1.71E-01	1.71E-01	1.71E-01
SR-90+Y-90	0.	0.	5.09E+10	2.29E+06	1.02E+01	0.	0.	0.	0.	0.	0.
ZR-93	0.	0.	2.05E+03	2.05E+03	2.05E+03	2.05E+03	2.04E+03	2.00E+03	1.96E+03	1.63E+03	1.29E+03
NB-93M	0.	0.	3.90E+03	4.10E+03	4.10E+03	4.10E+03	4.09E+03	4.01E+03	3.92E+03	3.26E+03	2.59E+03
TC-99	0.	0.	4.23E+04	4.22E+04	4.22E+04	4.16E+04	4.09E+04	3.59E+04	3.04E+04	8.13E+03	1.56E+03
RU-106+RH-106	0.	0.	2.21E-01	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	0.	3.21E+04	3.21E+04	3.21E+04	3.21E+04	3.21E+04	3.20E+04	3.18E+04	3.06E+04	2.91E+04
AG-110M	0.	0.	1.09E-08	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	0.	1.61E+06	3.04E-03	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	0.	7.19E+02	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	0.	4.67E+05	4.66E+05	4.64E+05	4.51E+05	4.36E+05	3.31E+05	2.34E+05	1.46E+04	4.59E+02
I-129	0.	0.	5.44E+05	5.44E+05	5.44E+05	5.44E+05	5.44E+05	5.43E+05	5.42E+05	5.33E+05	5.22E+05
CS-134	0.	0.	1.03E+06	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	0.	2.64E+03	2.64E+03	2.64E+03	2.64E+03	2.63E+03	2.61E+03	2.58E+03	2.39E+03	2.10E+03
CS-137+BA-137	0.	0.	1.13E+09	9.58E+04	9.28E-01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	0.	9.19E-04	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	0.	4.22E+03	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	0.	1.75E+06	6.91E+04	1.29E+03	1.90E-11	0.	0.	0.	0.	0.
EU-152	0.	0.	6.11E+03	4.05E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	0.	2.27E+07	5.27E-01	2.09E-10	0.	0.	0.	0.	0.	0.
EU-155	0.	0.	3.49E+01	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	1.04E-10	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	5.21E+10	4.16E+06	1.23E+06	1.20E+06	1.18E+06	1.03E+06	8.92E+05	5.94E+05	5.59E+05
URANIUM ORE INDEX	0.	0.	5.09E+02	4.78E-02	1.42E-02	1.38E-02	1.36E-02	1.18E-02	1.03E-02	6.83E-03	6.43E-03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.4.3b. Hazard Index--Once-Through Cycle--Growth Case 3, m^3 water/MTHM$^{(A)}$

Actinides

RADIONUCLIDES (B)	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	0.	4.27E+04	4.12E+04	3.95E+04	2.83E+04	1.86E+04	6.49E+02	9.79E+00	0.	0.
CM-244	0.	0.	1.01E+07	3.37E+00	1.63E-08	0.	0.	0.	0.	0.	0.
CM-243	0.	0.	2.11E+05	3.19E+01	6.31E-04	0.	0.	0.	0.	0.	0.
CM-242	0.	0.	3.27E+05	5.13E+04	5.24E+03	6.28E-05	0.	0.	0.	0.	0.
AM-243+NP-239	0.	0.	3.47E+06	3.35E+06	3.20E+06	2.23E+06	1.41E+06	3.77E+04	4.06E+02	0.	0.
AM-242M+AM-242	0.	0.	2.07E+06	3.25E+05	3.32E+04	3.97E-04	0.	0.	0.	0.	0.
AM-241	0.	0.	8.41E+08	4.72E+08	2.12E+08	3.81E+05	1.88E+04	6.50E+02	9.81E+00	0.	0.
PU-242	0.	0.	3.12E+05	3.12E+05	3.11E+05	3.09E+05	3.06E+05	2.85E+05	2.60E+05	1.25E+05	5.01E+04
PU-241	0.	0.	3.60E+07	8.26E+02	7.02E+02	5.66E+02	3.72E+02	1.30E+01	1.96E-01	0.	0.
PU-240	0.	0.	8.88E+07	8.52E+07	8.10E+07	5.37E+07	3.22E+07	5.32E+05	3.16E+03	0.	0.
PU-239	0.	0.	5.77E+07	5.71E+07	5.63E+07	5.05E+07	4.40E+07	1.43E+07	3.45E+06	4.00E+01	2.71E-05
PU-238	0.	0.	2.60E+08	1.13E+07	2.72E+05	6.06E-04	0.	0.	0.	0.	0.
PU-236	0.	0.	1.46E+00	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	0.	1.23E+05	2.32E+05	3.12E+05	3.73E+05	3.73E+05	3.68E+05	3.62E+05	3.18E+05	2.71E+05
U-238+TH-234+ PA-234M	0.	0.	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04
U-236	0.	0.	7.43E+03	7.59E+03	7.80E+03	9.07E+03	1.01E+04	1.16E+04	1.16E+04	1.15E+04	1.13E+04
U-235+TH-231	0.	0.	6.79E+02	6.83E+02	6.88E+02	7.28E+02	7.72E+02	9.71E+02	1.04E+03	1.06E+03	1.06E+03
U-234	0.	0.	4.16E+04	5.54E+04	5.71E+04	5.67E+04	5.40E+04	5.12E+04	4.59E+04	2.20E+04	1.34E+04
U-233	0.	0.	5.19E+00	3.34E+01	9.35E+01	6.85E+02	1.44E+03	6.85E+03	1.23E+04	2.87E+04	2.78E+04
U-232	0.	0.	3.59E+03	7.20E+01	5.84E-01	0.	0.	0.	0.	0.	0.
PA-231	0.	0.	5.41E+01	2.10E+02	4.26E+02	2.06E+03	4.05E+03	1.67E+04	2.51E+04	3.08E+04	3.08E+04
TH-230	0.	0.	3.11E+02	2.81E+03	6.66E+03	3.54E+04	6.99E+04	2.84E+05	4.39E+05	3.98E+05	2.21E+05
TH-229+7 DAUGHTERS	0.	0.	6.24E-01	1.94E+01	1.09E+02	3.48E+03	1.49E+04	1.65E+05	3.38E+05	8.65E+05	8.39E+05
TH-228+6 DAUGHTERS	0.	0.	7.69E+03	1.54E+02	1.26E+00	4.20E-02	9.16E-02	5.32E-01	1.15E+00	5.86E+00	1.17E+01
AC-227+7 DAUGHTERS	0.	0.	6.77E+01	3.64E+02	7.41E+02	3.67E+03	7.25E+03	2.09E+04	4.49E+04	5.50E+04	5.50E+04
TH-232+2 DAUGHTERS	0.	0.	1.73E-02	1.60E-01	3.41E-01	2.05E+00	4.07E+00	2.49E+01	5.99E+01	2.86E+02	5.70E+02
RA-226+5 DAUGHTERS	0.	0.	2.90E+02	1.57E+04	7.79E+04	1.39E+06	3.66E+06	1.02E+07	2.98E+07	2.68E+07	1.49E+07
PB-210+2 DAUGHTERS	0.	0.	4.57E+01	5.07E+03	2.45E+04	4.75E+05	1.24E+06	6.84E+06	1.02E+07	9.12E+06	5.06E+06
TOTAL	0.	0.	1.31E+09	6.30E+08	3.54E+08	1.10E+08	8.34E+07	4.18E+07	4.50E+07	3.78E+07	2.15E+07
URANIUM ORE INDEX	0.	0.	1.50E+01	7.24E+00	4.07E+00	1.26E+00	9.39E-01	6.81E-01	5.17E-01	4.34E-01	2.47E-01

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.4.4a. Hazard Index--Once-Through Cycle--Growth Case 4, m^3 water/MTHM(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	0.	8.02E+03	9.42E-07	0.	0.	0.	0.	0.	0.	0.
C-14	0.	0.	1.04E+03	9.89E+02	9.31E+02	5.74E+02	3.14E+02	2.49E+00	5.90E-03	0.	0.
MN-54	0.	0.	1.63E-06	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	0.	2.35E+02	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	0.	2.93E+05	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	0.	1.51E+04	1.50E+04	1.49E+04	1.44E+04	1.38E+04	9.78E+03	6.34E+03	1.99E+02	2.62E+00
NI-63	0.	0.	1.05E+07	4.95E+05	1.15E+04	9.56E-10	0.	0.	0.	0.	0.
SE-79	0.	0.	1.14E+05	1.14E+05	1.13E+05	1.08E+05	1.03E+05	6.71E+04	3.44E+04	5.55E+02	2.69E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	0.	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01	1.69E-01
SR-90+Y-90	0.	0.	5.89E+10	2.65E+06	1.18E+01	0.	0.	0.	0.	0.	0.
ZR-93	0.	0.	2.04E+03	2.03E+03	2.03E+03	2.03E+03	2.03E+03	1.99E+03	1.94E+03	1.62E+03	1.28E+03
NB-93M	0.	0.	3.79E+03	4.07E+03	4.07E+03	4.07E+03	4.06E+03	3.98E+03	3.89E+03	3.23E+03	2.57E+03
TC-99	0.	0.	4.20E+04	4.20E+04	4.19E+04	4.13E+04	4.07E+04	3.56E+04	3.02E+04	8.08E+03	1.55E+03
RU-106+RH-106	0.	0.	1.35E+00	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	0.	3.20E+04	3.20E+04	3.20E+04	3.20E+04	3.20E+04	3.19E+04	3.17E+04	3.05E+04	2.90E+04
AG-110M	0.	0.	1.66E-07	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	0.	2.25E+06	4.25E-03	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	0.	2.69E+03	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	0.	4.65E+05	4.64E+05	4.62E+05	4.49E+05	4.34E+05	3.29E+05	2.33E+05	1.46E+04	4.57E+02
I-129	0.	0.	5.41E+05	5.41E+05	5.41E+05	5.41E+05	5.40E+05	5.40E+05	5.38E+05	5.30E+05	5.19E+05
CS-134	0.	0.	4.78E+06	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	0.	2.61E+03	2.61E+03	2.61E+03	2.61E+03	2.60E+03	2.58E+03	2.55E+03	2.33E+03	2.07E+03
CS-137+BA-137	0.	0.	1.30E+09	1.10E+05	1.06E+00	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	0.	5.03E-03	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	0.	1.38E+04	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	0.	1.83E+06	7.20E+04	1.34E+03	1.98E-11	0.	0.	0.	0.	0.
EU-152	0.	0.	8.86E+03	5.88E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	0.	3.01E+07	7.01E-01	2.98E-10	0.	0.	0.	0.	0.	0.
EU-155	0.	0.	1.72E+02	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	8.35E-10	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	6.03E+10	4.55E+06	1.23E+06	1.20E+06	1.17E+06	1.02E+06	8.87E+05	5.91E+05	5.56E+05
URANIUM ORE INDEX	0.	0.	6.93E+02	5.23E-02	1.41E-02	1.37E-02	1.35E-02	1.17E-02	1.02E-02	6.79E-03	6.39E-03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.4.4b. Hazard Index--Once-Through Cycle--Growth Case 4, m^3 water/MTHM(A)

Actinides

RADIONUCLIDES (B)	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	0.	4.23E+04	4.08E+04	3.92E+04	2.80E+04	1.84E+04	6.43E+02	9.70E+00	0.	0.
CM-244	0.	0.	2.44E+07	4.32E+00	2.08E-08	0.	0.	0.	0.	0.	0.
CM-243	0.	0.	2.39E+05	3.62E+01	7.15E-04	0.	0.	0.	0.	0.	0.
CM-242	0.	0.	3.33E+05	5.22E+04	5.34E+03	6.40E-05	0.	0.	0.	0.	0.
AM-243+NP-239	0.	0.	3.45E+06	3.32E+06	3.17E+06	2.21E+06	1.40E+06	3.74E+04	4.03E+02	0.	0.
AM-242M+AM-242	0.	0.	2.11E+06	3.31E+05	3.38E+04	4.04E-04	0.	0.	0.	0.	0.
AM-241	0.	0.	8.23E+08	4.75E+08	2.14E+08	3.83E+05	1.86E+04	6.44E+02	9.72E+00	0.	0.
PU-242	0.	0.	3.10E+05	3.10E+05	3.09E+05	3.07E+05	3.04E+05	2.83E+05	2.58E+05	1.24E+05	4.98E+04
PU-241	0.	0.	4.96E+07	8.18E+02	7.65E+02	5.61E+02	3.69E+02	1.29E+01	1.94E-01	0.	0.
PU-240	0.	0.	8.88E+07	8.52E+07	8.10E+07	5.37E+07	3.22E+07	5.32E+05	3.16E+03	0.	0.
PU-239	0.	0.	5.78E+07	5.71E+07	5.64E+07	5.05E+07	4.40E+07	1.43E+07	3.45E+06	4.01E+01	2.71E-05
PU-238	0.	0.	2.70E+08	1.18E+07	2.41E+05	6.17E-04	0.	0.	0.	0.	0.
PU-236	0.	0.	5.64E+00	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	0.	1.20E+05	2.27E+05	3.10E+05	3.71E+05	3.71E+05	3.67E+05	3.61E+05	3.17E+05	2.70E+05
U-238+TH-234+ PA-234M	0.	0.	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04
U-236	0.	0.	7.36E+03	7.52E+03	7.73E+03	9.00E+03	1.00E+04	1.15E+04	1.15E+04	1.14E+04	1.12E+04
U-235+TH-231	0.	0.	6.68E+02	6.78E+02	6.77E+02	7.17E+02	7.81E+02	9.40E+02	1.03E+03	1.05E+03	1.05E+03
U-234	0.	0.	4.01E+04	5.43E+04	5.63E+04	5.58E+04	5.52E+04	5.04E+04	4.52E+04	2.18E+04	1.33E+04
U-233	0.	0.	4.87E+00	3.20E+01	9.19E+01	6.80E+02	1.43E+03	6.82E+03	1.23E+04	2.86E+04	2.77E+04
U-232	0.	0.	3.76E+03	7.98E+01	6.12E-01	0.	0.	0.	0.	0.	0.
PA-231	0.	0.	5.11E+01	2.02E+02	4.16E+02	2.02E+03	3.99E+03	1.65E+04	2.48E+04	3.05E+04	3.04E+04
TH-230	0.	0.	2.78E+02	2.67E+03	6.49E+03	3.47E+04	6.68E+04	2.80E+05	4.33E+05	3.93E+05	2.19E+05
TH-229+7 DAUGHTERS	0.	0.	5.16E-01	1.82E+01	1.06E+02	3.84E+03	1.48E+04	1.65E+05	3.37E+05	8.62E+05	8.37E+05
TH-228+6 DAUGHTERS	0.	0.	8.06E+03	1.62E+02	1.32E+00	4.15E-02	9.08E-02	5.48E-01	1.14E+00	5.83E+00	1.16E+01
AC-227+7 DAUGHTERS	0.	0.	6.06E+01	3.48E+02	7.44E+02	3.61E+03	7.13E+03	2.95E+04	4.44E+04	5.45E+04	5.44E+04
TH-232+2 DAUGHTERS	0.	0.	1.38E-02	1.52E-01	3.34E-01	2.02E+00	4.43E+00	2.67E+01	5.55E+01	2.84E+02	5.67E+02
RA-226+5 DAUGHTERS	0.	0.	2.45E+02	1.46E+04	7.33E+04	1.37E+06	3.60E+06	1.89E+07	2.94E+07	2.65E+07	1.48E+07
PB-210+2 DAUGHTERS	0.	0.	3.76E+01	4.64E+03	2.96E+04	4.65E+05	1.22E+06	6.44E+06	1.00E+07	9.02E+06	5.03E+06
TOTAL	0.	0.	1.32E+09	6.34E+08	3.55E+08	1.10E+08	8.33E+07	4.14E+07	4.44E+07	3.74E+07	2.13E+07
URANIUM ORE INDEX	0.	0.	1.92E+01	7.28E+00	4.08E+00	1.26E+00	9.58E-01	4.76E-01	5.10E-01	4.30E-01	2.45E-01

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.4.5a. Hazard Index--Once-Through Cycle--Growth Case 5, m^3 water/MTHM$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	0.	9.56E+03	1.12E-06	0.	0.	0.	0.	0.	0.	0.
C-14	0.	0.	1.05E+03	9.97E+02	9.39E+02	5.79E+02	3.16E+02	2.51E+00	5.96E-03	0.	0.
MN-54	0.	0.	2.22E-06	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	0.	3.19E+02	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	0.	3.83E+05	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	0.	1.52E+04	1.51E+04	1.50E+04	1.45E+04	1.39E+04	9.84E+03	6.38E+03	2.00E+02	2.63E+00
NI-63	0.	0.	1.09E+07	5.13E+05	1.19E+04	9.89E-10	0.	0.	0.	0.	0.
SE-79	0.	0.	1.15E+05	1.14E+05	1.14E+05	1.09E+05	1.03E+05	6.74E+04	3.96E+04	5.57E+02	2.70E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	0.	1.70E-01	1.70E-01	1.70E-01	1.70E-01	1.70E-01	1.70E-01	1.70E-01	1.70E-01	1.70E-01
SR-90+Y-90	0.	0.	6.44E+10	2.90E+06	1.29E+01	0.	0.	0.	0.	0.	0.
ZR-93	0.	0.	2.04E+03	2.04E+03	2.04E+03	2.04E+03	2.04E+03	2.00E+03	1.95E+03	1.62E+03	1.29E+03
NB-93M	0.	0.	3.76E+03	4.09E+03	4.09E+03	4.08E+03	4.07E+03	4.00E+03	3.91E+03	3.25E+03	2.58E+03
TC-99	0.	0.	4.22E+04	4.22E+04	4.21E+04	4.15E+04	4.09E+04	3.58E+04	3.04E+04	8.12E+03	1.56E+03
RU-106+RH-106	0.	0.	1.87E+00	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	0.	3.23E+04	3.22E+04	3.22E+04	3.22E+04	3.22E+04	3.21E+04	3.19E+04	3.07E+04	2.92E+04
AG-110M	0.	0.	2.34E-07	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	0.	2.66E+06	5.03E-03	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	0.	3.68E+03	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	0.	4.68E+05	4.66E+05	4.65E+05	4.52E+05	4.37E+05	3.31E+05	2.34E+05	1.47E+04	4.60E+02
I-129	0.	0.	5.44E+05	5.44E+05	5.44E+05	5.43E+05	5.43E+05	5.42E+05	5.41E+05	5.33E+05	5.22E+05
CS-134	0.	0.	6.65E+06	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	0.	2.62E+03	2.62E+03	2.62E+03	2.62E+03	2.61E+03	2.59E+03	2.56E+03	2.33E+03	2.08E+03
CS-137+BA-137	0.	0.	1.41E+09	1.20E+05	1.16E+00	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	0.	6.90E-03	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	0.	1.85E+04	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	0.	1.89E+06	7.45E+04	1.39E+03	2.05E-11	0.	0.	0.	0.	0.
EU-152	0.	0.	1.06E+04	7.00E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	0.	3.50E+07	8.14E-01	3.23E-10	0.	0.	0.	0.	0.	0.
EU-155	0.	0.	2.40E+02	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	1.15E-09	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	6.59E+10	4.83E+06	1.23E+06	1.20E+06	1.18E+06	1.03E+06	8.92E+05	5.94E+05	5.59E+05
URANIUM ORE INDEX	0.	0.	7.58E+02	5.55E-02	1.42E-02	1.38E-02	1.36E-02	1.18E-02	1.03E-02	6.83E-03	6.43E-03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.4.5b. Hazard Index--Once-Through Cycle--Growth Case 5, m^3 water/MTHM$^{(A)}$

Actinides

	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)								
RADIONUCLIDES (B)	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	0.	4.26E+04	4.12E+04	3.95E+04	2.82E+04	1.86E+04	6.48E+02	9.78E+00	0.	0.
CM-244	0.	0.	2.81E+07	4.97E+00	2.40E-08	0.	0.	0.	0.	0.	0.
CM-243	0.	0.	2.60E+05	3.94E+01	7.79E-04	0.	0.	0.	0.	0.	0.
CM-242	0.	0.	3.41E+05	5.35E+04	5.47E+03	6.55E-05	0.	0.	0.	0.	0.
AM-243+NP-239	0.	0.	3.47E+06	3.35E+06	3.20E+06	2.23E+06	1.42E+06	3.77E+04	4.07E+02	0.	0.
AM-242M+AM-242	0.	0.	2.16E+06	3.39E+05	3.47E+04	4.14E-04	0.	0.	0.	0.	0.
AM-241	0.	0.	8.21E+08	4.82E+08	2.17E+08	3.88E+05	1.87E+04	6.49E+02	9.80E+00	0.	0.
PU-242	0.	0.	3.12E+05	3.12E+05	3.12E+05	3.10E+05	3.07E+05	2.85E+05	2.60E+05	1.25E+05	5.02E+04
PU-241	0.	0.	5.80E+07	8.25E+02	7.92E+02	5.66E+02	3.72E+02	1.30E+01	1.96E-01	0.	0.
PU-240	0.	0.	8.94E+07	8.58E+07	8.15E+07	5.41E+07	3.24E+07	5.36E+05	3.18E+03	0.	0.
PU-239	0.	0.	5.80E+07	5.74E+07	5.66E+07	5.08E+07	4.42E+07	1.43E+07	3.47E+06	4.02E+01	2.72E-05
PU-238	0.	0.	2.80E+08	1.22E+07	2.40E+05	6.32E-04	0.	0.	0.	0.	0.
PU-236	0.	0.	7.80E+00	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	0.	1.19E+05	2.27E+05	3.11E+05	3.74E+05	3.74E+05	3.69E+05	3.64E+05	3.19E+05	2.72E+05
U-238+TH-234+PA-234M	0.	0.	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.37E+04	2.38E+04	2.38E+04	2.38E+04
U-236	0.	0.	7.38E+03	7.54E+03	7.75E+03	9.03E+03	1.01E+04	1.16E+04	1.16E+04	1.14E+04	1.13E+04
U-235+TH-231	0.	0.	6.61E+02	6.64E+02	6.70E+02	7.10E+02	7.55E+02	9.54E+02	1.03E+03	1.05E+03	1.05E+03
U-234	0.	0.	3.95E+04	5.42E+04	5.42E+04	5.58E+04	5.51E+04	5.08E+04	4.52E+04	2.18E+04	1.33E+04
U-233	0.	0.	4.70E+00	3.16E+01	9.19E+01	6.84E+02	1.44E+03	6.87E+03	1.24E+04	2.88E+04	2.79E+04
U-232	0.	0.	3.92E+03	7.87E+01	6.38E-01	0.	0.	0.	0.	0.	0.
PA-231	0.	0.	4.96E+01	1.98E+02	4.10E+02	2.00E+03	3.95E+03	1.64E+04	2.47E+04	3.03E+04	3.03E+04
TH-230	0.	0.	2.58E+02	2.63E+03	6.45E+03	3.47E+04	6.87E+04	2.80E+05	4.33E+05	3.93E+05	2.20E+05
TH-229+7 DAUGHTERS	0.	0.	4.73E-01	1.78E+01	1.05E+02	3.86E+03	1.49E+04	1.86E+05	3.39E+05	8.68E+05	8.43E+05
TH-228+6 DAUGHTERS	0.	0.	8.41E+03	1.69E+02	1.38E+00	4.16E-02	9.10E-02	5.40E-01	1.14E+00	5.85E+00	1.17E+01
AC-227+7 DAUGHTERS	0.	0.	5.73E+01	3.41E+02	7.34E+02	3.57E+03	7.06E+03	2.93E+04	4.41E+04	5.42E+04	5.41E+04
TH-232+2 DAUGHTERS	0.	0.	1.28E-02	1.51E-01	3.53E-01	2.03E+00	4.44E+00	2.68E+01	5.58E+01	2.85E+02	5.69E+02
RA-226+5 DAUGHTERS	0.	0.	2.16E+02	1.42E+04	7.45E+04	1.36E+06	3.59E+06	1.89E+07	2.94E+07	2.65E+07	1.48E+07
PB-210+2 DAUGHTERS	0.	0.	3.22E+01	4.49E+03	2.34E+04	4.64E+05	1.22E+06	6.43E+06	1.00E+07	9.02E+06	5.04E+06
TOTAL	0.	0.	1.34E+09	6.42E+08	3.59E+08	1.10E+08	8.38E+07	4.15E+07	4.44E+07	3.74E+07	2.14E+07
URANIUM ORE INDEX	0.	0.	1.54E+01	7.37E+00	4.13E+00	1.27E+00	9.63E-01	4.77E-01	5.10E-01	4.30E-01	2.46E-01

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.4.6a. Hazard Index--Reprocessing Cycle--Growth Case 3--1990 Reprocessing Startup, m^3 water/MTHM$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
	2000	2050	2070	500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	0.	8.46E+02	1.04E-07	0.	0.	0.	0.	0.	0.	0.
C-14	0.	0.	9.49E+02	9.42E+02	8.86E+02	5.46E+02	2.99E+02	2.37E+00	5.62E-03	0.	0.
MN-54	0.	0.	2.96E-07	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	0.	5.32E+01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	0.	1.17E+05	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	0.	1.31E+04	1.31E+04	1.30E+04	1.26E+04	1.21E+04	8.52E+03	5.53E+03	1.73E+02	2.28E+00
NI-63	0.	0.	8.73E+06	4.10E+05	9.51E+03	7.92E-10	0.	0.	0.	0.	0.
SE-79	0.	0.	1.09E+05	1.09E+05	1.08E+05	1.04E+05	9.83E+04	6.42E+04	3.77E+04	5.31E+02	2.57E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	0.	1.51E-01	1.51E-01	1.51E-01	1.51E-01	1.51E-01	1.51E-01	1.51E-01	1.51E-01	1.51E-01
SR-90+Y-90	0.	0.	4.44E+10	2.00E+06	8.86E+00	0.	0.	0.	0.	0.	0.
ZR-93	0.	0.	2.03E+03	2.03E+03	2.03E+03	2.03E+03	2.02E+03	1.98E+03	1.94E+03	1.61E+03	1.28E+03
NB-93M	0.	0.	3.87E+03	4.06E+03	4.06E+03	4.06E+03	4.05E+03	3.97E+03	3.88E+03	3.23E+03	2.56E+03
TC-99	0.	0.	4.19E+04	4.18E+04	4.18E+04	4.12E+04	4.06E+04	3.59E+04	3.01E+04	8.06E+03	1.55E+03
RU-106+RH-106	0.	0.	2.56E-01	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	0.	4.01E+04	4.01E+04	4.01E+04	4.01E+04	4.00E+04	3.99E+04	3.97E+04	3.81E+04	3.63E+04
AG-110M	0.	0.	2.89E-08	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	0.	3.27E+06	6.17E-03	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	0.	8.70E+02	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	0.	5.45E+05	5.43E+05	5.41E+05	5.26E+05	5.08E+05	3.85E+05	2.73E+05	1.71E+04	5.35E+02
I-129	0.	0.	5.40E+05	5.80E+05	5.80E+05	5.79E+05	5.79E+05	5.78E+05	5.77E+05	5.68E+05	5.56E+05
CS-134	0.	0.	1.03E+06	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	0.	3.32E+03	3.32E+03	3.32E+03	3.32E+03	3.31E+03	3.28E+03	3.25E+03	2.96E+03	2.64E+03
CS-137+BA-137	0.	0.	1.13E+09	9.55E+04	9.25E-01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	0.	8.96E-04	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	0.	4.11E+03	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	0.	1.47E+06	7.36E+04	1.37E+03	2.03E-11	0.	0.	0.	0.	0.
EU-152	0.	0.	1.06E+04	7.05E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	0.	2.74E+07	6.36E-01	2.85E-10	0.	0.	0.	0.	0.	0.
EU-155	0.	0.	4.15E+01	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	1.31E-10	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	4.55E+10	3.91E+06	1.34E+06	1.31E+06	1.29E+06	1.12E+06	9.72E+05	6.40E+05	6.01E+05
URANIUM ORE INDEX	0.	0.	5.23E+02	4.50E-02	1.55E-02	1.51E-02	1.49E-02	1.29E-02	1.12E-02	7.35E-03	6.91E-03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.4.6b. Hazard Index--Reprocessing Cycle--Growth Case 3--1990 Reprocessing Startup, m^3 water/MTHM(A)

Actinides

RADIONUCLIDES (B)	YEAR 2000	 2050	 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	 1000	 5000	 10000	 50000	 100000	 500000	 1000000
CM-245	0.	0.	7.51E+05	7.26E+05	6.06E+05	4.98E+05	3.27E+05	1.14E+04	1.72E+02	0.	0.
CM-244	0.	0.	2.15E+08	3.79E+01	1.83E-07	0.	0.	0.	0.	0.	0.
CM-243	0.	0.	5.49E+05	8.31E+01	1.44E-03	0.	0.	0.	0.	0.	0.
CM-242	0.	0.	2.36E+06	3.71E+05	3.79E+04	4.54E-04	0.	0.	0.	0.	0.
AM-243+NP-239	0.	0.	1.62E+07	1.56E+07	1.49E+07	1.04E+07	6.61E+06	1.76E+05	1.90E+03	0.	0.
AM-242M+AM-242	0.	0.	1.50E+07	2.35E+06	2.40E+05	2.87E-03	0.	0.	0.	0.	0.
AM-241	0.	0.	4.34E+08	2.36E+08	1.06E+08	6.96E+05	3.28E+05	1.14E+04	1.73E+02	0.	0.
PU-242	0.	0.	1.09E+05	1.09E+05	1.09E+05	1.08E+05	1.07E+05	9.89E+04	9.11E+04	4.39E+04	1.76E+04
PU-241	0.	0.	9.68E+06	1.45E+04	1.39E+04	9.97E+03	6.85E+03	2.59E+02	3.45E+00	0.	0.
PU-240	0.	0.	1.03E+07	1.45E+07	1.38E+07	9.16E+06	5.68E+06	9.07E+04	5.38E+02	0.	0.
PU-239	0.	0.	3.01E+06	3.10E+06	3.23E+06	3.91E+06	4.24E+06	2.05E+06	3.09E+05	5.91E+00	4.00E-06
PU-238	0.	0.	6.20E+07	5.88E+06	4.14E+05	4.38E-03	0.	0.	0.	0.	0.
PU-236	0.	0.	6.94E+02	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	0.	2.09E+05	2.55E+05	2.65E+05	3.26E+05	3.27E+05	3.24E+05	3.19E+05	2.80E+05	2.38E+05
U-238+TH-234+ PA-234M	0.	0.	1.96E+02	1.96E+02	1.96E+02	1.96E+02	1.96E+02	1.96E+02	1.96E+02	1.98E+02	1.99E+02
U-236	0.	0.	9.13E+01	1.17E+02	1.53E+02	3.70E+02	5.45E+02	7.69E+02	8.02E+02	7.93E+02	7.82E+02
U-235+TH-231	0.	0.	5.35E+00	5.56E+00	5.87E+00	8.56E+00	1.24E+01	3.72E+01	4.76E+01	5.10E+01	5.09E+01
U-234	0.	0.	2.34E+03	7.19E+03	8.15E+03	8.12E+03	8.01E+03	7.17E+03	6.24E+03	2.09E+03	5.80E+02
U-233	0.	0.	4.46E+00	3.99E+01	9.07E+01	6.21E+02	1.29E+03	6.04E+03	1.09E+04	2.53E+04	2.45E+04
U-232	0.	0.	5.46E+05	1.10E+04	8.89E+01	0.	0.	0.	0.	0.	0.
PA-231	0.	0.	3.68E+01	3.78E+01	3.92E+01	5.29E+01	7.84E+01	4.09E+02	1.01E+03	1.47E+03	1.47E+03
TH-230	0.	0.	4.39E+01	3.13E+02	8.63E+02	4.95E+03	9.04E+03	4.02E+04	6.13E+04	4.34E+04	1.22E+04
TH-229+7 DAUGHTERS	0.	0.	3.58E-01	2.28E+01	1.22E+02	3.62E+03	1.34E+04	1.46E+05	2.98E+05	7.62E+05	7.39E+05
TH-228+6 DAUGHTERS	0.	0.	1.17E+06	2.35E+04	1.01E+02	9.47E-04	2.67E-03	2.37E-02	5.21E-02	2.78E-01	5.56E-01
AC-227+7 DAUGHTERS	0.	0.	5.40E+01	6.72E+01	7.01E+01	9.46E+01	1.40E+02	8.92E+02	1.81E+03	2.63E+03	2.63E+03
TH-232+2 DAUGHTERS	0.	0.	2.04E-04	2.06E-03	5.20E-03	4.62E-02	1.30E-01	1.16E+00	2.54E+00	1.35E+01	2.71E+01
RA-226+5 DAUGHTERS	0.	0.	7.03E+01	1.69E+03	9.57E+03	1.94E+05	5.18E+05	2.72E+06	4.16E+06	2.92E+06	8.23E+05
PB-210+2 DAUGHTERS	0.	0.	1.38E+01	5.36E+02	3.26E+03	6.61E+04	1.76E+05	9.29E+05	1.42E+06	9.95E+05	2.80E+05
TOTAL	0.	0.	7.93E+08	2.79E+08	1.00E+08	2.54E+07	1.82E+07	6.40E+06	6.88E+06	5.08E+06	2.14E+06
URANIUM ORE INDEX	0.	0.	9.14E+00	3.21E+00	1.41E+00	2.92E-01	2.09E-01	7.89E-02	7.91E-02	5.84E-02	2.46E-02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.4.7a. Hazard Index--Reprocessing Cycle--Growth Case 3--2010 Reprocessing Startup, m^3 water/MTHM$^{(A)}$

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	YEAR 2050	YEAR 2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	0.	8.59E+02	1.01E-07	0.	0.	0.	0.	0.	0.	0.
C-14	0.	0.	1.10E+03	1.05E+03	9.80E+02	6.11E+02	3.34E+02	2.65E+00	6.28E-03	0.	0.
MN-54	0.	0.	2.01E-07	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	0.	5.55E+01	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	0.	1.22E+05	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	0.	1.46E+04	1.46E+04	1.45E+04	1.40E+04	1.34E+04	9.80E+03	6.16E+03	1.93E+02	2.94E+00
NI-63	0.	0.	9.75E+06	4.59E+05	1.06E+04	8.85E-10	0.	0.	0.	0.	0.
SE-79	0.	0.	1.13E+05	1.12E+05	1.11E+05	1.07E+05	1.01E+05	6.61E+04	3.88E+04	5.47E+02	2.65E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	0.	1.64E-01	1.64E-01	1.64E-01	1.64E-01	1.64E-01	1.64E-01	1.64E-01	1.64E-01	1.64E-01
SR-90+Y-90	0.	0.	4.42E+10	2.17E+06	9.43E+00	0.	0.	0.	0.	0.	0.
ZR-93	0.	0.	2.12E+03	2.12E+03	2.12E+03	2.11E+03	2.11E+03	2.07E+03	2.02E+03	1.68E+03	1.33E+03
NB-93M	0.	0.	4.24E+03	4.23E+03	4.24E+03	4.23E+03	4.22E+03	4.14E+03	4.05E+03	3.36E+03	2.67E+03
TC-99	0.	0.	4.19E+04	4.18E+04	4.18E+04	4.12E+04	4.06E+04	3.55E+04	3.01E+04	8.06E+03	1.55E+03
RU-106+RH-106	0.	0.	2.55E-01	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	0.	3.43E+04	3.42E+04	3.42E+04	3.42E+04	3.42E+04	3.41E+04	3.39E+04	3.26E+04	3.10E+04
AG-110M	0.	0.	2.79E-08	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	0.	2.72E+06	5.14E-03	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	0.	8.66E+02	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	0.	4.87E+05	4.85E+05	4.84E+05	4.70E+05	4.54E+05	3.44E+05	2.44E+05	1.53E+04	4.78E+02
I-129	0.	0.	5.53E+05	5.53E+05	5.53E+05	5.53E+05	5.53E+05	5.52E+05	5.51E+05	5.42E+05	5.31E+05
CS-134	0.	0.	1.05E+06	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	0.	2.80E+03	2.80E+03	2.80E+03	2.80E+03	2.80E+03	2.77E+03	2.74E+03	2.50E+03	2.23E+03
CS-137+BA-137	0.	0.	1.12E+09	9.51E+04	9.21E-01	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	0.	8.70E-04	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	0.	4.09E+03	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	0.	1.77E+06	6.99E+04	1.31E+03	1.32E-11	0.	0.	0.	0.	0.
EU-152	0.	0.	8.04E+03	5.33E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	0.	2.08E+07	5.78E-01	2.29E-10	0.	0.	0.	0.	0.	0.
EU-155	0.	0.	4.18E+01	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	1.26E-10	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	4.53E+10	4.04E+06	1.26E+06	1.23E+06	1.21E+06	1.05E+06	9.13E+05	6.07E+05	5.71E+05
URANIUM ORE INDEX	0.	0.	5.67E+02	4.65E-02	1.45E-02	1.41E-02	1.39E-02	1.21E-02	1.05E-02	6.97E-03	6.56E-03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.4.7b. Hazard Index--Reprocessing Cycle--Growth Case 3--2010 Reprocessing Startup, m^3 water/MTHM(A)

Actinides

RADIONUCLIDES (A)	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	0.	1.90E+05	1.91E+05	1.83E+05	1.31E+05	8.62E+04	3.01E+03	4.54E+01	0.	0.
CM-244	0.	0.	7.68E+07	1.36E+01	6.54E-08	0.	0.	0.	0.	0.	0.
CM-243	0.	0.	3.15E+05	4.77E+01	9.03E-04	0.	0.	0.	0.	0.	0.
CM-242	0.	0.	7.75E+05	1.21E+05	1.24E+04	1.49E-04	0.	0.	0.	0.	0.
AM-243+NP-239	0.	0.	6.08E+06	5.86E+06	5.60E+06	3.90E+06	2.08E+06	6.60E+04	7.11E+02	0.	0.
AM-242M+AM-242	0.	0.	4.91E+06	7.70E+05	7.88E+04	9.41E-04	0.	0.	0.	0.	0.
AM-241	0.	0.	6.63E+08	3.47E+08	1.56E+08	3.95E+05	8.65E+04	3.01E+03	4.55E+01	0.	0.
PU-242	0.	0.	4.53E+03	4.53E+03	4.59E+03	4.56E+03	4.52E+03	4.20E+03	3.84E+03	1.85E+03	7.40E+02
PU-241	0.	0.	5.46E+05	3.83E+03	3.47E+03	2.63E+03	1.73E+03	6.03E+01	9.10E-01	0.	0.
PU-240	0.	0.	1.81E+06	2.01E+06	1.91E+06	1.27E+06	7.59E+05	1.26E+04	7.45E+01	0.	0.
PU-239	0.	0.	6.22E+05	6.62E+05	7.19E+05	1.02E+06	1.21E+06	6.04E+05	1.61E+05	1.97E+00	1.27E-06
PU-238	0.	0.	5.05E+06	9.82E+05	1.16E+05	1.04E-03	0.	0.	0.	0.	0.
PU-236	0.	0.	3.89E-02	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	0.	1.42E+05	2.21E+05	2.81E+05	3.26E+05	3.26E+05	3.23E+05	3.17E+05	2.79E+05	2.37E+05
U-238+TH-234+ PA-234M	0.	0.	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02	1.92E+02
U-236	0.	0.	6.69E+01	7.04E+01	7.55E+01	1.05E+02	1.30E+02	1.65E+02	1.65E+02	1.63E+02	1.61E+02
U-235+TH-231	0.	0.	5.38E+00	5.43E+00	5.50E+00	6.15E+00	7.23E+00	1.48E+01	1.81E+01	1.92E+01	1.91E+01
U-234	0.	0.	4.04E+02	8.38E+02	1.00E+03	1.11E+03	9.98E+02	8.01E+02	7.95E+02	3.16E+02	1.42E+02
U-233	0.	0.	2.23E+00	3.00E+01	8.57E+01	6.03E+02	1.27E+03	6.07E+03	1.08E+04	2.51E+04	2.44E+04
U-232	0.	0.	4.11E+01	8.25E-01	6.49E-03	0.	0.	0.	0.	0.	0.
PA-231	0.	0.	3.82E+01	3.91E+01	4.05E+01	5.18E+01	6.53E+01	2.26E+02	4.02E+02	5.54E+02	5.53E+02
TH-230	0.	0.	1.11E+02	1.42E+02	2.08E+02	7.16E+02	1.33E+03	5.10E+03	7.76E+03	6.12E+03	2.54E+03
TH-229+7 DAUGHTERS	0.	0.	1.28E-01	1.56E+01	9.84E+01	3.43E+03	1.31E+04	1.45E+05	2.96E+05	7.58E+05	7.36E+05
TH-228+6 DAUGHTERS	0.	0.	8.82E+01	1.77E+00	1.04E-02	3.88E-04	8.70E-04	5.48E-03	1.15E-02	5.91E-02	1.18E-01
AC-227+7 DAUGHTERS	0.	0.	4.92E+01	6.95E+01	7.24E+01	9.08E+01	1.17E+02	4.04E+02	7.18E+02	9.90E+02	9.89E+02
TH-232+2 DAUGHTERS	0.	0.	1.92E-04	1.34E-03	3.20E-03	1.89E-02	4.24E-02	2.67E-01	8.60E-01	2.88E+00	5.75E+00
RA-226+5 DAUGHTERS	0.	0.	1.74E+02	1.37E+03	3.80E+03	2.99E+04	7.08E+04	3.44E+05	5.27E+05	4.12E+05	1.71E+05
PB-210+2 DAUGHTERS	0.	0.	3.23E+01	4.43E+02	1.19E+03	1.02E+04	2.41E+04	1.17E+05	1.79E+05	1.40E+05	5.82E+04
TOTAL	0.	0.	7.40E+08	3.58E+08	1.65E+08	7.09E+06	5.06E+06	1.68E+06	1.51E+06	1.62E+06	1.23E+06
URANIUM ORE INDEX	0.	0.	8.74E+00	4.11E+00	1.89E+00	8.15E-02	5.82E-02	1.93E-02	1.73E-02	1.87E-02	1.42E-02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.4.8a. Hazard Index--Reprocessing Cycle--Growth Case 4--2000 Reprocessing Startup, m^3 water/MTHM(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	2050	2070	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	0.	1.29E+05	1.51E-07	0.	0.	0.	0.	0.	0.	0.
C-14	0.	0.	1.03E+03	9.80E+02	9.23E+02	5.69E+02	3.11E+02	2.47E+00	5.86E-03	0.	0.
MN-54	0.	0.	1.81E-06	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	0.	1.89E+02	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	0.	2.73E+05	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	0.	1.37E+04	1.36E+04	1.36E+04	1.31E+04	1.26E+04	8.64E+03	5.76E+03	1.80E+02	2.38E+00
NI-63	0.	0.	9.50E+06	4.47E+05	1.04E+04	8.62E-10	0.	0.	0.	0.	0.
SE-79	0.	0.	1.10E+05	1.09E+05	1.09E+05	1.04E+05	9.88E+04	6.45E+04	3.78E+04	5.33E+02	2.59E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	0.	1.55E-01	1.55E-01	1.55E-01	1.55E-01	1.55E-01	1.55E-01	1.55E-01	1.55E-01	1.55E-01
SR-90+Y-90	0.	0.	5.28E+10	2.38E+06	1.05E+01	0.	0.	0.	0.	0.	0.
ZR-93	0.	0.	2.05E+03	2.05E+03	2.05E+03	2.04E+03	2.04E+03	2.00E+03	1.96E+03	1.63E+03	1.29E+03
NB-93M	0.	0.	3.83E+03	4.10E+03	4.10E+03	4.09E+03	4.08E+03	4.01E+03	3.92E+03	3.26E+03	2.59E+03
TC-99	0.	0.	4.16E+04	4.16E+04	4.15E+04	4.10E+04	4.03E+04	3.53E+04	2.99E+04	8.00E+03	1.54E+03
RU-106+RH-106	0.	0.	1.72E+00	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	0.	3.76E+04	3.76E+04	3.76E+04	3.76E+04	3.76E+04	3.74E+04	3.73E+04	3.58E+04	3.41E+04
AG-110M	0.	0.	2.77E-07	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	0.	4.07E+06	8.31E-03	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	0.	3.30E+03	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	0.	5.19E+05	5.18E+05	5.16E+05	5.02E+05	4.85E+05	3.68E+05	2.60E+05	1.63E+04	5.11E+02
I-129	0.	0.	5.66E+05	5.66E+05	5.66E+05	5.66E+05	5.66E+05	5.65E+05	5.64E+05	5.54E+05	5.43E+05
CS-134	0.	0.	4.85E+06	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	0.	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.05E+03	3.01E+03	2.75E+03	2.45E+03
CS-137+BA-137	0.	0.	1.24E+09	1.09E+05	1.06E+00	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	0.	5.22E-03	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	0.	1.35E+04	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	0.	1.91E+06	7.53E+04	1.01E+03	2.07E-11	0.	0.	0.	0.	0.
EU-152	0.	0.	1.43E+04	9.51E-07	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	0.	3.57E+07	8.30E-01	3.30E-10	0.	0.	0.	0.	0.	0.
EU-155	0.	0.	2.12E+02	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	7.38E-10	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	5.41E+10	4.30E+06	1.31E+06	1.27E+06	1.25E+06	1.09E+06	9.43E+05	6.23E+05	5.86E+05
URANIUM ORE INDEX	0.	0.	6.22E+02	4.95E-02	1.50E-02	1.46E-02	1.44E-02	1.25E-02	1.08E-02	7.16E-03	6.73E-03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.4.8b. Hazard Index--Reprocessing Cycle--Growth Case 4--2000 Reprocessing Startup, m^3 water/MTHM$^{(A)}$

Actinides

	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
RADIONUCLIDES (B)	2000	2050	2170	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	0.	4.77E+05	4.61E+05	4.42E+05	3.16E+05	2.06E+05	7.25E+03	1.09E+02	0.	0.
CM-244	0.	0.	1.94E+06	3.43E+01	1.66E-07	0.	0.	0.	0.	0.	0.
CM-243	0.	0.	5.14E+05	7.79E+01	1.54E-05	0.	0.	0.	0.	0.	0.
CM-242	0.	0.	1.60E+06	2.50E+05	2.86E+04	3.07E-04	0.	0.	0.	0.	0.
AM-243+NP-239	0.	0.	1.03E+07	1.04E+07	9.05E+06	6.93E+06	4.40E+06	1.17E+05	1.26E+03	0.	0.
AM-242M+AM-242	0.	0.	1.01E+07	1.59E+06	1.62E+05	1.94E-13	0.	0.	0.	0.	0.
AM-241	0.	0.	4.70E+08	2.46E+08	1.11E+08	5.13E+05	2.08E+05	7.26E+03	1.10E+02	0.	0.
PU-242	0.	0.	7.19E+03	7.60E+03	7.72E+03	7.68E+03	7.61E+03	7.07E+03	5.45E+03	3.10E+03	1.24E+03
PU-241	0.	0.	1.10E+06	9.22E+03	6.85E+03	6.33E+03	4.16E+03	1.45E+02	2.19E+00	0.	0.
PU-240	0.	0.	3.85E+06	4.88E+06	4.17E+06	2.77E+06	1.46E+06	2.74E+04	1.63E+02	0.	0.
PU-239	0.	0.	7.67E+05	8.42E+05	9.07E+05	1.53E+06	1.89E+06	1.06E+06	2.67E+05	3.10E+00	2.10E-06
PU-238	0.	0.	1.21E+07	2.11E+06	2.01E+05	2.96E-03	0.	0.	0.	0.	0.
PU-236	0.	0.	2.22E-01	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	0.	1.90E+05	2.47E+05	2.49E+05	3.21E+05	3.22E+05	3.19E+05	3.14E+05	2.76E+05	2.34E+05
U-238+TH-234+PA-234M	0.	0.	1.95E+02	1.95E+02	1.95E+02	1.95E+02	1.95E+02	1.95E+02	1.95E+02	1.95E+02	1.95E+02
U-236	0.	0.	8.60E+01	9.37E+01	1.05E+02	.77E+02	2.23E+02	3.07E+02	3.01E+02	2.97E+02	2.95E+02
U-235+TH-231	0.	0.	5.34E+00	5.39E+00	5.48E+00	6.42E+00	8.06E+00	2.04E+01	2.58E+01	2.76E+01	2.76E+01
U-234	0.	0.	5.74E+02	1.57E+03	1.82E+03	1.93E+03	1.91E+03	1.72E+03	1.50E+03	5.47E+02	2.00E+02
U-233	0.	0.	3.31E+00	3.68E+01	9.56E+01	6.09E+02	1.26E+03	5.04E+03	1.07E+04	2.40E+04	2.41E+04
U-232	0.	0.	7.23E+01	1.45E+00	1.18E-02	0.	0.	0.	0.	0.	0.
PA-231	0.	0.	3.82E+01	3.91E+01	4.04E+01	5.10E+01	6.71E+01	2.93E+02	5.58E+02	7.97E+02	7.97E+02
TH-230	0.	0.	6.17E+01	1.18E+02	2.45E+02	1.22E+03	2.40E+03	9.63E+03	1.47E+04	1.10E+04	3.81E+03
TH-229+7 DAUGHTERS	0.	0.	2.11E-01	2.01E+01	1.19E+02	3.53E+03	1.32E+04	1.43E+05	2.93E+05	7.49E+05	7.27E+05
TH-228+6 DAUGHTERS	0.	0.	1.55E+02	3.11E+00	2.53E-02	5.04E-04	1.13E-03	7.23E-03	1.51E-02	7.81E-02	1.56E-01
AC-227+7 DAUGHTERS	0.	0.	5.16E+01	6.95E+01	7.23E+01	9.12E+01	1.20E+02	5.17E+02	9.97E+02	1.43E+03	1.42E+03
TH-232+2 DAUGHTERS	0.	0.	1.64E-04	1.75E-03	4.14E-03	2.05E-02	5.53E-02	3.52E-01	7.49E-01	3.81E+00	7.60E+00
RA-226+5 DAUGHTERS	0.	0.	1.00E+02	9.40E+02	3.26E+03	4.84E+04	1.26E+05	6.57E+05	9.97E+05	7.39E+05	2.56E+05
PB-210+2 DAUGHTERS	0.	0.	1.91E+01	3.04E+02	1.11E+03	1.65E+04	4.26E+04	2.21E+05	3.40E+05	2.52E+05	8.73E+04
TOTAL	0.	0.	7.05E+08	2.67E+08	1.27E+08	1.25E+07	8.89E+06	2.58E+06	2.25E+06	2.06E+06	1.34E+06
URANIUM ORE INDEX	0.	0.	8.11E+00	3.97E+00	1.46E+00	1.43E-01	1.02E-01	2.07E-02	2.54E-02	2.36E-02	1.54E-02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
   TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
   AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
   TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
   RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
   PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

TABLE A.4.9a. Hazard Index--Reprocessing Cycle--Growth Case 5--2000 Reprocessing Startup, m^3 water/MTHM(A)

Fission and Activation Products

MAJOR RADIONUCLIDES	YEAR 2000	2050	2100	GEOLOGIC TIME (YEARS BEYOND 1975) 500	1000	5000	10000	50000	100000	500000	1000000
H-3	0.	0.	1.53E+03	1.40E-07	0.	0.	0.	0.	0.	0.	0.
C-14	0.	0.	1.03E+03	9.81E+02	9.23E+02	5.69E+02	3.11E+02	2.47E+00	5.66E-03	0.	0.
MN-54	0.	0.	2.52E-06	0.	0.	0.	0.	0.	0.	0.	0.
FE-55	0.	0.	2.56E+02	0.	0.	0.	0.	0.	0.	0.	0.
CO-60	0.	0.	3.58E+05	0.	0.	0.	0.	0.	0.	0.	0.
NI-59	0.	0.	1.37E+04	1.36E+04	1.36E+04	1.31E+04	1.25E+04	8.67E+03	5.75E+03	1.80E+02	2.37E+00
NI-63	0.	0.	9.76E+06	4.59E+05	1.06E+04	4.85E-10	0.	0.	0.	0.	0.
SE-79	0.	0.	1.10E+05	1.09E+05	1.09E+05	1.04E+05	9.69E+04	6.64E+04	3.79E+04	5.34E+02	2.59E+00
KR-85	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RB-87	0.	0.	1.54E-01	1.54E-01	1.54E-01	1.54E-01	1.54E-01	1.54E-01	1.54E-01	1.54E-01	1.54E-01
SR-90+Y-90	0.	0.	5.75E+10	2.58E+06	1.14E+01	0.	0.	0.	0.	0.	0.
ZR-93	0.	0.	2.05E+03	2.05E+03	2.05E+03	2.05E+03	2.04E+03	2.00E+03	1.96E+03	1.63E+03	1.29E+03
NB-93M	0.	0.	3.74E+03	4.10E+03	4.10E+03	4.09E+03	4.08E+03	4.01E+03	3.92E+03	3.26E+03	2.59E+03
TC-99	0.	0.	4.16E+04	4.18E+04	4.17E+04	4.12E+04	4.05E+04	3.55E+04	3.01E+04	9.04E+03	1.55E+03
RU-106+RH-106	0.	0.	2.35E+00	0.	0.	0.	0.	0.	0.	0.	0.
PD-107	0.	0.	3.86E+04	3.86E+04	3.86E+04	3.85E+04	3.85E+04	3.84E+04	3.82E+04	3.67E+04	3.49E+04
AG-110M	0.	0.	4.01E-07	0.	0.	0.	0.	0.	0.	0.	0.
CD-113M	0.	0.	5.24E+06	9.88E-03	0.	0.	0.	0.	0.	0.	0.
SB-125+TE-125M	0.	0.	4.58E+05	0.	0.	0.	0.	0.	0.	0.	0.
SN-126+SB-126	0.	0.	5.27E+05	5.26E+05	5.26E+05	5.11E+05	4.94E+05	3.75E+05	2.65E+05	1.66E+04	5.20E+02
I-129	0.	0.	5.72E+05	5.72E+05	5.72E+05	5.72E+05	5.72E+05	5.71E+05	5.70E+05	5.60E+05	5.49E+05
CS-134	0.	0.	6.75E+06	0.	0.	0.	0.	0.	0.	0.	0.
CS-135	0.	0.	3.14E+03	3.14E+03	3.14E+03	3.14E+03	3.13E+03	3.10E+03	3.07E+03	2.80E+03	2.49E+03
CS-137+BA-137	0.	0.	1.41E+09	1.19E+05	1.16E+00	0.	0.	0.	0.	0.	0.
CE-144+PR-144	0.	0.	7.16E-03	0.	0.	0.	0.	0.	0.	0.	0.
PM-147	0.	0.	1.81E+04	0.	0.	0.	0.	0.	0.	0.	0.
SM-151	0.	0.	1.38E+06	7.82E+04	1.64E+03	2.15E-11	0.	0.	0.	0.	0.
EU-152	0.	0.	1.72E+04	1.14E-06	0.	0.	0.	0.	0.	0.	0.
EU-154	0.	0.	4.10E+07	9.67E-01	3.84E-10	0.	0.	0.	0.	0.	0.
EU-155	0.	0.	2.93E+02	0.	0.	0.	0.	0.	0.	0.	0.
OTHER	0.	0.	1.05E-09	0.	0.	0.	0.	0.	0.	0.	0.
TOTAL	0.	0.	5.87E+10	4.55E+06	1.32E+06	1.29E+06	1.27E+06	1.10E+06	9.55E+05	6.39E+05	5.92E+05
URANIUM ORE INDEX	0.	0.	6.75E+02	5.23E-02	1.52E-02	1.48E-02	1.45E-02	1.27E-02	1.10E-02	7.24E-03	6.81E-03

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

TABLE A.4.9b. Hazard Index--Reprocessing Cycle--Growth Case 5--2000 Reprocessing Startup, m^3 water/MTHM(A)

Actinides

	YEAR			GEOLOGIC TIME (YEARS BEYOND 1975)							
RADIONUCLIDES (A)	2000	2050	2075	500	1000	5000	10000	50000	100000	500000	1000000
CM-245	0.	0.	5.54E+05	5.40E+05	5.18E+05	3.71E+05	2.44E+05	8.51E+03	1.28E+02	0.	0.
CM-244	0.	0.	2.07E+08	4.36E+01	2.11E-07	0.	0.	0.	0.	0.	0.
CM-243	0.	0.	5.95E+05	9.01E+01	1.78E-03	0.	0.	0.	0.	0.	0.
CM-242	0.	0.	1.84E+06	2.95E+05	3.02E+04	3.61E-04	0.	0.	0.	0.	0.
AM-243+NP-239	0.	0.	1.24E+07	1.20E+07	1.14E+07	7.95E+06	5.05E+06	1.35E+05	1.05E+03	0.	0.
AM-242M+AM-242	0.	0.	1.19E+07	1.87E+06	1.01E+05	2.29E-03	0.	0.	0.	0.	0.
AM-241	0.	0.	4.74E+08	2.52E+08	1.13E+08	5.75E+05	2.44E+05	8.52E+03	1.29E+02	0.	0.
PU-242	0.	0.	1.10E+04	1.13E+04	1.14E+04	1.14E+04	1.13E+04	1.05E+04	9.55E+03	4.60E+03	1.84E+03
PU-241	0.	0.	1.8 E+06	1.06E+04	1.04E+04	7.42E+03	4.88E+03	1.79E+02	2.57E+00	0.	0.
PU-240	0.	0.	4.50E+06	5.19E+06	4.05E+06	3.24E+06	1.07E+06	3.25E+04	1.93E+02	0.	0.
PU-239	0.	0.	8.04E+05	9.36E+05	1.06E+06	1.72E+06	2.15E+06	1.21E+06	3.04E+05	3.53E+00	2.39E-06
PU-238	0.	0.	1.00E+07	2.07E+06	2.84E+05	3.49E-03	0.	0.	0.	0.	0.
PU-236	0.	0.	4.46E+02	0.	0.	0.	0.	0.	0.	0.	0.
NP-237+PA-233	0.	0.	1.74E+05	2.32E+05	2.75E+05	3.18E+05	3.09E+05	3.06E+05	3.02E+05	2.65E+05	2.25E+05
U-238+TH-234+ PA-234M	0.	0.	1.96E+02	1.96E+02	1.96E+02	1.96E+02	1.96E+02	1.96E+02	1.96E+02	1.96E+02	1.97E+02
U-236	0.	0.	7.02E+01	8.92E+01	1.01E+02	1.79E+02	2.42E+02	3.35E+02	3.34E+02	3.30E+02	3.25E+02
U-235+TH-231	0.	0.	5.14E+00	5.25E+00	5.35E+00	6.41E+00	8.27E+00	2.23E+01	2.85E+01	3.09E+01	3.05E+01
U-234	0.	0.	5.69E+02	1.72E+03	2.13E+03	2.16E+03	2.15E+03	1.81E+03	1.47E+03	6.03E+02	2.14E+02
U-233	0.	0.	2.02E+00	3.40E+01	8.08E+01	6.82E+02	1.21E+03	5.71E+03	1.03E+04	2.39E+04	2.31E+04
U-232	0.	0.	1.41E+04	3.22E+02	2.62E+00	0.	0.	0.	0.	0.	0.
PA-231	0.	0.	3.53E+01	3.62E+01	3.75E+01	4.81E+01	6.08E+01	3.09E+02	6.11E+02	8.92E+02	8.82E+02
TH-230	0.	0.	5.85E+01	1.16E+02	2.27E+02	1.35E+03	2.66E+03	1.07E+04	1.63E+04	1.21E+04	4.12E+03
TH-229+7 DAUGHTERS	0.	0.	1.79E-01	1.83E+01	1.07E+02	3.36E+03	1.26E+04	1.38E+05	2.62E+05	7.20E+05	6.09E+05
TH-228+6 DAUGHTERS	0.	0.	3.03E+04	6.91E+02	5.61E+00	4.84E-04	1.12E-03	7.07E-03	1.58E-02	8.18E-02	1.63E-01
AC-227+7 DAUGHTERS	0.	0.	4.67E+01	6.45E+01	6.70E+01	8.60E+01	1.16E+02	5.53E+02	1.09E+03	1.58E+03	1.58E+03
TH-232+2 DAUGHTERS	0.	0.	1.08E-04	1.61E-03	3.84E-03	2.36E-02	5.45E-02	3.64E-01	7.69E-01	3.99E+00	7.96E+00
RA-226+5 DAUGHTERS	0.	0.	8.68E+01	9.82E+02	3.29E+03	5.30E+04	1.39E+05	7.24E+05	1.11E+06	8.17E+05	2.77E+05
PB-210+2 DAUGHTERS	0.	0.	1.62E+01	2.84E+02	1.12E+03	1.80E+04	4.74E+04	2.45E+05	3.78E+05	2.78E+05	9.44E+04
TOTAL	0.	0.	7.75E+08	2.76E+08	1.32E+08	1.43E+07	1.02E+07	2.84E+06	2.42E+06	2.12E+06	1.33E+06
URANIUM ORE INDEX	0.	0.	8.91E+00	3.17E+00	1.52E+00	1.64E-01	1.17E-01	3.27E-02	2.78E-02	2.44E-02	1.53E-02

A. VALUES LESS THAN 1.0E-10 HAVE BEEN DESIGNATED AS ZERO.

B. TH-229, 7 DAUGHTERS ARE RA-225, AC-225, FR-221, AT-217, BI-213, PB-209 AND TL-209 IS 9% OF TH-229 AND PO-213 IS 91% OF TH-229.
TH-228, 6 DAUGHTERS ARE RA-224, RN-220, PO-216, PB-212, BI-212 AND TL-208 IS 36% OF TH-228 AND PO-212 IS 64% OF TH-228.
AC-227, 7 DAUGHTERS ARE TH-227, RA-223, RN-219, PO-215, PB-211, BI-211 AND TL-207.
TH-232, 2 DAUGHTERS ARE RA-228 AND AC-228.
RA-226, 5 DAUGHTERS ARE RN-222, PO-218, PB-214, BI-214 AND PO-214.
PB-210, 2 DAUGHTERS ARE BI-210 AND PO-210.

NOTE. IN ACCOUNTING FOR THE ACTIVITY IN THIS MANNER, BRANCHING DECAY IN THE CASE OF TL-208 (36%) - PO-212 (64%), AND TL-209 (9%) - PO-213 (91%) WERE COUNTED AS A SINGLE DAUGHTER IN EACH CASE. MINOR BRANCHING (1% OR LESS) WAS IGNORED.

A.5 SUPPLEMENTARY DOSE TABLES

The radiation dose tables (A.5.1a through A.5.2d) provide detail on regional population and world-wide doses. Each table, one for the once-through cycle and one for the reprocessing cycle, is composed of four tables. Each sub-table provides the whole-body, bone, lung and thyroid doses.

TABLE A.5.1a. Whole-Body Dose to the Population for the Once-Through Cycle, Man-Rem

Case	Growth Assumption	Repository Start-Up Date	Storage of Spent Fuel	BWR Fuel Shipments	PWR Fuel Shipments	Total
1	Present Inventory	None	2.18×10^{-1}	0	0	2.18×10^{-1}
1		1990	1.30×10^{-1}	1.64×10^{1}	1.97×10^{1}	3.62×10^{1}
1		2010	1.53×10^{-1}	1.64×10^{1}	1.97×10^{1}	3.62×10^{1}
1		2030	1.68×10^{-1}	1.64×10^{1}	1.97×10^{1}	3.63×10^{1}
2	Present Capacity to Retirement	None	1.63×10^{0}	3.32×10^{1}	5.57×10^{1}	9.05×10^{1}
2		1990	9.17×10^{-1}	8.21×10^{1}	1.18×10^{2}	2.01×10^{2}
2		2010	1.33×10^{0}	1.01×10^{2}	1.50×10^{2}	2.53×10^{2}
2		2030	1.54×10^{0}	1.05×10^{2}	1.57×10^{2}	2.64×10^{2}
3	250 GWe in 2000 and Decline to 0 in 2040	None	7.92×10^{0}	1.77×10^{2}	2.98×10^{2}	4.83×10^{2}
3		1990	4.41×10^{0}	3.65×10^{2}	5.66×10^{2}	9.35×10^{2}
3		2010	6.35×10^{0}	4.81×10^{2}	7.61×10^{2}	1.25×10^{3}
3		2030	7.61×10^{0}	5.10×10^{2}	8.10×10^{2}	1.33×10^{3}
4	250 GWe in 2000 and Steady to 2040	2000	6.73×10^{0}	5.49×10^{2}	8.64×10^{2}	1.42×10^{3}
4		2020	9.18×10^{0}	6.75×10^{2}	1.08×10^{3}	1.76×10^{3}
5	250 GWe in 2000 and 500 GWe in 2040	2000	8.68×10^{0}	7.20×10^{2}	1.14×10^{3}	1.87×10^{3}
5		2020	1.25×10^{1}	9.00×10^{2}	1.44×10^{3}	2.35×10^{3}

TABLE A.5.1b. Bone Dose to the Population for the Once-Through Cycle, Man-Rem

Case	Growth Assumption	Repository Start-Up Date	Storage of Spent Fuel	BWR Fuel Shipments	PWR Fuel Shipments	Total
1	Present Inventory	None	4.46×10^{-1}	0	0	4.46×10^{-1}
1		1990	2.55×10^{-1}	0	0	2.55×10^{-1}
1		2010	3.06×10^{-1}	0	0	3.06×10^{-1}
1		2030	3.41×10^{-1}	0	0	3.41×10^{-1}
2	Present Capacity to Retirement	None	2.30×10^{0}	0	0	2.30×10^{0}
2		1990	1.75×10^{0}	0	0	1.75×10^{0}
2		2010	2.63×10^{0}	0	0	2.63×10^{0}
2		2030	3.07×10^{0}	0	0	3.07×10^{0}
3	250 GWe in 2000 and Decline to 0 in 2040	None	1.58×10^{1}	0	0	1.58×10^{1}
3		1990	8.29×10^{0}	0	0	8.29×10^{0}
3		2010	1.24×10^{1}	0	0	1.24×10^{1}
3		2030	1.51×10^{1}	0	0	1.51×10^{1}
4	250 GWe in 2000 and Steady to 2040	2000	1.29×10^{1}	0	0	1.29×10^{1}
4		2020	1.81×10^{1}	0	0	1.81×10^{1}
5	250 GWe in 2000 and 500 GWe in 2040	2000	1.69×10^{1}	0	0	1.69×10^{1}
5		2020	2.46×10^{1}	0	0	2.46×10^{1}

TABLE A.5.1c. Lung Dose to the Population for the Once-Through Cycle, Man-Rem

Case	Growth Assumption	Repository Start-Up Date	Storage of Spent Fuel	BWR Fuel Shipments	PWR Fuel Shipments	Total
1	Present Inventory	None	9.85×10^{-2}	0	0	9.85×10^{-2}
1		1990	7.00×10^{-2}	0	0	7.00×10^{-2}
1		2010	7.22×10^{-2}	0	0	7.22×10^{-2}
1		2030	7.61×10^{-2}	0	0	7.61×10^{-2}
2	Present Capacity to Retirement	None	7.58×10^{-1}	0	0	7.58×10^{-1}
2		1990	5.14×10^{-1}	0	0	5.14×10^{-1}
2		2010	6.42×10^{-1}	0	0	6.42×10^{-1}
2		2030	7.18×10^{-1}	0	0	7.18×10^{-1}
3	250 GWe in 2000 and Decline to 0 in 2040	None	3.73×10^{0}	0	0	3.73×10^{0}
3		1990	2.58×10^{0}	0	0	2.58×10^{0}
3		2010	3.18×10^{0}	0	0	3.18×10^{0}
3		2030	3.59×10^{0}	0	0	3.59×10^{0}
4	250 GWe in 2000 and Steady to 2040	2000	3.70×10^{0}	0	0	3.70×10^{0}
4		2020	4.46×10^{0}	0	0	4.46×10^{0}
5	250 GWe in 2000 and 500 GWe in 2040	2000	4.92×10^{0}	0	0	4.92×10^{0}
5		2020	6.02×10^{0}	0	0	6.02×10^{0}

TABLE A.5.1d. Thyroid Dose to the Population for the Once-Through Cycle, Man-Rem

Case	Growth Assumption	Repository Start-Up Date	Storage of Spent Fuel	BWR Fuel Shipments	PWR Fuel Shipments	Total
1	Present Inventory	None	3.83×10^{-1}	0	0	3.83×10^{-1}
1		1990	3.93×10^{0}	0	0	3.93×10^{0}
1		2010	3.99×10^{0}	0	0	3.99×10^{0}
1		2030	4.04×10^{0}	0	0	4.04×10^{0}
2	Present Capacity to Retirement	None	2.38×10^{0}	0	0	2.38×10^{0}
2		1990	2.49×10^{1}	0	0	2.49×10^{1}
2		2010	2.55×10^{1}	0	0	2.55×10^{1}
2		2030	2.60×10^{1}	0	0	2.60×10^{1}
3	250 GWe in 2000 and Decline to 0 in 2040	None	1.06×10^{1}	0	0	1.06×10^{1}
3		1990	1.25×10^{2}	0	0	1.25×10^{2}
3		2010	1.27×10^{2}	0	0	1.27×10^{2}
3		2030	1.30×10^{2}	0	0	1.30×10^{2}
4	250 GWe in 2000 and Steady to 2040	2000	1.65×10^{2}	0	0	1.65×10^{2}
4		2020	1.69×10^{2}	0	0	1.69×10^{2}
5	250 GWe in 2000 and 500 GWe in 2040	2000	2.24×10^{2}	0	0	2.24×10^{2}
5		2020	2.29×10^{2}	0	0	2.29×10^{2}

TABLE A.5.2a. Whole-Body Dose to the Population for the Reprocessing Cycle, Man-Rem

Case	Growth Assumption	Reprocessing Start-up Date	Repository Start-Up Date	Storage of Spent Fuel	BWR Fuel Shipments	PWR Fuel Shipments	FRP Treatment System	MOX-FFP Treatment System	Reprocessing Waste Shipments	Total
3	250 GWe in 2000 and Decline to 0 in 2040	1990	1990	1.34×10^0	2.33×10^2	3.92×10^2	3.18×10^4	2.97×10^{-1}	5.97×10^2	3.31×10^4
3		1990	2010	1.34×10^0	2.33×10^2	3.92×10^2	3.18×10^4	2.97×10^{-1}	5.97×10^2	3.31×10^4
3		2010	2010	5.24×10^0	3.47×10^2	5.82×10^2	1.14×10^4	6.55×10^{-2}	5.78×10^2	1.29×10^4
3		1990	2030	1.34×10^0	2.33×10^2	3.92×10^2	3.18×10^4	2.97×10^{-1}	5.97×10^2	3.31×10^4
3		2010	2030	5.24×10^0	3.47×10^2	5.82×10^2	1.14×10^4	6.55×10^{-2}	5.78×10^2	1.29×10^4
4	250 GWe in 2000 and Steady State to 2040	2000	2000	3.84×10^0	3.78×10^2	6.35×10^2	3.07×10^4	2.91×10^{-1}	7.74×10^2	3.25×10^4
4		2000	2020	3.84×10^0	3.78×10^2	6.35×10^2	3.07×10^4	2.91×10^{-1}	7.74×10^2	3.25×10^4
5	250 GWe in 2000 and 500 GWe in 2040	2000	2000	4.73×10^0	4.94×10^2	8.30×10^2	4.34×10^4	5.03×10^{-1}	1.05×10^3	4.58×10^4
5		2000	2020	4.73×10^0	4.94×10^2	8.30×10^2	4.34×10^4	5.03×10^{-1}	1.05×10^3	4.58×10^4

TABLE A.5.2b. Bone Dose to the Population for the Reprocessing Cycle, Man-Rem

Case	Growth Assumption	Reprocessing Start-up Date	Repository Start-Up Date	Storage of Spent Fuel	BWR Fuel Shipments	PWR Fuel Shipments	FRP Treatment System	MOX-FFP Treatment System	Reprocessing Waste Shipments	Total
3	250 GWe in 2000 and Decline to 0 in 2040	1990	1990	2.01×10^0	0	0	2.50×10^4	6.43×10^0	0	2.50×10^4
3		1990	2010	2.01×10^0	0	0	2.50×10^4	6.43×10^0	0	2.50×10^4
3		2010	2010	9.15×10^0	0	0	8.55×10^2	1.42×10^0	0	8.66×10^2
3		1990	2030	2.01×10^0	0	0	2.50×10^4	6.43×10^0	0	2.50×10^4
3		2010	2030	9.15×10^0	0	0	8.55×10^2	1.42×10^0	0	8.66×10^2
4	250 GWe in 2000 and Steady State to 2040	2000	2000	6.31×10^0	0	0	1.49×10^4	6.31×10^0	0	1.49×10^4
4		2000	2020	6.31×10^0	0	0	1.49×10^4	6.31×10^0	0	1.49×10^4
5	250 GWe in 2000 and 500 GWe in 2040	2000	2000	7.67×10^0	0	0	1.81×10^4	1.09×10^1	0	1.81×10^4
5		2000	2020	7.67×10^0	0	0	1.81×10^4	1.09×10^1	0	1.81×10^4

TABLE A.5.2c. Lung Dose to the Population for the Reprocessing Cycle, Man-Rem

Case	Growth Assumption	Reprocessing Start-up Date	Repository Start-Up Date	Storage of Spent Fuel	BWR Fuel Shipments	PWR Fuel Shipments	FRP Treatment System	MOX-FFP Treatment System	Reprocessing Waste Shipments	Total
3	250 GWe in 2000 and Decline to 0 in 2040	1990	1990	6.44×10^{-1}	0	0	1.84×10^{6}	1.17×10^{0}	0	1.84×10^{6}
3		1990	2010	6.44×10^{-1}	0	0	1.84×10^{6}	1.17×10^{0}	0	1.84×10^{6}
3		2010	2010	2.53×10^{0}	0	0	4.34×10^{4}	2.56×10^{-1}	0	4.34×10^{4}
3		1990	2030	6.44×10^{-1}	0	0	1.84×10^{6}	1.17×10^{0}	0	1.84×10^{6}
3		2010	2030	2.53×10^{0}	0	0	4.34×10^{4}	2.56×10^{-1}	0	4.34×10^{4}
4	250 GWe in 2000 and Steady State to 2040	2000	2000	1.85×10^{0}	0	0	1.10×10^{6}	1.13×10^{0}	0	1.10×10^{6}
4		2000	2020	1.85×10^{0}	0	0	1.10×10^{6}	1.13×10^{0}	0	1.10×10^{6}
5	250 GWe in 2000 and 500 GWe in 2040	2000	2000	2.28×10^{0}	0	0	1.33×10^{6}	1.98×10^{0}	0	1.33×10^{6}
5		2000	2020	2.28×10^{0}	0	0	1.33×10^{6}	1.98×10^{0}	0	1.33×10^{6}

TABLE A.5.2d. Thyroid Dose to the Population for the Reprocessing Cycle, Man-Rem

Case	Growth Assumption	Reprocessing Start-up Date	Repository Start-Up Date	Storage of Spent Fuel	BWR Fuel Shipments	PWR Fuel Shipments	FRP Treatment System	MOX-FFP Treatment System	Reprocessing Waste Shipments	Total
3	250 GWe in 2000 and Decline to 0 in 2040	1990	1990	9.88×10^{-1}	0	0	4.82×10^{4}	3.49×10^{-9}	0	4.82×10^{4}
3		1990	2010	9.88×10^{-1}	0	0	4.82×10^{4}	3.49×10^{-9}	0	4.82×10^{4}
3		2010	2010	4.71×10^{0}	0	0	2.99×10^{4}	7.64×10^{-10}	0	2.99×10^{4}
3		1990	2030	9.88×10^{-1}	0	0	4.82×10^{4}	3.49×10^{-9}	0	4.82×10^{4}
3		2010	2030	4.71×10^{0}	0	0	2.99×10^{4}	7.64×10^{-10}	0	2.99×10^{4}
4	250 GWe in 2000 and Steady State to 2040	2000	2000	3.16×10^{0}	0	0	5.40×10^{4}	3.36×10^{-9}	0	5.40×10^{4}
4		2000	2020	3.16×10^{0}	0	0	5.40×10^{4}	3.36×10^{-9}	0	5.40×10^{4}
5	250 GWe in 2000 and 500 GWe in 2040	2000	2000	3.87×10^{0}	0	0	7.55×10^{4}	5.88×10^{9}	0	7.55×10^{4}
5		2000	2020	3.87×10^{0}	0	0	7.55×10^{4}	5.88×10^{9}	0	7.55×10^{4}

A.6 RESOURCE COMMITMENTS

Resource commitment tables (A.6.1 through A.6.3) list requirements by resource for all of the cases analyzed. The first table lists requirements for the once-through cycle; the second lists requirements for the reprocessing fuel cycles; and the third lists requirements for shipping casks.

TABLE A.6.1. Resource Commitments With the Once-Through Cycle

Growth Assumptions	Repository Startup Date	Repository Media	Steel, MT	Cement, MT	Diesel, M^3	Gasoline, M^3	Propane, M^3	Electricity, KW - hr	Manpower, Man - Year
Present Inventory	None		0	0	0	0	0	0	0
	1990	Salt	6.8×10^3	3.4×10^3	5.7×10^4	1.8×10^3	2.5×10^2	1.7×10^8	2.4×10^3
		Granite	1.4×10^4	4.4×10^3	5.3×10^4	2.5×10^3	3.4×10^2	1.9×10^8	2.8×10^3
		Shale	8.8×10^3	4.8×10^3	6.0×10^4	2.3×10^3	3.7×10^2	2.0×10^8	3.1×10^3
		Basalt	1.4×10^4	3.8×10^3	5.3×10^4	2.1×10^3	2.8×10^2	1.9×10^8	3.1×10^3
	2010	Salt	6.8×10^3	3.4×10^3	5.7×10^4	1.8×10^3	2.5×10^2	1.7×10^8	2.4×10^3
		Granite	1.1×10^4	3.5×10^3	4.9×10^4	2.0×10^3	2.7×10^2	1.5×10^8	2.2×10^3
		Shale	8.8×10^3	4.8×10^3	6.0×10^4	2.3×10^3	3.7×10^2	2.0×10^8	3.1×10^3
		Basalt	1.1×10^4	3.0×10^3	4.9×10^4	1.7×10^3	2.2×10^2	1.5×10^8	2.5×10^3
	2030	Salt	6.8×10^3	3.4×10^3	5.7×10^4	1.8×10^3	2.5×10^2	1.7×10^8	2.4×10^5
		Granite	8.4×10^3	2.6×10^3	4.5×10^4	1.5×10^3	2.0×10^2	1.1×10^8	1.7×10^3
		Shale	8.8×10^3	4.8×10^3	6.0×10^4	2.3×10^3	3.7×10^2	2.0×10^8	3.1×10^3
		Basalt	8.1×10^3	2.3×10^3	4.5×10^4	1.3×10^3	1.7×10^2	1.1×10^8	1.9×10^3
Present Capacity to Retirement	None		2.1×10^5	4.9×10^5	1.1×10^5	4.7×10^4	7.0×10^3	5.2×10^8	3.2×10^4
	1990	Salt	9.2×10^4	1.3×10^5	3.4×10^5	2.3×10^4	3.3×10^3	1.3×10^9	2.4×10^4
		Granite	1.3×10^5	1.3×10^5	2.9×10^5	2.5×10^4	3.5×10^3	1.2×10^9	2.3×10^4
		Shale	8.8×10^4	1.2×10^5	3.1×10^5	2.1×10^4	3.4×10^3	1.1×10^9	2.3×10^4
		Basalt	1.2×10^5	1.2×10^5	2.9×10^5	2.3×10^4	3.1×10^3	1.2×10^9	2.6×10^4
	2010	Salt	2.2×10^5	4.2×10^5	4.1×10^5	5.1×10^4	7.5×10^3	1.6×10^9	4.3×10^4
		Granite	2.2×10^5	4.2×10^5	3.2×10^5	4.8×10^4	7.1×10^3	1.2×10^9	3.7×10^4
		Shale	2.1×10^5	4.2×10^5	3.8×10^5	4.9×10^4	7.6×10^3	1.4×10^9	4.2×10^4
		Basalt	2.3×10^5	4.2×10^5	3.3×10^5	4.7×10^4	6.8×10^3	1.2×10^9	3.9×10^4
	2030	Salt	2.6×10^5	5.1×10^5	4.2×10^5	6.0×10^4	8.8×10^3	1.7×10^9	4.9×10^4
		Granite	2.6×10^5	5.1×10^5	3.3×10^5	5.7×10^4	8.4×10^3	1.3×10^9	4.3×10^4
		Shale	2.4×10^5	5.1×10^5	3.6×10^5	5.6×10^4	8.5×10^3	1.3×10^9	4.5×10^4
		Basalt	2.7×10^5	5.1×10^5	3.4×10^5	5.6×10^4	8.1×10^3	1.3×10^9	4.5×10^4
250 GWe in 2000 and Decline to 0 in 2040	None		1.1×10^6	2.6×10^6	6.0×10^5	2.5×10^5	3.7×10^4	2.8×10^9	1.7×10^5
	1990	Salt	3.0×10^5	2.8×10^5	1.6×10^6	7.9×10^4	1.1×10^4	6.1×10^9	8.9×10^4
		Granite	4.9×10^5	3.0×10^5	1.4×10^6	8.6×10^4	1.3×10^4	5.8×10^9	9.4×10^4
		Shale	2.9×10^5	2.9×10^5	1.5×10^6	7.5×10^4	1.2×10^4	5.4×10^9	8.6×10^4
		Basalt	4.8×10^5	2.7×10^5	1.4×10^6	7.8×10^4	1.1×10^4	5.8×10^9	9.9×10^4
	2010	Salt	8.8×10^5	1.6×10^6	1.9×10^6	2.0×10^5	3.0×10^4	7.3×10^9	1.8×10^5
		Granite	1.0×10^6	1.6×10^6	1.6×10^6	2.1×10^5	2.9×10^4	6.4×10^9	1.7×10^5
		Shale	8.6×10^5	1.6×10^6	1.8×10^6	2.0×10^5	3.0×10^4	6.4×10^9	1.7×10^5
		Basalt	1.0×10^6	1.6×10^6	1.5×10^6	1.9×10^5	2.8×10^4	6.4×10^9	1.8×10^5
	2030	Salt	1.3×10^6	2.5×10^6	2.1×10^6	2.9×10^5	4.3×10^4	8.1×10^9	2.4×10^5
		Granite	1.3×10^6	2.5×10^6	1.7×10^6	2.8×10^5	4.0×10^4	6.2×10^9	2.1×10^5
		Shale	1.2×10^6	2.5×10^6	1.9×10^6	2.8×10^5	4.2×10^4	6.7×10^9	2.2×10^5
		Basalt	1.2×10^6	2.5×10^6	1.6×10^6	2.7×10^5	3.9×10^4	6.2×10^9	2.2×10^5
250 GWe in 2000 and Steady State to 2040	2000	Salt	6.6×10^5	9.3×10^5	2.3×10^6	1.6×10^5	2.4×10^4	9.3×10^9	1.7×10^5
		Granite	9.0×10^5	9.4×10^5	1.9×10^6	1.7×10^5	2.4×10^4	7.4×10^9	1.6×10^5
		Shale	6.4×10^5	9.3×10^5	2.1×10^6	1.6×10^5	2.4×10^4	8.0×10^9	1.5×10^5
		Basalt	8.1×10^5	9.5×10^5	1.9×10^6	1.6×10^5	2.3×10^4	7.4×10^9	1.7×10^5
	2020	Salt	1.4×10^6	2.4×10^6	2.7×10^6	3.0×10^5	4.5×10^4	1.0×10^{10}	2.7×10^5
		Granite	1.4×10^6	2.4×10^6	2.2×10^6	3.0×10^5	4.3×10^4	8.3×10^9	2.4×10^5
		Shale	1.2×10^6	2.4×10^6	2.4×10^6	2.9×10^5	4.4×10^4	8.2×10^9	2.4×10^5
		Basalt	1.4×10^6	2.4×10^6	2.2×10^6	2.9×10^5	4.2×10^4	8.3×10^9	2.5×10^5
250 GWe in 2000 and 500 GWe in 2040	2000	Salt	7.8×10^5	1.0×10^6	3.0×10^6	1.9×10^5	2.8×10^4	1.2×10^{10}	2.1×10^5
		Granite	1.1×10^6	1.0×10^6	2.6×10^6	2.0×10^5	2.9×10^4	1.0×10^{10}	2.0×10^5
		Shale	7.4×10^5	1.0×10^6	2.8×10^6	1.8×10^5	2.9×10^4	1.0×10^{10}	2.0×10^5
		Basalt	1.1×10^6	1.0×10^6	2.6×10^6	1.8×10^5	2.7×10^4	1.1×10^{10}	2.1×10^5
	2020	Salt	1.6×10^6	3.1×10^6	3.6×10^6	3.9×10^5	5.7×10^4	1.4×10^{10}	3.4×10^5
		Granite	1.8×10^6	3.1×10^6	2.9×10^6	3.7×10^5	5.5×10^4	1.4×10^{10}	3.1×10^5
		Shale	1.6×10^6	3.1×10^6	3.2×10^6	3.6×10^5	5.6×10^4	1.1×10^{10}	3.1×10^5
		Basalt	1.7×10^6	3.1×10^6	2.9×10^6	3.6×10^5	5.3×10^4	1.1×10^{10}	3.2×10^5

TABLE A.6.2. Resource Commitments with the Reprocessing Cycle

Growth Assumptions	Reprocessing Startup Date	Repository Startup Date	Repository Media	Steel, MT	Cement, MT	Diesel, M^3	Gasoline, M^3	Propane, M^3	Electricity, KW - hr	Manpower, Man - Year
250 GWe in 2000 and Decline to 0 in 2040	1990	1990	Salt	4.8×10^5	5.5×10^5	1.4×10^6	1.1×10^5	3.5×10^7	1.8×10^{10}	1.4×10^5
			Granite	7.2×10^5	6.2×10^5	1.4×10^6	1.5×10^5	3.5×10^7	1.9×10^{10}	1.8×10^5
			Shale	3.8×10^5	6.4×10^5	1.6×10^6	1.5×10^5	3.5×10^7	1.9×10^{10}	1.8×10^5
			Basalt	7.4×10^5	6.1×10^5	1.4×10^6	1.5×10^5	3.5×10^7	1.8×10^{10}	2.0×10^5
	1990	2010	Salt	6.7×10^5	5.9×10^5	1.4×10^6	6.3×10^4	3.5×10^7	1.8×10^{10}	1.5×10^5
			Granite	8.4×10^5	6.4×10^5	1.4×10^6	2.3×10^5	3.5×10^7	1.8×10^{10}	1.8×10^5
			Shale	5.6×10^5	6.7×10^5	1.6×10^6	2.4×10^5	3.5×10^7	1.8×10^{10}	2.0×10^5
			Basalt	8.6×10^5	6.4×10^5	1.4×10^6	2.3×10^5	3.5×10^7	1.8×10^{10}	1.9×10^5
	2010	2010	Salt	9.3×10^5	1.8×10^6	1.3×10^6	2.2×10^5	3.4×10^7	1.7×10^{10}	2.0×10^5
			Granite	1.1×10^6	1.8×10^6	1.3×10^6	2.5×10^5	3.4×10^7	1.7×10^{10}	2.3×10^5
			Shale	9.0×10^5	1.9×10^6	1.5×10^6	2.5×10^5	3.4×10^7	1.8×10^{10}	2.4×10^5
			Basalt	1.1×10^6	1.8×10^6	1.3×10^6	2.5×10^5	3.4×10^7	1.7×10^{10}	2.4×10^5
	1990	2030	Salt	7.2×10^5	7.7×10^5	1.7×10^6	2.4×10^5	3.5×10^7	1.7×10^{10}	1.5×10^5
			Granite	8.7×10^5	8.1×10^5	1.8×10^6	2.7×10^5	3.5×10^7	1.7×10^{10}	1.7×10^5
			Shale	6.4×10^5	8.4×10^5	1.9×10^6	2.7×10^5	3.5×10^7	1.7×10^{10}	1.8×10^5
			Basalt	8.9×10^5	8.1×10^5	1.7×10^6	2.7×10^5	3.5×10^7	1.7×10^{10}	1.8×10^5
	2010	2030	Salt	1.2×10^6	2.0×10^6	1.9×10^6	3.4×10^5	3.4×10^7	1.7×10^{10}	2.2×10^5
			Granite	1.4×10^6	2.0×10^6	1.9×10^6	3.8×10^5	3.4×10^7	1.8×10^{10}	2.5×10^5
			Shale	1.1×10^6	2.0×10^6	2.0×10^6	3.8×10^5	3.4×10^7	1.8×10^{10}	2.6×10^5
			Basalt	1.3×10^6	2.0×10^6	1.9×10^6	3.8×10^5	3.4×10^7	1.7×10^{10}	1.8×10^5
250 GWe in 2000 and Steady State to 2040	2000	2000	Salt	8.4×10^5	1.3×10^6	1.8×10^6	1.8×10^5	4.5×10^7	2.3×10^{10}	2.1×10^5
			Granite	1.1×10^6	1.4×10^6	1.8×10^6	2.3×10^5	4.5×10^7	2.4×10^{10}	2.5×10^5
			Shale	7.2×10^5	1.5×10^6	2.0×10^6	2.4×10^5	4.5×10^7	2.4×10^{10}	2.6×10^5
			Basalt	1.1×10^6	1.4×10^6	1.7×10^6	2.3×10^5	4.5×10^7	2.3×10^{10}	2.7×10^5
	2000	2030	Salt	1.1×10^6	1.5×10^6	2.3×10^6	3.1×10^5	4.5×10^7	2.3×10^{10}	2.3×10^5
			Granite	1.3×10^6	1.6×10^6	2.3×10^6	3.4×10^5	4.5×10^7	2.4×10^{10}	2.6×10^5
			Shale	9.4×10^5	1.6×10^6	2.6×10^6	3.6×10^5	4.5×10^7	2.4×10^{10}	2.8×10^5
			Basalt	1.3×10^6	1.6×10^6	2.2×10^6	3.4×10^5	4.5×10^7	2.4×10^{10}	2.8×10^5
250 GWe in 2000 and 500 GWe in 2040	2000	2000	Salt	1.1×10^6	1.4×10^6	2.3×10^6	2.3×10^5	6.0×10^7	3.0×10^{10}	2.7×10^5
			Granite	1.4×10^6	1.6×10^6	2.4×10^6	2.9×10^5	6.0×10^7	3.2×10^{10}	3.4×10^5
			Shale	8.3×10^5	1.6×10^6	2.8×10^6	3.0×10^5	6.0×10^7	3.2×10^{10}	3.4×10^5
			Basalt	1.4×10^6	1.5×10^6	2.3×10^6	2.8×10^5	6.0×10^7	3.1×10^{10}	3.5×10^5
	2000	2020	Salt	1.3×10^6	1.7×10^6	3.2×10^6	3.9×10^5	6.0×10^7	3.1×10^{10}	2.9×10^5
			Granite	1.6×10^6	1.9×10^6	3.2×10^6	4.3×10^5	6.0×10^7	3.2×10^{10}	3.4×10^5
			Shale	1.2×10^6	1.9×10^6	3.5×10^6	4.5×10^5	6.0×10^7	3.3×10^{10}	3.6×10^5
			Basalt	1.7×10^6	1.8×10^6	3.1×10^6	4.4×10^5	6.0×10^7	3.2×10^{10}	3.6×10^5

TABLE A.6.3. Resource Commitments for Shipping Casks

Growth Assumption	Reprocessing Startup Date	Repository Startup Date	Steel, MT	Lead, MT
Once-Through Cycle				
Present inventory	NA(a)	1990	1.9×10^2	5.2×10^2
	NA	2010	1.9×10^2	5.2×10^2
	NA	2030	1.9×10^2	5.2×10^2
Present capacity to retirement	NA	1990	9.2×10^2	2.5×10^3
	NA	2010	1.3×10^3	3.3×10^3
	NA	2030	1.4×10^3	3.5×10^3
250 GWE in 2000 and decline to 0 in 2040	NA	1990	4.1×10^3	1.1×10^4
	NA	2010	6.2×10^3	1.6×10^4
	NA	2030	6.8×10^3	1.8×10^4
250 GWe in 2000 and steady state to 2040	NA	2000	6.7×10^3	1.8×10^4
	NA	2020	9.0×10^3	2.3×10^4
250 GWe in 2000 and 500 GWe in 2040	NA	2000	8.7×10^3	2.3×10^4
	NA	2040	1.2×10^4	3.1×10^4
Present capacity to retirement	NA	No action	7.0×10^2	1.9×10^3
250 GWe in 2000 and decline to 0 in 2040	NA	No action	3.6×10^3	9.4×10^3
Reprocessing Cycles				
250 GWe in 2000 and decline to 0 in 2040	1990	1990	6.1×10^3	1.7×10^4
	1990	2010	8.2×10^3	2.3×10^4
	2010	2010	8.1×10^3	2.2×10^4
	1990	2030	8.3×10^3	2.3×10^4
	2010	2030	1.0×10^4	2.8×10^4
250 GWe in 2000 and steady state to 2040	2000	2000	9.3×10^3	2.5×10^4
	2000	2020	1.2×10^4	3.4×10^4
250 GWe in 2000 and 500 GWE in 2040	2000	2000	1.2×10^4	3.3×10^4
	2000	2040	1.6×10^4	4.5×10^4

(a) NA = not applicable.

A.7 TRANSPORTATION REQUIREMENTS

The transportation requirements tables (A.7.1 and A.7.2) show the number of shipments required by waste type, case and mode of transportation for both fuel cycles and for all cases analyzed.

TABLE A.7.1. Transportation Requirements Using the Once-Through Fuel Cycle

Case	Growth Assumption	Repository Start-Up Date	Transport Mode	Spent Fuel Shipments (thousands)
1	Present Inventory Only	None	Rail	0
			Truck	0
		1990	Rail	2.3
			Truck	2.3
		2010	Rail	2.3
			Truck	2.3
		2030	Rail	2.3
			Truck	2.3
2	Present Capacity--Normal Life	None	Rail	8.4
			Truck	8.6
		1990	Rail	13.3
			Truck	11.1
		2010	Rail	18.0
			Truck	11.1
		2030	Rail	19.0
			Truck	11.1
3	250 GWe System by Year 2000	None	Rail	45.0
			Truck	45.8
		1990	Rail	60.5
			Truck	55.6
		2010	Rail	88.6
			Truck	55.6
		2030	Rail	95.7
			Truck	55.6
4	250 GWe System and Steady State	2000	Rail	96.6
			Truck	73.4
		2020	Rail	127.2
			Truck	73.4
5	500 GWe System by 2040	2000	Rail	125.7
			Truck	99.4
		2020	Rail	169.5
			Truck	99.4

TABLE A.7.2. Transportation Requirements Using the Reprocessing Cycle

					Thousands of Shipments						
Case	Growth Assumption	Reprocessing Start-Up Date	Repository Start-Up Date	Transport Mode	Spent Fuel	HLW	Canisters	RH-TRU Drums	CH-TRU Drums & Boxes	Decommissioning Waste	Total
1	Present Inventory Only	NA[a]	NA	NA	NA	NA	NA	NA	NA	NA	NA
2	Present Capacity--Normal Life	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	250 GWe System by Year 2000	1990	1990	Rail	59	8.8	22	--	--	--	90
				Truck	56	--	--	108	21	4.7	190
		1990	2010	Rail	59	17	43	--	--	--	119
				Truck	56	--	--	213	40	4.7	314
		2010	2010	Rail	86	8.7	22	--	--	--	117
				Truck	56	--	--	108	14	3.7	182
		1990	2030	Rail	59	17	44	--	--	--	120
				Truck	56	--	--	215	41	4.7	317
		2010	2030	Rail	86	17	44	--	--	--	147
				Truck	56	--	--	215	29	3.7	304
4	250 GWe System and Steady State	2000	2000	Rail	95	12	29	--	--	--	136
				Truck	73	--	--	142	33	2.4	250
		2000	2020	Rail	95	23	58	--	--	--	176
				Truck	73	--	--	284	53	2.4	412
5	500 GWe System by Year 2040	2000	2000	Rail	124	16	39	--	--	--	179
				Truck	99	--	--	192	50	2.4	343
		2000	2020	Rail	124	31	78	--	--	--	233
				Truck	99	--	--	385	80	2.4	566

(a) NA = not applicable.

A.8 SUPPLEMENTARY PREDISPOSAL COST DATA

The predisposal cost tables (A.8.1 through A.8.4) list the capital, operating, and levelized unit cost estimates for facilities for spent fuel treatment and storage, treatment of wastes from uranium and plutonium recycle, and interim storage of treated wastes. Costs for the example concepts (used in the system simulation cost determination) and for other optional methods are both shown. A table is also included showing capital costs for shipping casks and freight charge estimates for waste transportation over the generic distances used in this Statement.

TABLE A.8.1. Cost Estimates for Treatment and Storage of Spent Fuel

Activity	Total Capital Cost(a) $\$10^6$	Annual Operation and Maintenance $\$10^6/yr$	Levelized Unit Cost Private Ownership(b) $/kg HM	 Federal Ownership(b) $/kg HM
Independent Unpackaged Water Basin Storage	234	5	212 ± 35%	117 ± 35%
Incremental 1000 MTHM Receiving Capacity at Above Facility	28	1.5	7 ± 40%	3.5 ± 35%
Spent Fuel Packaging Facility	128	13	29.6 ± 30%	18.30 ± 25%
Independent Spent Fuel Receiving Facility	92	1.5	---	9.5 ± 30%
Long-Term Packaged Spent Fuel Storage				
• Water Basin	296	392(c)	---	38.40 ± 20%
• Air-Cooled Vault	595	1.3	---	34.90 ± 30%
• Dry Caisson	341	39(d)	---	22.20 ± 25%
• Surface Cask	258	264(e)	---	30.20 ± 20%

(a) Includes owner's costs.
(b) See DOE/ET-0028, Vol. 1, Section 3.8 for financial parameters relating to ownership.
(c) Includes $389 million for incremental costs of using stainless steel canisters and storage racks.
(d) Include $37 million for carbon steel storage casks

(e) Includes $262 million for storage casks.

TABLE A.8.2. Cost Estimates for Treatment of Waste from Uranium and Plutonium Recycle

Activity	Total Capital Cost $\$10^6$	Annual Operation and Maintenance $\$10^6$/yr	Levelized Unit Cost $/kg HM(a)
5-Yr High-Level Liquid Waste Storage	282	6.6	42.00 ± 30%
High-Level Liquid Waste Solidification			
• Calcination	76	6.8	13.00 ± 35%
• Vitrification	55	7.1	10.40 ± 35%
Fuel Residue Packaging			
• Packaging Without Compaction	17	4.8	4.90 ± 25%
• Mechanical Compaction	20	3.5	4.60 ± 30%
• Melting	27	3.2	5.20 ± 35%
Failed Equipment and Non-Combustible Waste Packaging			
• At Reprocessing Plant	27	1.6	4.20 ± 55%
• At MOX Fuel Fabrication Plant	3.7	0.4	0.60 ± 55%
Combustible and Compactable Waste Treatment			
• At Reprocessing Plant			
- Incineration	16.9	1.6	3.40 ± 35%
- Package Only	18.1	0.8	2.30 ± 35%
• At MOX Fuel Fabrication Plant			
- Incineration	6.4	0.3	1.00 ± 35%
- Package Only	2.9	0.1	0.40 ± 35%
Degraded Solvent Treatment	8	0.1	1.40 ± 40%
Waste Immobilization			
• At Reprocessing Plant			
- In Bitumen	16	0.6	2.30 ± 35%
- In Cement	16	0.7	2.30 ± 35%
• At MOX Fuel Fabrication Plant			
- In Bitumen	14	0.3	1.40 ± 35%
- In Cement	13.5	0.3	1.40 ± 35%
Off-Gas Treatment			
• Iodine Recovery	12.8	0.8	2.00 ± 40%
• Carbon Recovery (w/o krypton recovery)	8.2	0.1	1.20 ± 40%
• Krypton Recovery (w/o carbon recovery)	25.8	1.3	4.00 ± 40%
• Combined Iodine, Carbon and Krypton Recovery	39.8	2.2	6.10 ± 40%
• Vessel Off-Gas Treatment	26.7	2.6	3.90 ± 35%
Off-Gas Filtration at Reprocessing Plant			
• Prefilters and HEPA Filters	11.7	0.6	1.80 ± 35%
• Sand Filter and HEPA Filters	28.1	0.6	3.80 ± 40%
• Deep-Bed Glass Filter and HEPA Filters	12.8	0.6	2.50 ± 40%

(a) Costs may be expressed in $/GW-yr by multiplying by 38,000 kgHM/GW-yr

TABLE A.8.3. Cost Estimates for Interim Storage of Waste from Uranium and Plutonium Recycle

Activity	Total Capital Cost $10^6	Annual Operation and Maintenance $10^6/yr	Levelized Unit Cost: Private Ownership $/kg HM	Levelized Unit Cost: Federal Ownership $/kg HM
5-Yr Solidified High-Level Waste Basin Storage and Shipping Facility at Reprocessing Plant	99	3	13.80 ± 40%	---
Solidified High-Level Waste Storage Using the Sealed Cask Concept				
• HLW Accumulated to:				
- 1990	105	3.3	---	30.80 ± 70%
- 1995	115	8.5	---	15.80 ± 20%
- 2000	126	12.7	---	12.90 ± 20%
Fuel Residue Storage				
• 5-Yr Storage at Reprocessing Plant				
- Vault Concept	140	0.6	41.40 ± 25%	---
- Near-Surface Concept	41	0.3	12.30 ± 25%	---
• Storage to 1995 at Independent Site				
- Vault Concept	673	1.0	---	20.30 ± 25%
- Near-Surface Concept	191	0.9	---	6.20 ± 25%
TRU Intermediate-Level Waste Storage				
• 5-Yr Storage at Reprocessing Plant				
- Outdoor Subsurface Concept	45	0.2	9.30 ± 30%	---
- Indoor Shielded Concept	19	0.1	5.20 ± 30%	---
• Storage to 1995 at Independent Site				
- Outdoor Subsurface Concept	222	0.6	---	5.90 ± 30%
- Indoor Shielded Concept	87	0.4	---	2.60 ± 30%
TRU Low-Level Waste Storage				
• 5-Yr Storage at Reprocessing Plant				
- Outdoor Surface Concept	1.3	0.02	0.40 ± 30%	---
- Indoor Unshielded Concept	1.5	0.03	0.50 ± 25%	---
• 5-Yr Storage at MOX-FFP				
- Outdoor Surface Concept	1.2	0.02	0.40 ± 25%	---
- Indoor Unshielded Concept	1.2	0.02	0.40 ± 25%	---
• Storage to 1995 at Independent Site				
- Outdoor Surface Concept	6.4	0.1	---	0.30 ± 25%
- Indoor Unshielded Concept	10.7	0.1	---	0.40 ± 20%
Plutonium Oxide Storage(a)				
• 30 MT Facilities at Reprocessing Plant	281	4	33.70 ± 20%	---
• 200 MT Facility at Reprocessing Plant	494	3.2	50.00 ± 30%	---
• 200 MT Independent Site Facility				
- Accumulate to 1990	263	3.2	---	22.90 ± 25%
- Accumulate to 2000	1,053	6.7	---	22.50 ± 25%
Krypton Storage	192	0.2	16.40 ± 40%	---

(a) Plutonium oxide storage where plutonium is considered a waste is only needed in the event that spent fuel is reprocessed to recover the uranium value and remove plutonium.

TABLE A.8.4. Cost Estimates for Waste Transportation

Waste Shipment	Transport Mode	Cask Type	Single Cask Cost $\$10^3$	Distance, miles	Round Trip Freight Cost Cost, $\$10^3$	Unit Cost \$/kg HM
Unpackaged Spent Fuel	Rail	NLI 10/25	3,500	1,000	22	16.20
		IF-300	3,500	1,500	25	22.50
	Truck	NFS-4	1,050	1,000	3	18.50
				1,500	5	26.40
Packaged Spent Fuel	Rail	Modified NLI 10/24	3,500	1,500	25	32.00
Solidified High-Level Waste(a)	Rail	Conceptual	2,900	1,500	25	3.40
Fuel Residues						
Packaged Only	Rail	Conceptual	700	1,500	25	3.50
Mechanically Compacted	Rail	Conceptual	700	1,500	25	2.00
Melted	Rail	Conceptual	700	1,500	25	1.40
Non-High-Level TRU with a Surface Radiation Rate of						
0.2 R/hr	Truck	36 Drums(c)	100	1,500	3,200	0.24
				(1,000)	(2,300)	(0.21)
0.2 to 1.0 R/hr	Truck	36 Drums(c)	160	1,500	3,200	0.54
				(1,000)	(2,300)	(0.38)
1.0 to 1.0 R/hr	Truck	14 Drums(c)	140	1,500	3,200	0.30
				(1,000)	(2,300)	(0.21)
10 R/hr	Truck	6 Drums(c)	180	1,500	3,200	1.43
				(1,000)	(2,300)	(1.06)
Plutonium Oxide	Truck	PPP-1	260	1,500	16	0.80(d)

(a) Costs of high-level waste transportation are about the same for calcined or vitrified waste.

(b) The costs shown in the table assume combustible waste is incinerated and all drummed waste is immobilized in cement.

(c) All casks are Type B casks. All casks are shielded except for the cask with drums measuring less than 0.2 R/hr. (DOE/ET-0028, Vol. 4, Section 6.6).

(d) Equivalent to about \$9 per gram of plutonium.

A.9 SUPPLEMENTARY SYSTEM COST DATA

The systems cost tables (A.9.1a through A.9.6) provide additional detail on the breakdown of power costs by major functions and the differences in power cost as influenced by repository media. Four sets of tables are included. The first two sets break down the costs by the functions of spent fuel storage and transport; spent fuel treatment; other waste treatment, storage and transport; disposal; and research and development for both fuel cycles. The latter two sets break down the total system costs by repository media for both fuel cycles. Each set consists of three tables with costs calculated at discount rates of 0, 7 and 10%. In addition to these tables, two tables are provided to display the estimated research and development costs (including site verification costs) for waste isolation.

TABLE A.9.1a. Allocation of Total-System Waste Management Unit Costs with the Once-Through Cycle Using a 0% Discount Rate, mills/kWh

Case	Nuclear Power Growth Assumption	Repository Startup Date	Spent Fuel Storage and Transport	Spent Fuel Treatment	Disposal	Research and Development	Total
1	Present Inventory Only	1990	0.63	0.10	0.51 to 0.62	1.6	2.9 to 3.0
		2010	1.31	0.10	0.51 to 0.62	2.3	4.2 to 4.3
		2030	1.98	0.10	0.51 to 0.62	5.0	7.6 to 7.7
		None	3.28			0.36	3.6
2	Present Capacity--Normal Life	1990	0.42	0.08	0.22 to 0.37	0.26	1.0 to 1.1
		2010	0.79	0.08	0.22 to 0.37	0.36	1.5 to 1.6
		2030	0.92	0.08	0.22 to 0.37	0.79	2.0 to 2.2
		None	1.0			0.06	1.1
3	250 GWe system by Year 2000 and Normal Life	1990	0.33	0.08	0.22 to 0.37	0.06	0.69 to 0.84
		2010	0.69	0.08	0.22 to 0.37	0.08	1.1 to 1.2
		2030	0.84	0.08	0.22 to 0.37	0.17	1.3 to 1.5
		None	0.87			0.01	0.88
4	250 GWe System by Year 2000 and Steady State	2000	0.46	0.07	0.21 to 0.36	0.05	0.80 to 0.95
		2020	0.75	0.08	0.21 to 0.36	0.10	1.1 to 1.3
5	500 GWe System by Year 2040	2000	0.42	0.07	0.21 to 0.35	0.04	0.74 to 0.88
		2020	0.74	0.07	0.21 to 0.35	0.07	1.1 to 1.2

TABLE A.9.1b. Allocation of Total-System Waste Management Unit Costs with the Once-Through Cycle Using a 7% Discount Rate, mills/kWh

Case	Nuclear Power Growth Assumption	Repository Startup Date	Spent Fuel Storage and Transport	Spent Fuel Treatment	Disposal	Research and Development	Total
1	Present Inventory	1990	0.35	0.04	0.18 to 0.22	1.1	1.6 to 1.7
		2010	0.44	0.01	0.05 to 0.06	1.1	1.6
		2030	0.47	0.002	0.01	1.5	2.0
		None	0.48			0.30	.78
2	Present Capacity--Normal Life	1990	0.34	0.03	0.10 to 0.17	0.37	0.85 to 0.92
		2010	0.45	0.01	0.03 to 0.04	0.39	0.87 to 0.89
		2030	0.45	0.0025	0.01	0.53	1.0
		None	0.45			0.11	0.56
3	250 GWe System by Year 2000 and Normal Life	1990	0.29	0.04	0.11 to 0.19	0.17	0.61 to 0.69
		2010	0.44	0.01	0.04 to 0.06	0.16	0.65 to 0.68
		2030	0.46	0.003	0.01 to 0.02	0.21	0.68
		None	0.45			0.04	0.49
4	250 GWe System by Year 2000 and Steady State	2000	0.41	0.02	0.07 to 0.12	0.16	0.66 to 0.71
		2020	0.45	0.01	0.02 to 0.03	0.19	0.67 to 0.69
5	500 GWe System by Year 2040	2000	0.40	0.03	0.07 to 0.12	0.14	0.64 to 0.69
		2020	0.46	0.01	0.02 to 0.03	0.17	0.66 to 0.67

TABLE A.9.1c. Allocation of Total-System Waste Management Unit Costs with the Once-Through Cycle Using a 10% Discount Rate, mills/kWh

Case	Nuclear Power Growth Assumption	Repository Startup Date	Spent Fuel Storage and Transport	Spent Fuel Treatment	Disposal	Research and Development	Total
1	Present Inventory Only	1990	0.28	0.02	0.12 to 0.15	0.90	1.3 to 1.4
		2010	0.32	0.004	0.02	0.87	1.2
		2030	0.33	0.0006	0.002 to 0.003	1.1	1.4
		None	0.33			0.28	0.61
2	Present Capacity--Normal Life	1990	0.31	0.02	0.07 to 0.11	0.39	0.79 to 0.83
		2010	0.37	0.004	0.01 to 0.02	0.38	0.77
		2030	0.37	0.0005	0.0015 to 0.0026	0.47	0.85
		None	0.38			0.12	0.50
3	250 GWe System by Year 2000 and Normal Life	1990	0.28	0.03	0.08 to 0.14	0.21	0.59 to 0.65
		2010	0.37	0.01	0.02 to 0.03	0.19	0.58 to 0.59
		2030	0.38	0.0007	0.002 to 0.004	0.23	0.61
		None	0.38			0.06	0.44
4	250 GWe System by Year 2000 and Steady State	2000	0.36	0.01	0.04 to 0.06	0.20	0.61 to 0.63
		2020	0.38	0.002	0.01	0.22	0.60 to 0.61
5	500 GWe System by Year 2040	2000	0.36	0.01	0.04 to 0.07	0.19	0.60 to 0.62
		2020	0.38	0.002	0.01	0.21	0.59 to 0.60

TABLE A.9.2a. Allocation of Total-System Waste Management Unit Costs with the Reprocessing Cycle Using a 0% Discount Rate, mills/kWh

Case	Nuclear Power Growth Assumption	Repository Startup Date	Reprocessing Startup Date	Spent Fuel Storage and Transport	Waste Treatment Storage and Transport	Disposal	Research and Development	Total
1	Present Inventory Only	NA[a]	NA	NA	NA	NA	NA	NA
2	Present Capacity--Normal Life	NA	NA	NA	NA	NA	NA	NA
3	250 GWe System by Year 2000 and Normal Life	1990	1990	0.23	0.53 to 0.76	0.23 to 0.48	0.06	1.1 to 1.5
		2010	1990	0.24	0.51 to 0.58	0.21 to 0.36	0.08	1.0 to 1.3
		2010	2010	0.65	0.47 to 0.56	0.18 to 0.31	0.08	1.4 to 1.6
		2030	1990	0.24	0.51	0.19 to 0.30	0.17	1.1 to 1.2
		2030	2010	0.65	0.49 to 0.51	0.18 to 0.28	0.17	1.5 to 1.6
4	250 GWe System by Year 2000 and Steady State	2000	2000	0.40	0.49 to 0.61	0.20 to 0.35	0.05	1.1 to 1.4
		2020	2000	0.41	0.48 to 0.53	0.18 to 0.32	0.10	1.2 to 1.4
5	500 GWe System by Year 2040	2000	2000	0.37	0.48 to 0.62	0.20 to 0.36	0.04	1.1 to 1.4
		2020	2000	0.37	0.47 to 0.53	0.18 to 0.32	0.07	1.1 to 1.3

(a) NA = not applicable.

TABLE A.9.2b. Allocation of Total-System Waste Management Unit Costs with the Reprocessing Cycle Using a 7% Discount Rate, mills/kWh

Case	Nuclear Power Growth Assumption	Repository Startup Date	Reprocessing Startup Date	Spent Fuel Storage and Transport	Waste Treatment Storage and Transport	Disposal	Research and Development	Total
1	Present Inventory Only	NA(a)	NA	NA	NA	NA	NA	NA
2	Present Capacity--Normal Life	NA	NA	NA	NA	NA	NA	NA
3	250 GWe system by Year 2000 and Normal Life	1990	1990	0.25	0.25 to 0.32	0.09 to 0.18	0.17	0.76 to 0.91
		2010	1990	0.25	0.24	0.03 to 0.06	0.16	0.68 to 0.71
		2010	2010	0.43	0.07	0.02 to 0.04	0.16	0.68 to 0.70
		2030	1990	0.25	0.23	0.01 to 0.02	0.21	0.70
		2030	2010	0.43	0.06	0.01	0.21	0.71 to 0.72
4	250 GWe System by Year 2000 and Steady State	2000	2000	0.38	0.16	0.05 to 0.09	0.16	0.73 to 0.79
		2000	2020	0.39	0.13 to 0.14	0.02 to 0.03	0.19	0.73 to 0.74
5	500 GWe System by Year 2040	2000	2000	0.37	0.15 to 0.18	0.05 to 0.09	0.15	0.72 to 0.79
		2020	2000	0.37	0.14 to 0.15	0.02 to 0.04	0.17	0.71 to 0.73

(a) NA = not applicable.

TABLE A.9.2c. Allocation of Total-System Waste Management Unit Costs with the Reprocessing Cycle Using a 10% Discount Rate, mills/kWh

Case	Nuclear Power Growth Assumption	Repository Startup Date	Reprocessing Startup Date	Spent Fuel Storage and Transport	Waste Treatment Storage and Transport	Disposal	Research and Development	Total
1	Present Inventory Only	NA[a]	NA	NA	NA	NA	NA	NA
2	Present Capacity--Normal Life	NA	NA	NA	NA	NA	NA	NA
3	250 GWe System by Year 2000 and Normal Life	1990	1990	0.24	0.17 to 0.22	0.06 to 0.09	0.21	0.68 to 0.77
		2000	1990	0.24	0.16	0.01 to 0.02	0.19	0.60 to 0.62
		2010	2010	0.37	0.03	0.01	0.19	0.59 to 0.60
		2030	1990	0.24	0.16	0.002 to 0.004	0.23	0.63
		2030	2010	0.37	0.02	0.002 to 0.003	0.23	0.62
4	250 GWe System by Year 2000 and Steady State	2000	2000	0.34	0.07 to 0.08	0.02 to 0.04	0.20	0.63 to 0.66
		2020	2000	0.34	0.07	0.01	0.22	0.63 to 0.64
5	500 GWe System by Year 2040	2000	2000	0.34	0.08 to 0.09	0.03 to 0.05	0.19	0.63 to 0.66
		2020	2000	0.34	0.07	0.01	0.21	0.62 to 0.63

(a) NA = not applicable.

TABLE A.9.3a. Repository Media Effect on Total-System Waste Management Unit Cost with the Once-Through Cycle Using a 0% Discount Rate

Case	Nuclear Power Growth Assumption	Startup Date	mills/kWh Salt Repository	 Granite Repository	 Shale Repository	 Basalt Repository
1	Present Inventory Only	1990	2.85	2.91	2.86	2.97
		2010	4.19	4.25	4.20	4.31
		2030	7.61	7.67	7.61	7.72
2	Present Capacity--Normal Life	1990	0.98	1.09	1.00	1.13
		2010	1.45	1.56	1.47	1.60
		2030	2.01	2.13	2.04	2.17
3	250 GWe System by Year 2000 and Normal Life	1990	0.69	0.80	0.71	0.84
		2010	1.07	1.18	1.09	1.22
		2030	1.31	1.42	1.34	1.46
4	250 GWe System by Year 2000 and Steady State	2000	0.80	0.91	0.82	0.95
		2020	1.14	1.25	1.16	1.28
5	500 GWe System by Year 2040	2000	0.74	0.84	0.76	0.88
		2020	1.10	1.20	1.12	1.24

TABLE A.9.3b. Repository Media Effect on Total-System Waste Management Unit Cost with the Once-Through Cycle Using a 7% Discount Rate

Case	Nuclear Power Growth Assumption	Startup Date	mills/kWh			
			Salt Repository	Granite Repository	Shale Repository	Basalt Repository
1	Present Inventory Only	1990	1.62	1.64	1.62	1.66
		2010	1.59	1.59	1.59	1.60
		2030	1.97	1.97	1.97	1.98
2	Present Capacity--Normal Life	1990	0.85	0.90	0.86	0.92
		2010	0.87	0.88	0.87	0.89
		2030	0.99	0.99	0.99	1.00
3	250 GWe System by Year 2000 and Normal Life	1990	0.61	0.67	0.63	0.69
		2010	0.65	0.67	0.66	0.68
		2030	0.68	0.68	0.68	0.68
4	250 GWe System by Year 2000 and Steady State	2000	0.66	0.70	0.67	0.71
		2020	0.67	0.68	0.68	0.69
5	500 GWe system by Year 2040	2000	0.64	0.68	0.65	0.69
		2020	0.66	0.67	0.66	0.67

TABLE A.9.3c. Repository Media Effect on Total-System Waste Management Unit Cost with the Once-Through Cycle Using a 10% Discount Rate

Case	Nuclear Power Growth Assumption	Startup Date	mills/kWh Salt Repository	Granite Repository	Shale Repository	Basalt Repository
1	Present Inventory Only	1990	1.32	1.33	1.32	1.35
		2010	1.22	1.22	1.22	1.22
		2030	1.42	1.42	1.42	1.42
2	Present Capacity--Normal Life	1990	0.79	0.82	0.79	0.83
		2010	0.77	0.77	0.77	0.77
		2030	0.85	0.85	0.85	0.85
3	250 GWe System by Year 2000 and Normal Life	1990	0.59	0.63	0.60	0.65
		2010	0.58	0.59	0.58	0.59
		2030	0.61	0.61	0.61	0.61
4	250 GWe System by Year 2000 and Steady State	2000	0.61	0.63	0.61	0.63
		2020	0.60	0.61	0.61	0.61
5	500 GWe System by Year 2040	2000	0.60	0.62	0.60	0.62
		2020	0.59	0.60	0.60	0.60

TABLE A.9.4a. Repository Media Effect on Total-System Waste Management Unit Costs[a] with the Reprocessing Cycle Using a 0% Discount Rate

				mills/kWh			
Case	Nuclear Power Growth Assumption	Reprocessing Startup	Repository Startup	Salt Repository	Granite Repository	Shale Repository	Basalt Repository
1	Present Inventory Only	NA[b]	NA	NA	NA	NA	NA
2	Present Capacity--Normal Life	NA	NA	NA	NA	NA	NA
3	250 GWe System by Year 2000 and Normal Life	1990	1990	1.06	1.34	1.51	1.54
		1990	2010	1.04	1.21	1.21	1.26
		2010	2010	1.39	1.53	1.55	1.61
		1990	2030	1.10	1.20	1.16	1.22
		2010	2030	1.49	1.58	1.54	1.61
4	250 GWe System by Year 2000 and Steady State	2000	2000	1.14	1.36	1.38	1.42
		2000	2020	1.17	1.31	1.30	1.36
5	500 GWe System by Year 2040	2000	2000	1.08	1.31	1.35	1.38
		2000	2020	1.09	1.24	1.23	1.29

(a) Includes spent fuel handling and storage.
(b) NA = not applicable.

TABLE A.9.4b. Repository Media Effect on Total-System Waste Management Unit Costs[a] with the Reprocessing Cycle Using a 7% Discount Rate

Case	Nuclear Power Growth Assumption	Reprocessing Startup	Repository Startup	mills/kWh			
				Salt Repository	Granite Repository	Shale Repository	Basalt Repository
1	Present Inventory Only	NA[b]	NA	NA	NA	NA	NA
2	Present Capacity--Normal Life	NA	NA	NA	NA	NA	NA
3	250 GWe System by Year 2000 and Normal Life	1990	1990	0.76	0.86	0.89	0.91
		1990	2010	0.68	0.70	0.70	0.71
		2010	2010	0.68	0.69	0.69	0.70
		1990	2030	0.70	0.70	0.70	0.70
		2010	2030	0.71	0.72	0.72	0.72
4	250 GWe System by Year 2000 and Steady State	2000	2000	0.73	0.78	0.78	0.79
		2000	2020	0.73	0.74	0.74	0.74
5	500 GWe System by Year 2040	2000	2000	0.72	0.77	0.77	0.79
		2000	2020	0.71	0.72	0.73	0.73

(a) Includes spent fuel handling and storage.
(b) NA = not applicable.

TABLE A.9.4c. Repository Media Effect on Total-System Waste Management Unit Costs[a] with the Reprocessing Cycle Using a 10% Discount Rate

Case	Nuclear Power Growth Assumption	Reprocessing Startup	Repository Startup	mills/kWh			
				Salt Repository	Granite Repository	Shale Repository	Basalt Repository
1	Present Inventory Only	NA[b]	NA	NA	NA	NA	NA
2	Present Capacity--Normal Life	NA	NA	NA	NA	NA	NA
3	250 GWe System by Year 2000 and Normal Life	1990	1990	0.68	0.74	0.76	0.77
		1990	2010	0.60	0.61	0.61	0.62
		2010	2010	0.59	0.59	0.59	0.60
		1990	2030	0.63	0.63	0.63	0.63
		2010	2030	0.62	0.62	0.62	0.62
4	250 GWe System by Year 2000 and Steady State	2000	2000	0.63	0.66	0.66	0.66
		2000	2020	0.63	0.64	0.64	0.64
5	500 GWe System by Year 2040	2000	2000	0.63	0.65	0.65	0.66
		2000	2020	0.62	0.63	0.63	0.63

(a) Includes spent fuel handling and storage.
(b) NA = not applicable.

TABLE A.9.5. Estimated Research and Development Costs for Predisposal Management for a 1990 Repository Start, $ Millions[(a)]

	Spent Fuel Storage	Waste Treatment and Packaging	Waste Transport	Total
1980 Cumulative	35	105	5	145
81	20	30	1	51
82	20	30	2	52
83	20	30	3	53
84		30	3	33
85		30	3	33
86		30	3	33
87		30	2	32
88		30	2	32
89		30	2	32
90		30	2	32
91		25	2	27
92		20	2	22
93		15	1.5	16.5
94		10	1	11
95		5	0.5	5.5
	95	480	35	610

(a) For later repository start up assumptions the predisposal R & D costs are extended for longer periods as shown in Table A.9.6.

TABLE A.9.6. Estimated Research and Development Cost (including site verification) for Waste Isolation

	1990 Disposal Start			2000 Disposal Start			2010 Disposal Start			2020 Disposal Start	2030 Disposal Start
Cumulative	Predisposal	Disposal[a]	Total	Predisposal	Disposal[b]	Total	Predisposal	Disposal[c]	Total		
1980	145	437	582	145	437	582	145	437	582	582	582
1981	51	161	212	51	158	189	51	138	189	190	190
1982	52	241	293	52	184	236	52	184	236	190	190
1983	53	257	310	53	243	296	53	201	254	190	190
1984	33	251	284	33	239	272	33	198	231	190	190
1985	33	232	265	33	212	245	33	187	220	190	190
1986	33	212	245	33	177	210	33	152	185	190	190
1987	32	123	155	32	72	104	32	59	91	190	190
1988	32	139	171	32	70	102	32	50	82	190	190
1989	32	138	170	32	78	110	32	46	78	190	190
1990	32	130	162	32	97	129	32	51	83	190	190
1991	27	59	86	32	105	137	32	50	82	190	190
1992	22	65	87	32	103	135	32	43	75	190	190
1993	17	91	108	32	102	134	32	48	80	190	190
1994	11	91	102	32	97	129	32	48	80	190	190
1995	6	78	84	32	105	137	32	48	80	190	190
1996		41	41	27	105	132	32	48	80	190	190
1997		41	41	22	97	119	32	43	75	190	190
1998		53	53	17	77	94	32	51	83	190	190
1999		52	52	11	90	101	32	58	90	190	190
2000		39	39	6	82	88	32	58	90	190	190
2001					43	43	27	63	90	130	190
2002					45	45	22	63	85	130	190
2003					45	45	17	86	103	130	190
2004					53	53	11	98	109	130	190
2005					52	52	6	97	103	130	190
2006					39	39		92	92	130	190
2007								82	82	130	190
2008								96	96	130	190
2009								106	106	130	190
2010								92	92	130	190
2011								60	60	130	130
2012								66	66	130	130
2013								92	92	130	130
2014								90	90	130	130
2015								91	91	130	130
2016								41	41	130	130
2017								41	41	130	130
2018								53	53	130	130
2019								52	52	130	130
2020								39	39	130	130
2021										65	130
2022										65	130
2023										65	130
2024										65	130
2025										65	130
2026										65	130
2027										65	130
2028										65	130
2029										65	130
2030										65	130
2031											65
2032											65
2033											65
2034											65
2035											65
2036											65
2037											65
2038											65
2039											65
2040											65
TOTALS	611	2931	3542	771	3187	3958	931	3698	4629	7632	9532

(a) Includes $6.5 million/yr through 1993 for alternative disposal technologies.
(b) Includes $6.5 million/yr through 2003 for alternative disposal technologies.
(c) Includes $6.5 million/yr through 2013 for alternative disposal technologies.

A.10 SYSTEM REPOSITORY REQUIREMENTS

Tables A.10.1 and A.10.2 provide a complete listing of the calculated number of repositories required for each of system simulation cases for the once-through and reprocessing cycles, respectively.

TABLE A.10.1. Repository Requirements for Once-Through Cycle

Case	Nuclear Power Growth Assumption	Startup Date	Number of Repositories Salt Repository	 Granite Repository	 Shale Repository	 Basalt Repository
1	Present Inventory Only	1990	0.1	0.05	0.1	0.05
		2010	0.1	0.04	0.1	0.04
		2030	0.1	0.03	0.1	0.03
2	Present Capacity--Normal Life	1990	0.7	0.3	0.5	0.3
		2010	0.7	0.2	0.5	0.2
		2030	0.7	0.2	0.4	0.2
3	250 GWe System by Year 2000 and Normal Life	1990	3.5	1.5	2.6	1.5
		2010	3.6	1.3	2.4	1.3
		2030	3.5	1.0	2.1	1.0
4	250 GWe System by Year 2000 and Steady State	2000	4.7	1.9	3.4	1.9
		2020	4.8	1.6	3.0	1.6
5	500 GWe System by Year 2040	2000	6.3	2.6	4.6	2.6
		2020	6.5	2.1	4.1	2.1

TABLE A.10.2. Repository Requirements for Recycle Cases

				Number of Repositories			
Case	Nuclear Power Growth Assumption	Reprocessing Startup	Repository Startup	Salt Repository	Granite Repository	Shale Repository	Basalt Repository
1	Present Inventory Only	NA[a]	NA	NA	NA	NA	NA
2	Present Capacity--Normal Life	NA	NA	NA	NA	NA	NA
3	250 GWe System by Year 2000 and Normal Life	1990	1990	3.1	2.9	5.4	3.1
		1990	2010	2.8	2.4	4.7	2.6
		2010	2010	2.3	2.1	4.0	2.2
		1990	2030	2.3	2.0	3.9	2.2
		2010	2030	2.1	1.9	3.7	2.1
4	250 GWe System by Year 2000 and Steady State	2000	2000	3.6	3.3	6.3	3.5
		2000	2020	3.3	2.9	5.7	3.2
5	500 GWe System by Year 2040	2000	2000	5.0	4.6	8.7	4.9
		2000	2020	4.6	4.1	8.0	4.5

(a) Not Applicable.

APPENDIX B

GEOLOGIC DISPOSAL SUPPLEMENTARY INFORMATION

Factors relevant to selection of a geologic repository include the depth of the repository; the size and properties of waste form and host rock; seismic, tectonic and magnetic characteristics of the proposed repository; the hydrologic system and material resources near the repository; and the use of multiple geologic barriers. These factors will be considered in a three-stage site selection process.

B.1 DEPTH OF REPOSITORY

The optimum depth of the waste emplacement zone is a function of the geologic media and is thus site specific. A depth of 600 m is frequently cited because it is proposed depth for a test facility in salt in New Mexico (Claiborne and Gera 1974). A 1000 m depth has frequently been mentioned in the literature. The repository must be deep enough to rule out any significant effects from disruption by surface phenomena and to provide as long a pathway to man's environment as possible. Because of the variety of geologic media and settings in the United States, it should be possible to find a number of sites having appropriate host rock at suitable depths.

Because destructive natural surficial processes (for example, erosion, climate and weathering) may reduce the depth to the repository, the host rock should be deep enough to separate the repository from these processes and thus maintain geologic isolation. Baseline data to evaluate these factors can be obtained from historic and geologic evidence. Climatic conditions and associated erosional and weathering processes have an influence to variable depths, depending upon local conditions.

Climate and rock properties provide the conditions for erosion and weathering. The energy for transport of earth materials is provided by running water, moving ice, wind, and gravity. Records of present and paleoclimatic conditions must be evaluated to predict future climatic variations and to estimate possible depths of erosion. Typical climatic and related factors to be evaluated at a repository site include:

- daily and seasonal atmospheric conditions
- latitude and longitude
- altitude
- position with respect to ocean and/or global wind circulation patterns.

These four parameters are basic data required to establish the types of weathering forces and erosion that will act to reduce depth. For example, a high-latitude site and a possible past history of glaciation at these latitudes indicate a potential for glacial erosion.

The repository site can be characterized by its topography (land-surface configuration), unconsolidated surficial materials (soil), and underlying rock. Earth materials surrounding the repository are the prime barriers to movement of radioactive waste to the biosphere. These earth material properties must be known in order to determine rates of erosion. The properties of these materials that relate to erosional processes are the strength, hardness, chemical composition, consistency, uniformity, and homogeneity.

Topography (land-surface configuration) has an economic impact because of its influence on ease of access for materials and transportation, the amount of surface modification required for construction of facilities such as buildings and railroads, and any unique problems such as landslide potential or flash flooding. In addition, steep terrain frequently indicates tectonic instability. In general, a relatively flat and open area with low relief is considered desirable.

Weathering is the chemical and physical decomposition and/or transport of surface and near-surface earth materials by surface erosional processes. It can decompose earth materials into smaller components that are more easily carried and deposited by other erosional processes. The weathering process can break down earth materials as deep as several hundred feet. In addition to climatic forces, the rate of weathering depends also on the resistance of earth materials to chemical deterioration and physical pressures. The major chemical and physical weathering processes are freezing and thawing, hydration, hydrolysis, oxidation, carbonation, dissolution, and expansion caused by unloading, crystal growth, thermal difference, and organic activity. All of these may remove material and thus decrease the depth to the isolated waste.

Water (stream) erosion processes are a function of a base level (Office of Waste Isolation 1977). Base level is a surface below which moving water cannot erode. The ultimate base level for stream erosion is generally considered to be sea level. Base level can change, however, over geologic time; for example, large fluctuations of sea level can occur during glacial periods. The mechanisms of a stream erosion are acquisition of weathered earth materials, abrasion of material through particle impact, transit abrasion of materials, and transport by the traction, suspension, or solution of weathered rock debris.

Erosional processes unaffected by a base level are those related to ice, wind, and gravity. These processes are important because of their potential for eroding below base level.

Erosion by ice is caused by glaciation, and the continental type has the greatest potential impact on depth of isolation (Office of Waste Isolation 1977). Glaciers are a dynamic mass of recrystallized snow and ice, and the character and longevity of a glacier depend on climatic factors. Glacial action alters the land surface and could reduce the depth of a repository by 1) plowing or scraping earth materials from a site, 2) abrasion of intact rock, and 3) assimilation of plowed and abraded material into the ice mass (Verhoogen et al. 1970). The depth to the repository may be effectively reduced if fracturing or faulting results from the loading and unloading of the ice on the land surface. Parameters affecting glacial erosion are ice temperature and thickness, earth material and structure, and topography. The depth below base level at which glaciers may erode can be substantial. The lower depth of glacial erosion at a repository site can be predicted to some extent from the glacial history.

Erosion by wind energy is a mechanical process. It requires the environmental conditions of no vegetation and uncemented dry earth materials (Verhoogen et al. 1970). These conditions are most prevalent in desert environments. Depth of possible wind erosion is controlled by wind velocity, duration, and other climatic conditions (Office of Waste Isolation 1977).

Mass-wasting, or gravitational erosion, is the movement of earth materials by gravity independent of water, glacier, or wind. The significance of mass-wasting is that it affects the whole body of the earth material and is not confined to a land environment. Mass-wasting occurs when the force of gravity on a mass of earth material exceeds the cohesive strength between the individual earth particles. Environmental components important to the mass-wasting process are weathering, geomorphology (topography), processes of stream, glacial, and wind erosion and sometimes earthquakes (Claiborne and Gera 1974).

Surface geologic processes cause the transport of earth materials to sites of deposition. Rates of deposition may be as imperceptibly slow as rates of erosion. However, they also may be significant over hundreds of thousands of years. Agents of deposition that should be evaluated for candidate repository site regions include runoff and streams, wind, glacial processes, and volcanism. A surface environment conducive to long-term deposition is somewhat favorable to repository containment because as the depth of sedimentary cover continually and gradually increases, so would the depth of burial.

B.2 DIMENSIONS AND PROPERTIES OF HOST ROCKS AND MEDIA

The host rock must have the properties and dimensions to assure geologic isolation (Office of Waste Isolation 1977). One method for defining the required dimensions of a repository medium is use of an "equilibrium release fringe concept." The concept assumes that the repository system contains the waste within a known or definable zone for the necessary time period. After a period of time, the competing factors of radioactive decay and chemical migration processes will produce an equilibrium zone or fringe that will not move or will move so slowly as to be insignificant. Using these definitions, a three-dimensional zone consisting of host rock material, repository and waste, is defined on the basis of host rock and waste package properties beyond which no waste or activity beyond a specified range is expected to migrate for the necessary time period. The specified range lies between the values for radioisotope concentration at the maximum natural concentration found in the world and the average U.S. natural background concentration. This condition is defined as an equilibrium condition, i.e., any material or activity released beyond the fringe or boundaries of the zone would be within the range of that which occurs naturally.

The size of the zone of effect will probably change throughout the repository's history. After sealing, the zone will be very nearly the size of the repository and the fringe will be located by radiation effects. At a later time in the repository's history, when the canisters and overpack material may have lost their integrity as barriers, the waste will be partially in contact with the host rock. The waste may then move slowly into the host rock by diffusion, concentration gradients or whatever forces are present to move it. The fringe bounding the zone of effects will expand as the zone slowly moves out from the repository. The size of the zone of effect and the location of the equilibrium fringe will depend on the host rock properties, the form of the waste, the activity and thermal state of the waste at the time the canisters became ineffective as containment, and other factors such as presence of water.

The location of the equilibrium release fringe is difficult to predict, particularly over time periods greater than several thousand years. Simulation by modeling may furnish some estimates if the necessary input data are available. The modeling would proceed under the assumption that no intrusions or disruptions occurred.

The required dimensions of the host rock relate closely to the radius of equilibrium release and are established as a function of the medium's properties and of engineering design of the repository. Important media properties that affect the radius of equilibrium release can be classified as thermal, chemical, and hydrologic.

The host rock dimensions must be large enough with respect to the repository dimensions to adequately disperse or contain all of the perturbations and loads induced by the repository. These dimensions will depend directly on site-specific geologic properties of the host rock. The host rock must also be of sufficient thickness to ensure that excavation and construction can proceed on several depth levels and over many acres of lateral extent. Adequate thickness of the zone adds assurance that the specific medium is of sufficient mass and extent to contain the waste and buffer the repository from materials with different properties. The emplacement medium should be homogeneous and uniform in properties and composition, and the medium should extend some distance from the repository so that the response to the waste will be similar and more predictable. The concept of equilibrium-release radius can be used to derive the required host rock dimensions as discussed above. This is a consideration for modeling specific sites in the last stage of site selection.

Several engineered barriers will be built into repository design; however, they will probably have negligible permanence compared to the lifetime of the repository. The primary geologic barrier to waste migration will be the repository host rock itself. The effectiveness of the barrier will depend on the responses of the host rock to long-term effects of heating and irradiation. Rock response over the full range of expected repository conditions is not adequately understood; however, uncertainties can be overcome by more conservative design for waste emplacement.

Preliminary thermal loading analyses indicate that tensile forces will be induced near the outer margins of the repository (Office of Waste Isolation 1978f). Thus thermal expansion could create potential pathways for waste migration by fracturing or by opening pre-existing fractures. For salt strata this is not the problem; salt is expected to deform plastically and heal internal fractures. However, if the surrounding strata were breached by fracturing, salt could be vulnerable to rapid solution by ground water. Therefore, thermally induced permeability appears to be an important consideration for all host rock media.

Dip, inclination, or attitude of the units in the rock column or section is considered both from a construction standpoint and as indicators of past geologic stability. Flat or nearly horizontal units will probably be easier to tunnel through, mine and support if needed. Steeply dipping or inclined units, in general, indicate past deformation or movement and would likely be avoided if other areas can be found. Any geologic section with units of different inclinations or dip within the rock column may indicate the presence of erosion or weathering surfaces that might be selectively weak or permeable. Low and fairly uniform inclination or dips are probably most desirable.

Joints, fractures and faults are generally not favorable from a geologic site-selection point of view. They represent zones of weakness, movement, possible conduits for fluids and regions of anomalous properties compared to the general rock mass. They also increase the time and cost of investigations and complicate the modeling necessary for design. The presence of these features does not necessarily exclude a site; joints and fractures may be closed or sealed by mineral deposition and would not act as conduits and may be barriers to flow, and some faults can be shown to have had no movement for millions of years. However, in selecting general site areas risks and benefits of areas exhibiting these features need to be carefully considered.

A comparative survey of rock properties is included in Table B.2.1. Rock behavior and strength properties strongly affect design and underground construction. These aspects are discussed in following sections of this report.

TABLE B.2.1. Physical Properties of Media

Type of Properties	Parameter[(a)]	Salt	Granite	Shale	Basalt
Index	Unit weight, lb/ft^3 (density)	130 to 152	144 to 190	117 to 188	180
	Natural moisture content, %	0 to 1.1	0 to 0.32	0 to 38	nil
Stress-Strain	Young's modulus, $lb/in.^2$	0.09×10^6 to 7.25×10^6	2.3×10^6 to 12.1×10^6	2×10^3 to 26.4×10^6	1.8×10^6
	Poisson's ratio	0.22 x to 0.50	0.045 to 0.39	0.03 to 0.50	0.26
Strength	Cohesion (1,500 to 3,500 psi ranges), lb/in.	900 to 1,700	--	0 to 4,250	--
	Friction angle,	20 to 36	--	4.2 to 56	--
	Uniaxial compressive strength, $lb/in.^2$	2,300 to 7,250	5,100 to 51,200	70 to 37,000	18,000 to 40,000
	Tensile strength, $lb/in.^2$	120 to 458	500 to 8,100	0 to 1,540	1,800 to 3,500
Thermal	Coefficient of linear thermal expansion, F-1	2.1×10^{-5}	3.0×10^{-6} 6.0×10^{-6}	4×10^{-6}	3.0×10^{-6}
	Heat capacity, Btu/lb- F	0.19 to 47.00	0.16 to 0.33	0.20	0.17 to 0.23
	Thermal conductivity, Btu/hr-ft- F	at 32 F-3.5 at 752 F-1.2	at 32 F-1.65 at 752 F-1.24	at 32 F-1.1 at 752 F-0.8	at 32 F-0.65 at 752 F-0.85
Hydrologic	Permeability, ft/yr	1.7×10^{-15} to 1×10^{-2}	Very low if no joints or fractures	horizontal 10 to 10 vertical 1/2 to 1/10 times horizontal	Very low if unfractured and not jointed
	Porosity, %	1.4 to 10.0	0.5	0 to 45	0.6

(a) In English units.

Rocks are named and described according to their texture and mineralogy. However, their overall behavior may depend on details of petrography such as mineral composition, rock fabric, fluid inclusions, exotic mineral accumulations in joints and fractures, and trace element chemistry.

Petrography is important in determining the suitability of the host rock. These data will be collected and evaluated for specific sites during the site selection process. The basic properties of rock fabric and composition are discussed in Section 5.1.

Many chemical interactions are possible among mineral and fluid phases of the host rock, ground water, metal canisters, backfill material, and waste. The range of possible chemical interactions is described in Section 5.1. However, additional study of geochemical aspects is warranted.

Thermal properties of high diffusivity and conductivity and low thermal expansion are normally considered to be desirable. These properties result in maintaining lower waste temperatures and minimizing mechanical deformation (expansion). Design of a repository should restrict thermal loading so that excessive thermal expansion does not fracture the host rock and thereby increase permeability.

Chemical properties of different host rocks vary greatly, and the range of possible chemical reactions both before and after the containers may be breached may be significant. Favorable reactions between waste and the host rock include formation of insoluble radioactive compounds, formation of compounds containing water (thus reducing the quantity of free water), and sorption of radionuclides by the host rock. However, if corrosive fluids are produced by heating of the host rock, they may attack the canisters and result in early loss of this barrier. Chemical reactions between waste and host rock that form highly soluble or low melting-point compounds would be unfavorable. Chemical reactions can affect chemical transport by changing the composition and quantity of fluids and by changing the ionic strength of these fluids. Chemical reactions can produce liquids and gases under high pressure, and can change pH, Eh, viscosity, or density. Such factors can affect rock strength and rate of physical or chemical decomposition of the host rock.

Permeability is an important hydrologic property of the host rock and must be known to determine the rate of migration of radionuclides toward the biosphere. Very low permeability implies a relatively small radius of equilibrium release if other considerations are also favorable.

Properties of the medium also affect repository capacity and waste placement geometry. For example, low thermal conductivity of the host rock would require lower waste loading or greater spacing between canisters to maintain acceptable repository temperatures.

The total system of waste form, repository, surrounding geologic environment, and effects of waste disposal must be considered to identify any possible site-specific determinants of the radius of equilibrium release. If possible, the host rock dimensions should encompass the radius of equilibrium release. However, the radius may extend beyond the host rock and isolation of waste will be achieved by additional barriers in accordance with the multibarrier concept.

B.3 SEISMIC, TECTONIC AND MAGNETIC CONSIDERATIONS

The tectonic stability of the repository site must be sufficient to assure geologic isolation (Office of Waste Isolation 1977). Tectonics refers to the deformation of the lithosphere (the solid, near-earth-surface materials) caused by large-scale and local dynamic earth processes.

Tectonics, seismicity and volcanism relate to the stability of an area and reflect the past geological activity. Active or capable faults, a history of earthquakes and volcanism should not condemn an area if investigation can show that the activity was in the remote past (million to hundreds of million years ago) and has not occurred since. For preliminary selection of areas, crustal plate boundaries, areas of known active faults, and zones of recent earthquake and volcanic activity would be avoided.

Deformation of the lithosphere (tectonism) and the upward intrusion (or extrusion) of molten rock (magma) are important in site selection. Deformation of the crust may consist of folding, faulting, uplift, depression or diapirism. (A diapir is a fold in which the mobile core is injected into the overlying materials.) These processes, even though they may not directly disturb a repository site by fault displacement or venting of volcanic material, can significantly affect the regional hydrology over a hundred thousand years or more by altering the topography and the subsurface fluid flow. In this respect, magmatism and tectonism rank with climatic change as important factors in determining the evolution of the hydrologic environment. In selecting a site, optimal conditions of tectonic stability should be realized so that magmatism and tectonism will not adversely affect the hydrologic conditions at the site. To determine that only the site itself would not be directly disrupted by faulting or volcanism is not sufficient; the general region must be considered. In general, the tectonic constraints on site selection will generally be more difficult to satisfy for sites in the western U.S. than for sites east of the Rocky Mountains.

The theory of plate tectonics on a continental scale is believed appropriate for identifying areas of optimum tectonic stability in order to assess the constraints on site selection imposed by volcanic activity, tectonism, and seismicity. The plate tectonics theory explains in general the present global distribution of lithospheric deformation, magmatic activity and seismic activity, and also the geologic record of lithospheric deformation and magmatism over at least the past several hundred million years. Because volcanism has in general occurred in regions of crustal plate boundaries, some aspects of the evolution of the lithosphere during the next million years can be forecast quantitatively from plate tectonics; for example, it is possible to forecast, within a factor of about two, an increase of 50 km in the horizontal displacement across the San Andreas fault system in California. However, many important aspects of the evolution of the lithosphere can be forecast only in qualitative terms, if at all; for example, the effects of tectonism on the physiography of the Rio Grande Rift in New Mexico are difficult, if not impossible to forecast.

Through isotopic ratio dating, particularly for for pre-Paleozoic rocks (older than 600 million years), former zones of crustal activity or mobility have been defined. Knowledge of these zones has proved particularly useful in studies of the early history of the North American continent. The question of renewed or future activity at these zones is debatable. Some of the former mobile zones have stabilized to form areas like the Canadian Shield (Dott and Batten 1971), and their relationship, if any, to present crustal plate boundaries is not clear. The plate tectonic theory was formulated a decade ago as basically a kinetic theory, and is now in the early stages of development into a full physical and chemical theory, incorporating geologic knowledge acquired over the past centuries. The driving mechanisms for plate tectonics are not presently understood.

The geologic stability, over the past 100 million years or more, of the major part of the U.S. east of the Rocky Mountains is readily explained in the framework of the plate tectonic theory. In this region the lithosphere has behaved essentially as a rigid plate, undergoing rigid-body rotation away from the Mid-Atlantic Ridge. The broad features of the present-day tectonics of the western U.S. arose, after episodes of continental accretion associated with consumption of oceanic lithosphere along the western margin of the continent, when the North American plate overrode an oceanic rise system, the remnants of which (the Juan de Fuca Ridge, the Gorda Ridge, and the ridge system in the Gulf of California) continue to create new oceanic lithosphere. Remaining to be explained is the relation between these events and the incipient continental rifting represented by the Snake River and Yellowstone volcanism and the Rio Grande Rift.

Consideration of the optimal region or regions of tectonic stability for siting purposes proceeds from the continental scale to regional and local scales, to ensure that sites are viewed in their proper context. Simple projection into the future from local geologic history alone is not a satisfactory basis for repository site selection. On the regional and local scales, site selection will necessarily involve uncertain projections from the geologic record. These projections will tend to be more tenuous in the more tectonically active regions. At the same time, in the less active regions the tectonic regime may be more difficult to ascertain because of fewer opportunities for the study of seismotectonics (the inference of the geometry of tectonic stress and faulting from earthquake mechanism determinations). In the span of a hundred thousand years or more, significant aseismic deformation may occur. Even in the relatively stable eastern U.S., local vertical surface velocities of a millimeter or more per year are ubiquitous. Motions of this magnitude, persisting over a period of hundreds of thousands or millions of years as in the case of the uplift of the Adirondacks, could result in erosion of hundreds of meters of overburden. It is uncertain whether such movements could present a serious problem for waste isolation even if they were not anticipated.

Tectonic activity varies in intensity throughout different regions of the North American continent. Most of the intense tectonic activity and virtually all the volcanic activity of the North American continent occur along the crustal plate boundaries. A repository site will be located in a relatively stable tectonic region. In general, the underground parts of the repository are not expected to be damaged by vibratory earth motion, although the surface structures and access shafts are likely to be more vulnerable.

Isolation of a repository could be disrupted by tectonic activity and cause faulting, which may alter the hydrologic regime, or elevation and subsequent exposure through erosional processes. The tectonic stability of a host rock can be evaluated by investigating and delineating these tectonic processes of deformation and the rates of deformation. The processes and factors of the tectonic stability can be determined from the tectonic history and significant geologic structural features.

The occurrence of strong ground shaking at a repository site from local or regional earthquakes is not expected to have serious effects on the repository at depth (Dowding 1978), although some operational components of a waste isolation facility may be disrupted. The primary effect of earthquake occurrence is faulting, an important mode of tectonic deformation. Faulting may or may not be evident at the ground surface.

B.4 HYDROLOGIC CONSIDERATIONS

The hydrologic regime (the surface water and ground-water systems) at the repository site must be favorable to geologic isolation (Office of Waste Isolation 1977).

Surface hydrology includes the distribution and occurrence of water at the surface of the area. Large rivers and lakes represent collection areas for surface water from surrounding regions and may be areas where underground water is moving to the surface. Such areas will probably be avoided because of the risks of flooding and entrance of water into the repository workings.

Ground water is an important consideration in geologic site selection for two main reasons:

1. It is a valuable and widely used resource and a repository should not be located where it will affect the quality or availability to an unacceptable level.
2. Ground water is generally considered to be the most likely agent for transporting radioactivity away from the repository during its expected lifetime.

Ground water is present in varying degrees of saturation in nearly all subsurface earth materials. Also, all rock units have some permeability (although it may be small in some cases), and have hydraulic conductivity varying from relatively high to very low. Ground water can dissolve and transport radionuclides. Waste isolation requires that the properties of the host rock minimize transport of the waste and that the host rock be isolated from more permeable media. The ability of a disposal media to isolate radionuclides within a hydrologic regime is determined from the factors that govern hydrologic transport via the local and regional flow patterns.

The local flow regime of a repository site can be characterized by the geohydrologic properties of the host rock and of the hydraulic gradients (inducement to flow). Evaluation of the isolation potential of these components requires geologic studies, hydrologic testing, and analysis of water characteristics (de Marsily et al. 1977; ERDA 1976).

The geohydrologic character of the repository medium is concerned with intergranular fluid properties (Walton 1970). A rock substance is composed of minerals compacted and cemented or crystallized together into a matrix. Spaces between grains and cementation material (called pore space) can contain fluid. The percent of pore space in the total matrix is the porosity. The volume of fluid a repository medium can contain is described in terms of percent water saturation and porosity (secondary rock discontinuities also contribute to its fluid volume capacity). Pore space is an important property in determining: 1) the ability of a fluid to flow through a medium, 2) the volume of fluid flow and 3) the rate of flow. The evaluation of porosity for the repository medium includes the in-situ condition and the effect of radioactive waste-induced alteration, e.g., precipitation and/or solution. Porosity alone does not determine the permeability of a medium. For example, a shale has high porosity because of the clay size particles but is essentially impermeable because the pores are not interconnected or are so small that capillary forces dominate.

The flow potential of a repository medium depends on the interconnection of pore space (permeability) and the pressure differential. Geologic materials may be grouped in order of flow potential into aquifers and aquitards (confining units). The definition and delineation of these units require knowledge of the geologic stratigraphy and matrix and rock mass hydrologic properties of the medium. Conventional subsurface geologic techniques are used to define the lithologic and horizontal and vertical distribution of a flow unit. Fluid chemistry and core analysis of porosity and permeability allow the estimation of volume of fluid available for flow within a unit and of the hydrologic characteristics of the repository medium. Hydrologic field testing of the individual flow units completes the delineation of these units.

A flow unit may contain a large volume of fluid and a high permeability but require an inducement to flow (Davis and DeWiest 1966). A difference in hydraulic head (gradient) is necessary before a fluid will flow through a porous medium. A repository site contains local gradients, both vertical and horizontal, and a regional gradient for given flow potential units. A hydrologic gradient could exist because of elevation differences between the surface point where fluid enters the unit (recharge area) to the repository medium. Hydraulic gradient across the repository medium is generally determined by finding the difference in fluid level (potentiometric head) between wells of known depth.

The regional geohydrology is important to waste isolation in terms of conditions that may affect the local hydrologic regime. Possible effects include changes in hydraulic gradient from water usage or climatic changes.

Regional hydraulic parameters significant in maintaining isolation are recharge and discharge conditions. Recharge is of particular interest in establishing the volume of fluid available to an aquifer. Tectonic movements have the potential to significantly alter the hydraulic regime.

Hydrologic considerations enter into each stage of the site selection process. In the early stages the broad regional characteristics of surface and subsurface water flow are examined for compatibility with waste isolation. Regions may be eliminated from consideration on the basis of unfavorable characteristics, for example, high regional flow gradients, presence of aquifers near the proposed repository depth, or alteration of hydrologic regime from future climatic changes or tectonic events.

Other hydrologic characteristics may be of overriding importance to site selection. For example, interior drainage (surface runoff that does not drain to the ocean) is particularly well developed in the Great Basin of Nevada and Utah. The characteristics of such a hydrologic regime offer longer flow paths and greater travel times than does surface water flow to the migration of radionuclide wastes beyond the boundaries of the system. Other examples of favorable regional hydrologic conditions include arid climate and low hydraulic gradients (vertical and horizontal) in the surface and subsurface regimes.

Further consideration of hydrology involves more detailed characterization of the regional regimes that have passed the first phase. The collection of rock properties data and the field measurement of hydrologic parameters enumerated will be needed. These data will be input to hydrologic models of candidate areas for locating sites at which geologic barriers are particularly effective.

Detailed evaluation of individual sites will be required in order to predict the complicated interaction of a repository model and hydrologic regimes. An important field of research, for instance, is the prediction of thermal effects on rock permeability near a repository.

Site selection will probably avoid areas of known major aquifers. In areas other than those with major aquifers, a preliminary ground-water characterization would certainly be a factor to be considered in the early stages.

To characterize an area's ground-water supply and potential requires determination of such factors as depth to producing zone(s), yield (usually determined from pumping tests) and an estimate of the supply available. From available wells, porosity, permeability and change in water level caused by pumping are measured. These aquifer properties and how they change with distance are extrapolated over the area if other measurements are not available. Usually other existing wells supply information to help determine the configuration of the water table or artesian pressure surface, direction of flow and estimates of rates of movement. These methods are generally applied to areas and rock units that yield water in usable quantities, whether on a scale for cities or for a single dwelling (Walton 1970, Davis and DeWiest 1966). They are not as applicable and have not been applied as widely to areas where porosity, permeability and yield are very low--that is, where usable supply cannot be obtained.

The areas of very low ground-water supply or flow are more favorable candidate areas for waste repositories because of the smaller opportunity for moving water to contact the waste and possibly transport it. Flow properties will need to be determined because of the time periods associated with a repository. Flow rates and velocities of ground water that are insignificant over a 50-yr period may be significant over hundreds to thousands of years. Methods of evaluating free water and its movement in media of these areas are available (for example, laboratory determinations of porosity and permeability are made from field core samples) but zones of fracture or joint flow are difficult to evaluate and describe in laboratory tests. Field tests will be necessary to measure in-situ properties after a potential site is chosen.

When possible, future climatic changes (for example, a change to a much wetter climate) should be considered with the attendant possible effects such as change in ground-water levels on a repository.

It seems reasonable to assume as one possibility that free water, over thousands of years, may enter the repository even in shale and possibly salt. The effect of the water will depend on the condition and state of the waste at the time, and transport of radionuclides will depend on the rate of water movement, if any, through the repository and the physical-chemical properties of the repository medium.

B.5 NATURAL RESOURCE CONSIDERATIONS

Known occurrence of any natural resource will make an area less suitable for a repository. Construction of a repository will effectively remove the resource from use or limit access to it, and will need to be weighed against economic value, need and supply of the resource. Care will needed in estimating future need and predicting value of materials perhaps not considered to be resources today.

B.6 MULTIPLE GEOLOGIC BARRIERS

The multibarrier concept is a "defense-in-depth" or "multiple barrier" approach to offsetting the present lack of certainty or predictability in some factors of the waste disposal system. The basic purpose of the concept is to provide a series of independent barriers to radionuclide migration that taken together represent a compound or multiple barrier. The multibarrier concept includes basically two major elements: 1) the waste package, which consists of the waste in whatever form, any materials between the waste and its container, the container or canister and any overpack or material placed between the canister and the host rock; and 2) the material or naturally occurring barriers consisting of the geologic disposal medium, its dimensions, its properties, tectonic setting, properties of contiguous and surrounding rock materials and the disposal medium's position in the regional and local hydrologic systems.

Waste forms and canisters are discussed in Section 4.

The natural barriers consist first and most importantly of the repository host rock and its properties. The properties include its physical, chemical, thermal and hydrologic characteristics. The host rock with its properties provides the justification for geologic disposal and is the main element in containing the waste within the repository and in isolating the waste from man's environment over the long term. The disposal medium provides this isolation through the depth of burial within the medium below the land surface and by providing minimal or very low rate of movement pathways for transport.

For this Statement it is assumed that ground water is the most probable transporting agent over long time periods and the emphasis is thus on locating the repository in such a position and medium that it is as isolated as possible from ground water.

Four geologic media have been selected to illustrate the range of rock properties that need to be considered in a host rock for a radioactive waste repository. All four rock types possess properties that are favorable for waste isolation. These, as well as some unfavorable characteristics are discussed in the following pages.

B.6.1 Salt Deposit Properties

Salt (NaCl) deposits appropriate for disposal media occur in stratiform masses (bedded salts) and in salt domes. Salt deposits result from precipitation of halite (NaCl) by evaporation from seawater. Salt precipitation often alternates with the deposition of shale and carbonate minerals, resulting in salt deposits interbedded with other sedimentary rocks. Generally the degrees and mineralogical types of interbedding vary greatly. Salt domes are formed by the flow of bedded salts laterally to form masses which then move upward and deform and frequently penetrate overlying strata (diapirism). Salt flow is induced by the low specific gravity of salt plus variations in the lithostatic pressure and differential compaction of overlying sediments. Salt dome deposits are usually of higher purity, are more homogeneous and have fewer fluid inclusions than do bedded salts. Salt deposits applicable as disposal media are situated in distinct sedimentary basins throughout many of the contiguous 48 states, as illustrated in Figure B.6.2 (Office of Waste Isolation 1978b).

The existence of salt beds and formations that are known to be hundreds of millions of years old testifies to their isolation from water and their stability. Salt deposit strength properties are relatively fair to good in the undisturbed state. Salt is basically isotropic with minimal cohesive strength. The result is a highly plastic medium that tends to move (creep) under earth pressures, increasing with greater depth and temperature. Creep tends to seal discontinuities but is difficult to stabilize in tunnel openings. Although heat tends to reduce strength, high thermal conductivity of salt is conducive to heat dissipation. A salt deposit may contain moisture in interbed materials and in small cavities as brine inclusions. These brine inclusions have been shown to migrate or move toward a heat source (ERDA 1976). Salt moisture, if present, leads to increased heat effects and to the potential for strength loss from solution action. Undisturbed salt beds are essentially impermeable (Office of Waste Isolation 1978a,b).

Rock types associated with salt deposits include anhydrite ($CaSO_4$), limestone ($CaCO_3$), dolomite ($CaCO_3$ $MgCO_3$), and shale (SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O). Halite is highly soluble (Office of Waste Isolation 1978a). More information is needed about ion exchange rate, reaction to radioactivity, and potential chemical reactions with salt deposits, related rock types, and waste materials.

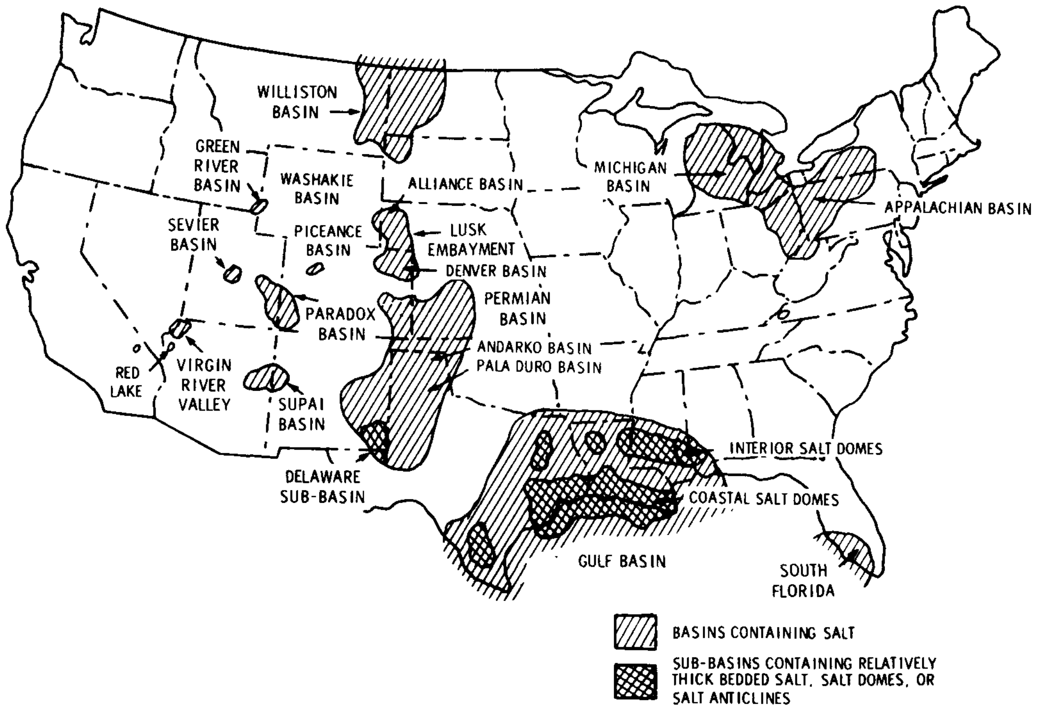

FIGURE B.6.1. Bedded Salt Deposits and Salt Domes in the United States (adapted from Office of Waste Isolation 1978a)

Salt deposit structures can be flat-lying, folded, or jointed. Jointing is generally parallel to bedding. Included within beds are large crystal masses, large rock masses of solidified impurities with lateral continuity, and lateral lithologic changes (Office of Waste Isolation 1978a). Joints can be anhydrite-filled, near vertical, unopen, moderately spaced, and generally extensive.

B.6.2 Granite Properties

Granite is an intrusive igneous rock with an equigranular, medium-to-coarse crystalline texture. It is generally light colored, composed principally of feldspar, quartz and, typically, hornblende and biotite. Granites are generally homogeneous in composition, with variations primarily in accessory minerals and secondary rock features. Granites are found as plutons, which are bodies of igneous rock that have formed beneath the earth's surface by consolidation from magma. Typical granite plutons include batholiths and smaller-scale stocks; they are very deeply rooted and enlarge with depth (Verhoogen et al. 1970, Holmes 1978).

Igneous rocks may have similar physical characteristics but range in chemical and mineralogical composition from granite to closely related rocks such as granodiorite. In many respects other closely related igneous rocks are similar to or identical to granite, but, because they vary significantly in major element, trace element and mineralogic composition, they are not considered to have the same disposal media properties as granite. The locations of potential repository granites within the contiguous 48 states are illustrated in Figure B.6.2. The areas identified represent large granite masses at or near the surface.

Granites are formed beneath the earth's surface. Their texture is a dense matrix of equigranular coarse grains. The porosity is low, with little or no natural moisture content. Intergranular permeability is extremely low. Also, strength is considered to be very high. Most component minerals are hard, resulting in high durability. Granites are generally very rigid, with little ability to deform under earth stress, but may exhibit fractures that could conduct water if they are open and water is available. Granites are basically resistant to temperature effects up to several hundred degrees Celsius. However, thermal expansion of particular minerals may be sufficient to cause fracture of the rock and possibly surface heave.

Granite is mostly composed of silica, alumina, and alkali elements, and forms minerals of quartz, feldspar, hornblende, and mica. Typical chemical composition of a granite is included in Ekren et al. (1974, Table 5.1.3). Mineral components of granite are almost inactive chemically under ambient temperature and pressure conditions. However, more data are needed about waste-granite reactions under repository conditions.

Granites have no bedding because of their intrusive igneous mode of formation, but may be layer-like. Joints tend to be blocky or sheet-like on a large scale, and their orientations may be vertical and intersect at right angles and/or horizontal and subparallel to the topographic surface. Joints, which range from sealed to partially opened and extensive often have little mineralization. Granite masses may contain dikes, veins and occasionally fragments of other rock material.

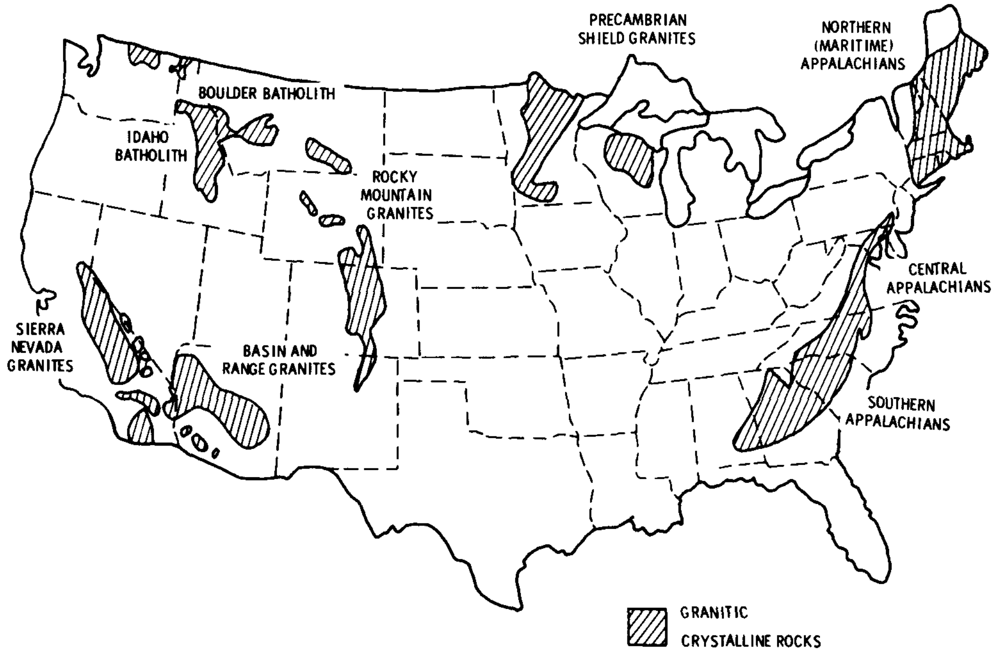

FIGURE B.6.2. Granitic Rock in the United States (adapted from Office of Waste Isolation 1978a)

B.6.3 Shale Properties

Shale is the product of the lithification or compaction and cementation of mud. Mud is predominantly composed of clay size particles (1/256 mm dia) and/or silt size particles (1/256 to 1/16 mm dia). The predominant constituents are clay minerals (hydrous aluminum silicates), and substantial amounts of mica, quartz, pyrite, and calcite (Table B.6.1) (Verhogen et al. 1970, Holmes 1978, Office of Waste Isolation 1978a). Mineral grains may either be poorly compacted in a soil-like manner or cemented like rock. Shales are in general stratified or laminated, and fissile, although some may show little layering and break into small angular blocks, as with mudstones. Shales are often interbedded with other sediments such as carbonates and sands. Shale units potentially applicable as disposal media are situated in sedimentary basins throughout many of the contiguous 48 states, as illustrated in Figure B.6.3 (Office of Waste Isolation 1978a).

Shales are relatively weak, partly because of the soft mineral components and weak cementation between grains. The general texture is fine-grained, and shale tends to split into flat, shell-like fragments in parallel bedding. The fine-grained clay minerals account for a very high natural moisture content and porosity. Because of fine pore size, intergranular permeability is low. Many shales have the ability to accommodate large deformations with a potential for plastic flow.

Clay minerals are known to have a high ion-exchange potential. Wetting and drying of shale will weaken the rock and may cause it to crumble. Shale may oxidize (as well as dry) when exposed to air, affecting both strength and volume characteristics. More data are

TABLE B.6.1. Average Chemical Composition by Oxides for Representative Disposal Media

Compound, % of Total	Rock Types Granite	Shale	Basalt
SiO_2	70.2	55.0	49.1
Al_2O_3	14.5	21.0	15.7
Fe_2O_3	1.6	5.0	5.4
FeO	1.8	1.5	6.4
CaO	1.9	1.6	9.0
Na_2O	3.4	0.8	3.1
K_2O	4.1	3.2	1.5
MgO	0.9	2.3	6.2
H_2O	0.8	8.1	1.6
X_yO	0.4	1.9	2.0

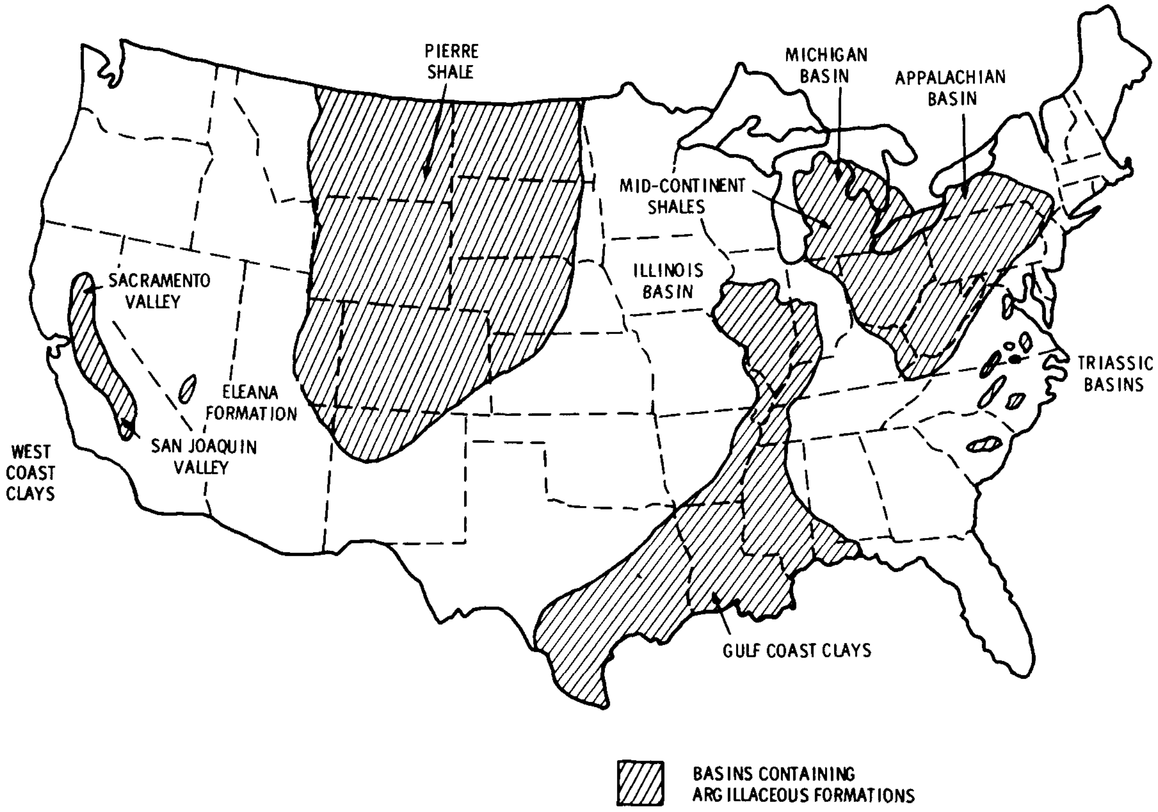

FIGURE B.6.3. Representative Shale Units in the United States (adapted from Office of Waste Isolation 1978a)

desirable regarding shale-waste reactions under repository conditions. Heating effects may be significant with shale as well as effects of temperature rise on contained water.

Shales may have discontinuities consisting of bedding, joints and fracture planes which are often filled with calcite, but also may be unfilled.

B.6.4 Basalt Properties

Terrestrial basalt flows are considered here to be applicable to conventional geologic disposal. Basalt is a black to medium gray, extrusive volcanic mafic rock (high in magnesium rock silicates) with the major mineral component calcic plagioclase (usually as phenocrysts) olivine and accessory minerals of magnetite, chlorite, sericite, and hematite (Office of Waste Isolation 1978e, Holmes 1978). The texture of a basalt may be either glassy or granular. Generally, basalt flows have a large areal extent. The locations of potential basalt repository areas are illustated in Figure B.6.4. The basalts of southeastern Idaho are not considered because of high permeability features such as the Lost River and known large open lava tubes.

Basalt is commonly a very dense, high-strength material. Consequently, porosity and permeability are favorably low, with negligible moisture content, although interflow sedimentary units may be more permeable. Basalts remain relatively strong under elevated temperatures but may exhibit expansion. An average chemical composition of basalt is included Table B.6.2. More data are needed about basalt-waste reactions under repository conditions.

Joints are generally platy or columnar. They may be filled with various secondary minerals, alteration or weathering products of basalt. Joints may be unopened or opened with wide spacing (∿0.3-1.8 m) and be smooth to rough. Joints in basalt may be extensive. They are generally unfavorable because of their potential for high permeability and ground water flow.

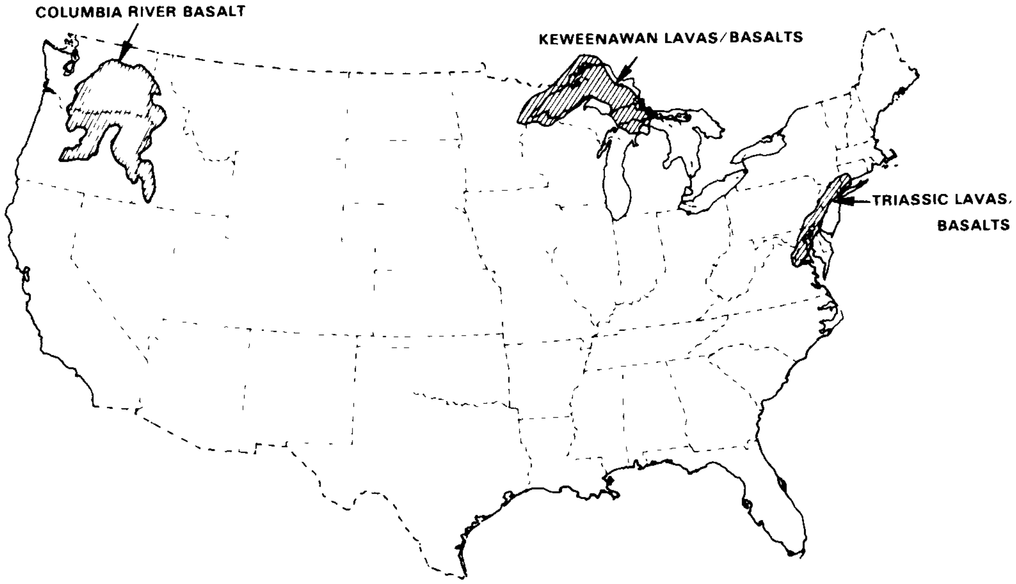

FIGURE B.6.4. Potential Repository Basalts in the United States (adapted from Office of Waste Isolation 1978a, Dott and Batten 1971)

B.7 THE SITE SELECTION PROCESS

Locating a site for geologic disposal of nuclear wastes must necessarily proceed in a certain sequence to attain the best available combinations of conditions. This optimization of siting considerations is employed to offset the uncertainties of geologic prediction.

At each step, appropriate technical criteria as well as optional siting considerations are required to guide the work and facilitate judgments of suitability. Licensing criteria are under development by the Nuclear Regulatory Commission and performance criteria by the Department of Energy (Gray et al. 1976). Such criteria are based on the need to reduce to the maximum extent achievable the risk of radionuclides being released from the repository to the human environment.

The site-selection process can also take on a different character (Gray et al. 1976). Because the practical aspects of gaining access to land for reconnaissance and exploration, at least over the near term, may impose severe restrictions on the area considered (Gray et al. 1976), sites can be selected for detailed investigation based on ownership by appropriate government agencies. Although satisfaction of appropriate technical criteria and siting considerations is essential at each stage, other factors also are relevant to the site-selection process, and could dominate. Among these are ease and cost of access, distance from other societal activities, and societal acceptance of the locations as a candidate repository site. Thus, certain sections of the country may be considered unavailable for further siting even though preliminary reconnaissance indicates generally favorable geologic conditions.

Also, the criteria for suitability of a site cannot be specified in great detail because of the complexity of the geologic settings; it is possible that the selection of initial regions for investigation may be done partly on the basis of nontechnical factors. Whether the process is begun this way or by a strictly technical approach, sites will be examined in detail and compared against the underlying radiological and environmental safety criteria. In the discussion that follows, a sequence of purely technical and scientific decisions is assumed, although it is recognized that socioeconomic and institutional factors must be considered in the site-selection process.

A purely technical approach to site selection begins on a broad nationwide scale in Stage I. A few basic considerations are used to arrive at candidate regions. Candidate regions are evaluated on a finer scale in Stage II using other geologic considerations to arrive at candidate areas. Stage III consists of individual site evaluations leading to selection of an optimum site from among a small number of possible alternatives. This selection process provides a systematic method to narrow the geographic area to be studied from the nation as a whole to smaller identified regions to even smaller geographic areas and finally to a small number of alternate sites. At each step unsuitable areas are discarded.

Stage I of the selection process begins with tectonic and hydrologic considerations that can be applied on a broad national scale (see Figure B.7.1). For each consideration, criteria need to be defined to serve as a basis for eliminating unsuitable regions and

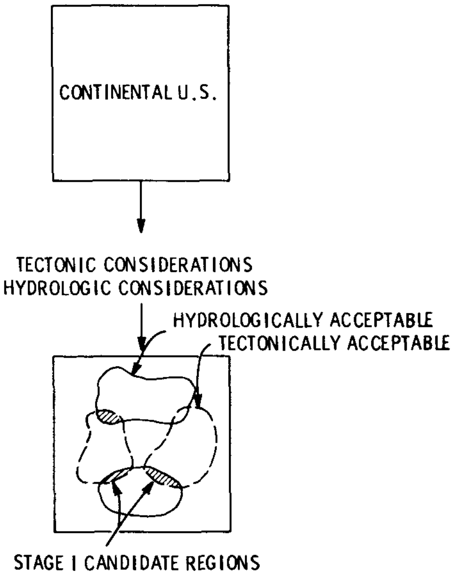

FIGURE B.7.1. Site Selection Process, Stage I

outlining the most suitable regions. Optimal choices for candidate regions are areas that satisfy both broad considerations. A hypothetical Stage I candidate region, for instance, could be an area that passes certain criteria both for optimal tectonic stability and hydrologic conditions. Selection of candidate regions can be accomplished by a thorough evaluation of available literature, existing geologic exploration data, and other existing information such as satellite imagery.

The candidate regions defined in Stage I enter into Stage II of the site selection process (see Figure B.7.2). General geologic considerations are applied on a scale appropriate to regional study, and criteria are again established to select areas with the most acceptable characteristics. A similar process is followed for each additional consideration (i.e, regional tectonics, hydrology, and depth). Optimal choices for candidate siting areas are those that have satisfied all Stage II considerations.

Data base additions required for evaluation in Stage II include extensive geologic mapping, generic research on rock properties (particularly their temperature dependence), characterizations of regional hydrology, climatic data, and instrumental data such as that obtained from geodetic, geophysical and microseismic networks.

A major task in Stage II will be to determine the activity or inactivity of fault systems within candidate areas. Repository siting will be ruled out within a designated distance from active faults to protect against possible fault rupture and the effects of strong seismic shaking. Repository siting criteria for seismic hazards have not been established. However, they may resemble current criteria of the Nuclear Regulatory Commission for siting of nuclear power plants.

The results of the above studies will be basic input to hydrologic considerations and Stage III modeling of specific sites. Stage III will require collection of as much

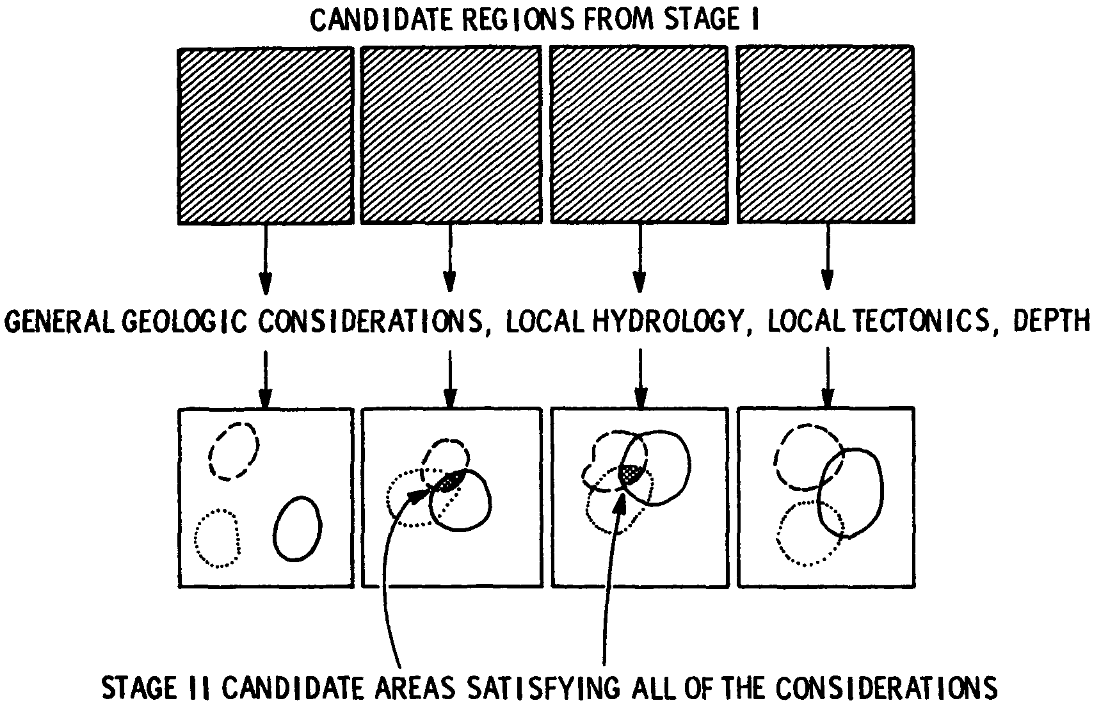

FIGURE B.7.2. Site Selection Process, Stage II

stratigraphic and structural data as possible without jeopardizing the isolation potential of the site. Drill holes, for example, are possible pathways for movement of water and loss of containment.

The candidate siting areas that result from Stage II enter into Stage III of the site selection process (see Figure B.7.3). All siting considerations are now applied on a site-specific scale. Again, under each consideration, criteria are used to eliminate unsuitable areas and to locate suitable sites.

Additional data base requirements (see Figure B.7.4) for Stage III are detailed site exploration data obtained by drilling, geophysical measurements, and possibly the opening of test tunnels. In-situ measurements of site-specific rock properties, state of stress, and hydrology will be conducted to the extent possible without compromising the future integrity of the repository.

It is possible that no site will be found to satisfy all criteria in Stage III. Tradeoffs then may have to be made, which may reduce ideal conditions under one criterion, yet results in an acceptable site for better overall performance. An optimum site and alternatives are chosen and ranked in case unforeseen field conditions or sociopolitical factors prevent the use of one or more sites.

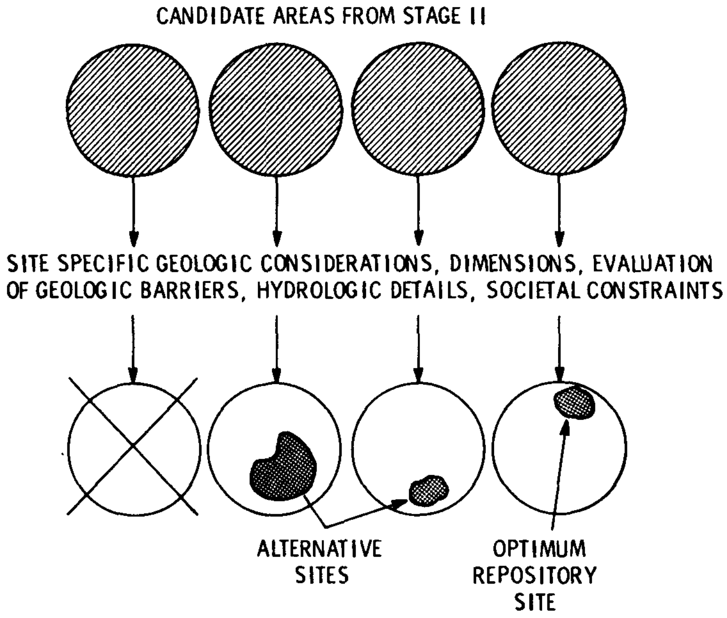

FIGURE B.7.3. Site-Selection Process, Stage III

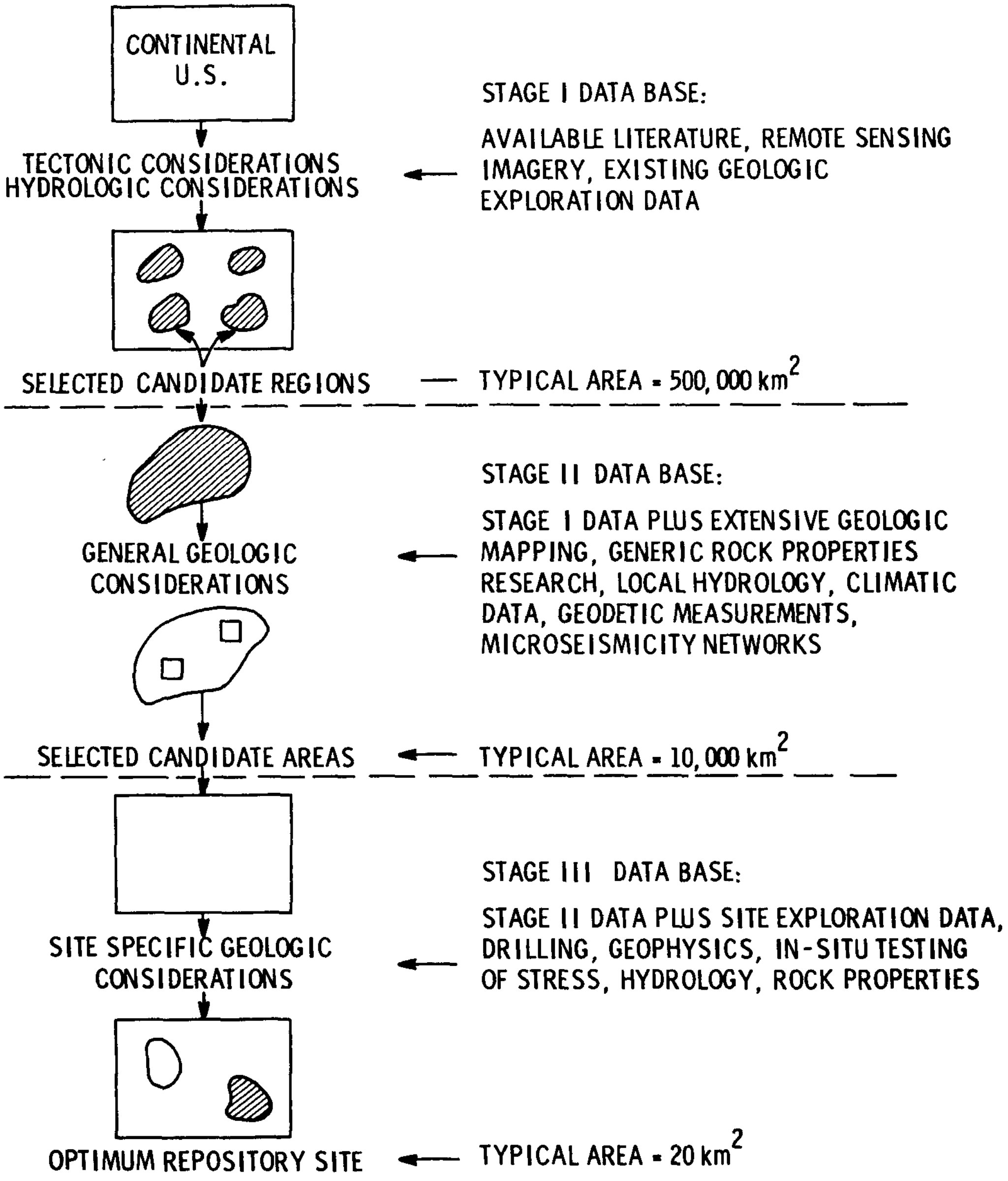

FIGURE B.7.4. Additional Data Base Requirements

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APPENDIX C

RADIOLOGICAL STANDARDS

Numerical values of annual dose limits have been set by the Nuclear Regulatory Commission (NRC) and Department of Energy (DOE). These limits and the Concentration Guides (10 CFR 20) derived from them are based on limits for occupationally exposed workers recommended by the National Committee on Radiation Protection and Measurements (NCRP 1957, 1959) and the International Commission on Radiological Protection (ICRP 1958, 1959). Minor modifications were made as a result of Federal Radiation Council (FRC) recommendations (1960) and more recent NCRP recommendations (1971). A review of the known biological effects of ionizing radiation by the National Academy of Sciences-National Research Council (NAS-NRC 1972) confirmed an earlier recommendation for limiting genetic exposure of the population, which corresponded to that of the NCRP. All these scientific bodies considered available data on both immediate and delayed effects:

- medical data on effects following therapeutic use of external radiation sources such as X-rays, and of radionuclides such as radium and iodine.
- occupational accident data on exposure of radiologists, X-ray and cyclotron workers, and workers in nuclear industry
- observations on population groups such as atomic bomb survivors and those irradiated by heavy nuclear weapons test fallout near the Marshall Islands.

Delayed effects, observable only years after exposure, were inferred from consideration of data from animal experimentation, from available epidemiological statistics, and from a limited number of case observations from medicine and industry (most notably a group of radium dial painters). The potential effects considered were 1) genetic effects and 2) somatic effects, including leukemia, skin changes, neoplasms, cataracts, changes in life span, and effects on growth and development. The delayed effects produced by ionizing radiation in an individual are not unique to radiation. For the most part they are indistinguishable from conditions normally present in the population, which may be induced by other causes.

In deriving the 10 CFR 20 Concentration Guides, a uniform exposure period of 50 years for adults was used. When dealing with intakes of radionuclides with effective half-lives in the body of less than 90 days, or where calculating doses directly from air and water concentrations by ratio to the appropriate Concentration Guides, the number of years of exposure makes little difference in the dose calculations. However, problems arise for non-uniform exposures to radionuclides with longer effective half-lives, especially when dealing with several exposure pathways and a heterogeneous population of varying ages and local residence periods. Although ICRP publications (1968, 1971) aid in making dose calculations, proper application of annual dose limits in such instances is controversial. The implied method is to calculate a total dose to an organ for a "standard man" for 50 years including the year of intake, and charge this total dose to that year for comparison with the dose standard. Alternatively, the total radionuclide intake for the year is compared to the annual intake used in calculating the Concentration Guide, and the resulting ratio is used. The latter is in keeping with the latest ICRP guidance (1977). In all cases the internal dose should be added to any dose from external sources.

According to Taylor (1973), the basic recommendation of both the NCRP and ICRP was that individuals in an exposed population (without the medical supervision given the worker and with no direct benefit from such incidental exposure) should not receive in excess of 1/10 the maximum permissible dose of radiation workers. As an allowance for the variability of exposure and the variable susceptibility to radiation effects of the general population (which includes different age groups, genetic backgrounds, and both sexes), the Radiation Protection Guides (RPG) (dose limits) of the FRC (1960) were further reduced by a factor of three for the average of general population groups. The resulting RPG of 0.17 rem per year average whole body dose for population groups coincided with the later ICRP recommendations (1964) for limiting average gonad dose of the population, based on the possibility of genetic effects, to 5 rem in 30 years, excluding medical exposures.

From these studies, the present guidlines have been derived. The "as low as reasonably achievable" guide, and the limits derived from 10 CFR 20 and other analyses, are identified below.

C.1 "AS LOW AS REASONABLY ACHIEVABLE" APPLICATION

The degree of risk to people from very low radiation doses is not apt to be answered by actual observations, now or in the future, because of the indicated low probability (ERDA 1975) of any observable health effect in individuals and the nonspecific nature of some effects. Although the ICRP and NCRP have previously recognized as working hypotheses the presumably conservative assumptions that all radiation effects would be linear with dose, have a zero threshold, and be independent of dose rate, the NCRP has reiterated its stand (1975) against using these assumptions for deriving numerical values for risk-benefit calculations. More recently, the ICRP (1977) has attempted to distinguish between certain somatic effects for which a threshold dose seems applicable and other somatic (primarily neoplasms) and genetic effects for which the zero threshold, linear hypotheses still should be applied. In any case, the basic principle of radiation protection is still that all radiation exposures of people should be kept to the lowest levels technically and economically practicable.

The Nuclear Regulatory Commission's 10 CFR 50 Appendix I (1975) defines "as low as reasonably achievable" (ALARA) population dose limits for light-water-cooled nuclear reactor effluents, primarily for design guidance, but also as an action level for operational control. Other nuclear facilities are not specifically covered. The NRC in the published summary of its formal opinion has adopted the use of the phrase "as low as is reasonably achievable" (as recommended by the ICRP in 1973) as a substitute for "as low as practicable," because ALARA is a more precise definition of the intention of this regulation. The numerical values of limits assigned by the NRC, for design guidance for each light-water reactor, are that whole-body doses to any individual shall not exceed 3 mrem per year from liquid effluents or 5 mrem per year from external radiation resulting from gaseous effluents.

At present, the dose limits cited in Section 2.2.1 still prescribe upper boundaries for permissible doses to people. Some fractions of these limits (or the corresponding Concentration Guides) are generally understood to be "as low as reasonably achievable" for routine waste management operations. Whether those should be 0.1, 0.01, or some other fractions of the dose limits can be evaluated for each facility and effluent stream only on a case-by-case basis by considering the effluent treatments and controls available and the costs of providing such treatment or controls.

C.2 DERIVED LIMITS AND ACTION LEVELS

In common with other radiation standards recommendations (NCRP 1959; ICRP 1959, 1977), 10 CFR 20 provides equivalent or alternative criteria as well as basic standards. The relationships among the several kinds of radiation standards criteria may be more easily understood by reference to Table C.2.1. This table relates various standards and guides to the stages between a source of radioactivity and a potential end point (health effect). Also shown are parameters that must be quantified for calculation between one step and the next (in either direction), as well as the measurements required to provide a basis for comparison with the appropriate standards criteria. The Regulatory Guides issued by the NRC provide generally accepted values and procedures for such quantification. No current standards provide specific limits in terms of health effects, although other criteria may imply acceptance of some level of probability of health effects.

It has been common practice to use the Concentration Guides for air and water given in 10 CFR 20 for direct comparison with environmental measurements of these media. However, without additional data, use of the Concentration Guides alone may lead to neglect of a significant pathway of population exposure. This can occur not only because other pathways of exposure may contribute to dose, but also because reconcentration or bioaccumulation processes may affect concentrations in other sources of intake or exposure. Alternatively, summing of fractions of Concentration Guides for a mixture of radionuclides may result in an overestimate of dose if the several nuclides behave differently in the body.

TABLE C.2.1. Comparison Chart of Radiation Standards and Recommendations

Stage	Factors	Bases for Evaluation	Standards or Criteria
Inventory	Quantities, physical and chemical forms	Measurements of containers, shipping records	Inventory Limits
Release	Release fractions, rates of release, effluent concentrations	Measurements of effluent	Release Guides, Operating Limits
Dispersion and/or Reconcentration	Meteorology, biology, hydrology, physical and chemical forms, concentration factors	Measurements of environmental concentrations, calculations	Concentration Guides
Intake and Exposure	Exposure periods consumption rates retention factors	Measurements of direct radiation, calculations, bioassays, whole-body counting	Intake Ranges - FRC Annual limits of Intake - ICRP
Dose	Biological half-lives, distributions in body, body dimensions, radiation types and energies	Dose calculations for maximum individual and population average	Dose limits - 10 CFR 20, 40 CFR 190-191, NCRP Reports, ICRP Reports
Health Effect	Dose/response relationships, demography	Calculated probabilities of specific effects	ICRP 26, 27, 28

Reliance on comparison of environmental concentration in air and water with the Concentration Guides requires additional caution, because the Guides are based on assumptions of standardized intake rates of air and water (20 m^3 of air and 1.2 liters of water per day for adults, with an additional intake of one liter of equivalent water at the same concentration in foods), as well as continuous exposure for periods of up to 50 years. Age-dependency of dose/intake ratios was not included in the derivations except for radioiodines in the infant thyroid. A result of the methodology is that an environmental concentration exceeding the Concentration Guide only briefly may scarcely affect the annual dose. Such an occurrence, however, would signal the need for investigation and possibly corrective action.

Although population doses can and should be calculated for comparison with the basic standards, the time lag and measurement sensitivities associated with most environmental measurements usually make it necessary to derive operating limits (or working limits) to be applied at the sources, i.e., the effluent streams.

Figure C.2.1 shows the generalized relationships between various levels of environmental concentrations (or effluent releases). The lowest level is the background measurement that would have been observed at the point of sampling if the operations under consideration did not exist. Some increases in concentrations may result from normal operations. An environmental impact (in the sense of a concentration difference) is the difference between an environmental level due only to background (which may include a contribution from other sources such as fallout) and the level due to background plus normal operations. Control of that impact is subject to the application of the ALARA principle. Both the "Normal Background" as well as the "Normal Background plus Normal Operations" are in reality distributions (rather than point values) that may and often do overlap or coincide.

Concentration Guides and external dose limits provide upper limits on acceptable release rates of radionuclides to the environment. Derived working limits or action levels refer to in-plant actions by management, such as redirecting an effluent stream to a freshly regenerated radionuclide absorber, and not to emergency actions outside the plant

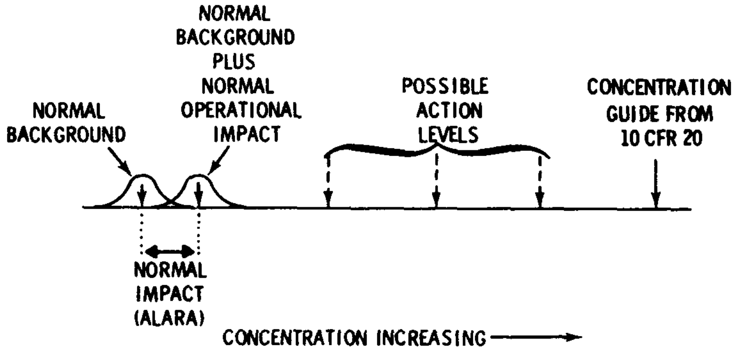

FIGURE C.2.1. Relationship of Operating Levels, Action Levels, and Concentration Guides (not to scale) boundary (e.g., evacuation). These action levels are commonly set between the Concentration Guides and the levels due to background plus normal operations. Since a Concentration Guide is a definite value and the background value is a distribution which is largely site-determined, selection of not only an ALARA impact but also any "Action Levels" will depend upon cost-benefit-risk considerations. In practice there will normally be a series of graded action levels, with the lowest only an "investigation level." For example, as a design objective the allowed impact due to normal operation might be "set" at 1% of the Concentration Guide and an immediate remedial action level might be established at that point. A working limit, or investigation level, might in addition be set based on some multiple of the expected normal impact, provided that was still lower than the remedial action level.

REFERENCES FOR APPENDIX C

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APPENDIX D

MODELS USED IN DOSE CALCULATIONS(a)

Calculational models and parameters were used in evaluating the radiological dose to both regional and world populations. The regional dose calculations are discussed for chronic and accidental releases. The worldwide dose considers the distribution of tritium, carbon-14 and krypton-85.

D.1 DOSE TO REGIONAL POPULATION

The doses caused by chronic and accidental releases of gaseous and liquid effluents from the facilities and processes investigated in this study were estimated using several calculational models. The models and parameters used were selected to give a realistic but conservative appraisal.

D.1.1 Chronic Releases

D.1.1.1 Air Concentration

The concentrations of radionuclides released in the atmosphere from these facilities were estimated using a Gaussian model (Slade 1968). Meteorological data on the joint frequency of occurrence of wind speed, wind direction, atmospheric stability and release parameters such as height and velocity for a particular plant were taken from the reference environment. The horizontal and vertical dispersion parameters, σ_y and σ_z, were taken from curves derived from the work of Pasquill and modified by Gifford (1977).

D.1.1.2 Air Submersion Dose

Air concentrations were estimated as outlined above for each of 16 sectors. For these sectors the centerline ground level dose was calculated for ten downwind distances from 1 to 80 km. Radiation doses to skin and to whole body were estimated from these air concentrations.

Both photons and beta particles can contribute significantly to the external dose to skin. The beta dose contribution is easily calculated using a semi-infinite cloud model. This model can be used because the range of beta particles in air is short compared to the dimensions of plumes considered. The gamma dose calculation is more complicated because of the relatively long range of photons in air. To properly determine the gamma contribution it is necessary to perform a space integration over the plume volume. The integration technique used in the reactor accident analysis computer program SUBDOSA (Strenge et al. 1975 is

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(a) In accordance with common practice, the term "dose," when applied to individuals and populations, is used in this report instead of the more precise term "dose equivalent" as defined by the International Commission on Radiation Units and Measurements (ICRU).

employed here except that the plume width is determined by sector boundaries rather than by a Gaussian concentration gradient. The contribution of gamma radiation to total-body dose was estimated by calculating the tissue dose at 5 cm depth. An occupancy factor may be used to account for the fraction of the year a person is exposed to the cloud. Also a shielding factor may be employed to correct for any shielding by buildings or structures between the recipient and the cloud.

D.1.1.3 Inhalation Dose

The air concentrations, derived as described above, were used along with the ventilation rate and dose factors to estimate the dose through the inhalation of radionuclides dispersed in the air.

The ventilation rate is the volume of air taken in by an individual per unit time. A value of 0.23 ℓ/sec was used in this study (ICRP 1959).

The inhalation dose factor is given in units of rem/yr per Ci/yr intake and is dependent on the complex transport, retention, and elimination of radionuclides through the respiratory and gastrointestinal tracts. The model of the respiratory tract adopted by the Task Group on Lung Dynamics forms the general basis for the calculation of this dose factor (ICRP 1966). The computer code used for the calculations was DACRIN (Houston et al. 1974).

D.1.1.4 Ground Contamination Dose

Radionuclides from the air may settle on the ground, where they can accumulate during the time of the release. These can be a source of radiation for an individual or population groups.

This dose is determined using the 1) air concentration, 2) deposition "velocity" of the radionuclides traveling to the surface from the air, 3) an exponential expression which accounts for the accumulation of the radionuclide on the ground over a certain time period, 4) a dose factor, and 5) an occupancy factor.

The deposition "velocity" given in terms of m/sec is highly dependent on surface roughness, wind speed, and particle size. Based on many experimental studies, values of 0.001 m/sec for particles and 0.01 m/sec for iodine gas were selected for use in this report (Slade 1969).

The time over which the radionuclides accumulate in the soil is dependent on the lifetime of the facility releasing the material. In this study a value of 30 years is used, which is considered to be about the average lifetime of a nuclear facility.

The dose factor for the dose from ground irradiation is calculated by assuming that a receptor is 1 m above a large, nearly uniform, thin sheet of contamination (Soldat 1971, Fletcher and Dotson 1971). A factor of 0.5 to account for dose reduction due to ground surface roughness is also included in dose factors. These dose factors have units of rem/hr per pCi/m^2 of surface.

D.1.1.5 Ingestion of Food Crops

Food crops may become contaminated by deposition of radionuclides directly from the air or from irrigation water upon the plant surfaces or by radionuclides taken up from soil previously contaminated via air or water. Many factors must be considered when calculating doses via ingestion of these foods. These factors account for the movement of radionuclides from release to the receptor and form a complex sequence (Baker et al. 1976).

Equations used to calculate such doses are given in two parts: the first accounts for direct deposition onto leaves and translocation to the edible parts of the plant, while the second accounts for long-term accumulation in the soil and root uptake.

For sprinkler irrigation and for deposition of airborne materials both parts of the equation are used, while only the part dealing with root uptake is required for ditch irrigation. Tables of transfer factors and plant uptake factors are stored in files in the program FOOD (Baker 1977). The program can handle nine crops and their pathways to man. The output of the program lists the concentrations of radionuclides in the food crops and the fraction of the concentration due to each part of the equation (i.e., leaf or root). It also lists the dose to each organ from each nuclide/crop combination, with a summary of total doses from all crops and nuclides combined.

The nuclides ^{3}H and ^{14}C are treated as special cases in the FOOD program. The concentrations in the initial environmental media (air or water) are calculated on the basis of the specific activity of the nuclide in the naturally occurring stable element.

D.1.1.6 Ingestion of Animal Products

Five products--milk, eggs, beef, pork, poultry--are included in the FOOD program. The concentrations in the animals' feed are first calculated as discussed above for human food crops.

The equation, the quantities of animal feed and water consumed, and a listing of the transfer factors (fraction of each day's intake appearing per liter of milk or kilogram of eggs or meat) are given by Baker et al. (1976). The output of FOOD lists doses to various organs by nuclide and food type and summarizes total dose from all nuclides in milk, eggs, and meat (beef, pork and poultry).

D.1.1.7 Accumulated Doses from Foods

The computer program PABLM was written to calculate cumulative radiation dose to people from the ingestion of food. A total of eight food categories (leafy vegetables, other above-ground vegetables, root vegetables, fruit, grain, eggs, milk, and meat) can be selected with corresponding consumption rates, growing periods, and irrigation rates or atmospheric dilution parameters assigned by the user. Radionuclides may be deposited by water used for irrigation or directly from the atmosphere onto vegetation or the ground for the expected operating life of the facility. Dose commitments to the whole body and six internal organs from 186 radionuclides can be accumulated for a specified dose period. However, computer core space limitations restrict input considerations to only four organs and 75 radionuclides. A summary of cumulative dose and percent contribution by nuclide for each food type is calculated. Radionuclide concentrations in soil, plants, and animal products are also calculated.

D.1.2 Accidental Releases

The dose to individuals exposed to a passing cloud of accidentally released radionuclides consists of external and internal components. The external radiation doses are calculated using the computer code SUBDOSA (1975), and the spatial distribution determined by the methods described in Meteorology and Atomic Energy (Slade 1968) and code XOQDOQ (Sagendorff and Goll 1977) for a semi-infinite cloud. External exposure results from both gamma radiation and beta particles emitted from radionuclides while they are airborne and external to the human receptor. This dose is dependent not only upon the type of radiation (i.e., gamma or beta) but also upon the energy of the radiation and the spatial distribution of the airborne radionuclides with respect to the receptor. The type and energy of radiation are characteristic of each radionuclide.

Because the range of beta particles in the air is only a few meters, the air concentration at ground level is sufficient to calculate the doses resulting from beta-emitting radionuclides. Ground-level air concentrations are not sufficient, however, for calculating the dose from gamma radiation. This is due to the relatively large range of gamma radiation in air. This range varies according to gamma energy and can be as long as a few hundred meters. As a result, the dose from external exposure to gamma radiation during cloud passage depends upon the air concentration at distances up to a few hundred meters. Thus the height of release has much less effect on gamma dose than it does on beta dose, particularly at close distances. As before for air submersion doses, both beta and gamma radiations contribute to skin dose; but only gamma radiation contributes to total-body dose (calculated at 5 cm depth).

Inhalation doses are calculated using the same models and codes used for chronic release except for increased ventilation rate (0.35 ℓ/sec) (Sagendorff and Goll 1977).

D.1.3 Dose to Biota Other Than Man

The doses to terrestrial and aquatic animals living within the influence of the nuclear facilities described in this report were not calculated separately. Two recent comprehensive reports (NAS-NRC 1971 and Garner 1972) have been concerned with radioactivity in the environment and pathways to biota other than man. Depending on the pathway being considered, terrestrial and aquatic organisms will receive either about the same radiation doses as man or somewhat greater doses. Although no guidelines have been established to set acceptable limits for radiation exposure to species other than man, it is generally agreed that the limits established for humans are also conservative for these species (Auerbach 1971).

The literature relating to radiation effects on organisms is extensive, but very few studies have been conducted on the effects of continuous low-level exposure to radiation from ingested radionuclides on natural aquatic or terrestrial populations. The most recent and pertinent studies point out that, while the existence of extremely radiosensitive biota is possible and while increased radiosensitivity in organisms may result from environmental interactions, no biota have yet been discovered that show a sensitivity to radiation exposures as low as those anticipated in the area surrounding fuel cycle plants. The BEIR Report (NAS-NRC 1972) states in summary that evidence to date indicates that no other living organisms are very much more radiosensitive than man. Therefore, no detectable radiological impact is expected on the aquatic biota or terrestrial mammals as a result of the quantity of radionuclides to be released into the River R and into the air by fuel cycle plants.

D.1.4 Direct Radiation from Transportation

The method used to calculate the dose to persons along the shipping route from a vehicle containing radioactive material follows that developed in WASH-1238 (USAEC 1972).

The equation used to estimate population doses incorporates several factors that integrate the dose to an individual as the radiation source passes his location. The formula then integrates the dose to all persons within a designated population distribution. The factors considered are radiation source strength, velocity of the transport vehicle, population density in areas of exposure to passing source, attenuation factors due to gamma interactions with air, and buildup factor to account for the contribution of scattered radiation.

The Department of Transportation's regulations limit the radiation level allowable outside the transport container rather than restrict the container's contents. However, there is still a radioactivity content limit for each kind of packaging and for each toxicity grouping of radionuclides. Consequently, the shipping containers are designed and loaded with that regulatory limit in mind. For this calculation, based on the regulatory limit of 10 mrem/hr at 6 ft from the surface of the vehicle, the maximum radiation dose rate at 10 ft from the apparent center of the source was estimated to be 10 mrem/hr (USAEC 1972). The radioactive shipment on the vehicle was considered to be a point source for distances from the source of 100 ft or more.

The length of time an individual spends near a source is a determining factor in the total dose received; thus the velocity of the source is important. It was assumed that a long-haul, maximum-weight motor carrier shipment averages 720 miles per day and that a carload rail shipment averages 200 miles per day. Based on a uniform distance traveled each day and uniform distribution of persons along the route, the cumulative radiation dose to the population is the same whether the vehicle is always moving at a constant rate of speed or is standing still part of the day. (Movement or lack of movement of the vehicle obviously will have an effect on the dose distribution among individuals within the exposed population.)

It was assumed that the average population density is 330 persons per square mile in the United States east of the Mississippi River and in California, and 110 persons per square mile in the other midwestern and western states. It is further assumed that no people live within 100 ft of the railroad or highway right-of-way. The dose to persons farther than 2600 ft is negligible. The population was assumed to be uniformly distributed between 100 and 2600 ft on each side of the route, grouped at 100 ft intervals. Since the nuclear power facilities under consideration are assumed to have useful lifetimes of 30 years, the 70-year cumulative dose from transportation of wastes from a given facility is approximated by multiplying the annual dose by 30.

D.2 DOSE TO WORLDWIDE POPULATION

Worldwide population doses were calculated for the three radionuclides that are considered to be the major contributors to total-body dose rates and long-term dose commitments: ^{3}H, ^{14}C, and ^{85}Kr. A constant world population of 6.4×10^9 persons was used for this analysis. This value, which is based on a United Nations projection, was reported by Killough (1977) for the year 2000. It agrees with the value of 6.3×10^9 derived from the method of the Environmental Protection Agency (EPA) (1973) using projections based on a 1970 population of 3.56×10^9 persons and an annual growth rate of 1.9%.

A different method was used to determine the quantity of each of the radionuclides to which the population was exposed. For ^{3}H, dispersion was calculated using a seven-compartment model that considered diffusion into and out of latitudinal bands. The exposure of the population was calculated using assumed diets whose concentrations of ^{3}H were related to those in local surface waters. A specific activity approach was used for ^{14}C in which the concentration of ^{14}C per gram of carbon in people was assumed to be equal to that in atmospheric carbon dioxide. It was assumed that ^{85}Kr diffused readily across latitudinal bands so that in a few years the concentration was uniform throughout the world's atmosphere. The dosimetry for ^{85}Kr is based on external exposure of the body to a semi-infinite cloud containing this radionuclide, with no accumulation within the body or in any environmental reservoirs other than the air.

Although the method for each radionuclide is different, each probably estimates the population dose to within an order of magnitude. Additional uncertainty is therefore introduced when doses from all three radionuclides are totaled. Moreover, care must be exercised in comparing the relative contributions of these three radionuclides because of the different methods and because of the uncertainty inherent in each.

Each of the three methods is discussed below.

D.2.1 Tritium

Tritium (^{3}H) and tritium oxide released to the environment mix rapidly with the ambient water and become part of the hydrologic cycle. Tritium rains out or is washed out of the atmosphere almost entirely in the hemisphere in which it is released. Transport across latitudinal bands even in the same hemisphere is slow (Renné et al. 1975). As a result, the tritium released from facilities in the United States will reach peak environmental concentrations in the 30° to 50° latitude band of the northern hemisphere, where most of the world's population resides.

Baker (1976) has calculated the radiation doses received by local (50-mile radius), regional (eastern United States), and worldwide populations from a continuous release of 1 Ci/yr of ^{3}H to the atmosphere using the "box" model of Renné et al. (1975). The facility releasing the ^{3}H was assumed to be located in the Midwest. Although the magnitude of the dose to the local population is sensitive to the specific site chosen, the regional population dose should be similar for most midwestern sites. In addition, the world population dose depends upon the latitude band and not the longitude of the release point.

Baker's analysis indicated that for a constant world population of 3.8 x 10^9 persons, the collective population dose rate, at equilibrium with a continuous release of 1 Ci/yr of ^{3}H, was 1 x 10^{-2} man-rem/yr for all three population groups combined. Less than 10% of this dose was received by persons residing within 80 km of the plant site but about half was received by the eastern U.S. population during the initial pass of the ^{3}H released from the midwestern site. The actual dose to the regional U.S. population from a ^{3}H release to the atmosphere could range from near zero for plants situated on the eastern seaboard to values approximately equal in magnitude to the equilibrium worldwide population dose for plants situated in the West or Midwest.

In Baker's model (Baker and Soldat 1976) the ^{3}H content of water and food consumed by the world's population was assumed to be related to, but not necessarily as high as, the ^{3}H concentration in the surface waters of the appropriate latitude band. Even so, the population-weighted average surface water concentrations were higher than those obtained in the simpler model used by the EPA (1973 and 1974), which assumed mixing of the ^{3}H in the circulating ocean water of the northern hemisphere. As a result, Baker's calculations of dose to the world population (excluding the United States) are about seven times greater than those estimated by EPA.[a]

For the commercial waste management study, the methods used by Baker were adopted with the exceptions of changing the world population from 3.8 x 10^9 persons to 6.4 x 10^9 persons and using a release time of 30 years in place of a continuous release out to equilibrium. The resulting dose factors per unit release are summarized in Table D.2.1.

TABLE D.2.1. Total-Body Dose Factors, and Dose Commitment Factors for the World Population (6.4 x 10^9 persons), man-rem per Ci/yr released[(a)]

Radionuclide	Dose Factor (1/1)[(b)]	Dose Factor (1/30)[(c)]	Accumulated Dose Factor (70/30)[(d)]	Dose Commitment Factor (70/1)[(e)]
^{3}H	4.7 x 10^{-4}	6.8 x 10^{-3}	2.4 x 10^{-1}	8.2 x 10^{-3}
^{14}C	2.4	7.2 x 10^1	4.0 x 10^3	1.7 x 10^2
^{85}Kr	3.1 x 10^{-5}	4.1 x 10^{-4}	1.4 x 10^{-2}	4.7 x 10^{-4}

(a) Exclusive of contribution to eastern U.S. population dose from first passage of fuel reprocessing plant (FRP) gaseous effluents if FRP is located in the Midwest or West.
(b) World population dose in first year after a 1-Ci release (instantaneous equilibrium).
(c) Annual world population dose in the 30th year (year 2000) after 30 years of continuous release of 1 Ci/yr.
(d) Seventy-year accumulated dose to the world population from 30 years of release at 1 Ci/yr followed by 40 years exposure to the residual environmental contamination.
(e) Seventy-year dose commitment to the world population from a 1-year release of 1 Ci/yr to the environment plus continued exposure to the residual environmental contamination.

(a) The calculated U.S. population dose, however, is only two times higher for the Baker model than for the EPA Model. The net result is that the combined world population dose (including the U.S. population) is about three times higher via Baker's model than via the model used by EPA.

D.2.2 Carbon-14

Most ^{14}C released to the atmosphere from nuclear facilities will be in the form of carbon dioxide (CO_2), with possible traces of organic compounds released from certain specific processes within the nuclear fuel cycle. After mixing with the existing CO_2 in the atmosphere, the $^{14}CO_2$ can either become incorporated directly in plant material or washed out of the atmosphere onto land or water surfaces.

Most analyses of the long-term radiation doses to large population groups from ^{14}C include the following assumptions:

1. Carbon-14 is released to the atmosphere as CO_2.
2. It mixes rapidly with all carbon in the world's atmosphere--6.2×10^{17} g (320 ppm CO_2).
3. Mechanisms that remove carbon into less accessible sinks such as the deep ocean or that dilute the $^{14}CO_2$ with increased CO_2 releases from future fossil-fuel combustion can be ignored.
4. The specific activity (that is, activity of ^{14}C per unit weight of carbon) in the tissues of man eventually equilibrates with that in the atmosphere.

More complicated models are possible. Machta (1973) developed a seven-compartment model for CO_2, similar to the one discussed for ^3H. It was further modeled by the EPA (Magno et al. 1974 and Fowler et al. 1976) for use in predicting radiation doses to large populations from ^{14}C injected into the troposphere by the nuclear industry. The EPA model was used only to predict the specific activity of ^{14}C in the troposphere including, however, modifications for the sinks mentioned in assumption 3. Assumption 4 was then used to calculate dose to man. Fowler et al. (1976) included an estimate that 99% of man's ^{14}C intake is through food and only 1% is through inhalation.

Killough (1977) further modified the EPA seven-compartment model to incorporate newer data on diffusive vertical transport of CO_2 in the deep ocean and the relationship between the concentration of inorganic carbon in the ocean surface waters and the partial pressure of dissolved CO_2. The computer code developed by Killough to implement the resulting model is documented in detail.

For purposes of the commercial waste management analysis, the conservative model outlined in assumptions 1 through 4 was adopted. This model was also adopted by the Nuclear Regulatory Commission (NRC) in its testimony at the Allied General Nuclear Services (AGNS) reprocessing plant license hearings (Eckerman 1974). By comparison the doses calculated using this simple approach are about 25% higher than those calculated by EPA (Fowler et al. 1976), 50% higher than those estimated by Baker (1976), and nearly seven times higher than those obtained by Killough (1977). The comparison with Killough is not, however, straightforward because of the assumptions of growing population and increasing CO_2 concentrations used by that author.

D.2.2.1 Dose Conversion Factors for Carbon-14

The assumptions that the specific activity of ^{14}C per gram of carbon in man eventually reaches equilibrium with that in the atmosphere and that there are 16.1 kg of carbon in the 70-kg body of Reference Man (ICRP 1959) lead to the derivation of dose and dose commitment factors as discussed in the following paragraphs.

At a release rate of 1 Ci/yr over 30 years the accumulated quantity of ^{14}C in the environment will be 30 Ci. At the end of an additional 40 years there will still be 30 Ci in the environment. Diluting 30 Ci in the 6.15×10^{17} g of carbon in the atmosphere (Killough 1977) yields a specific activity of

$$(30 \text{ Ci} \times 10^{12} \text{ pCi/Ci})/(6.16 \times 10^{17} \text{g}) = 4.87 \times 10^{-5} \text{pCi/g}$$

The dose rate (DR) factor after 30 years of release can be calculated from the following equation (Soldat 1976):

$$DR = 0.0187 \text{ CE rem/yr}$$

where

$$C = \text{concentration in body (pCi of } ^{14}C \text{ per g of body tissue)}$$

$$= (4.87 \times 10^{-5} \text{ pCi of } ^{14}C \text{ per g of C}) (1.61 \times 10^{4} \text{ g of C})/(7 \times 10^{4} \text{ g total body})$$

$$= 1.12 \times 10^{-5} \text{ pCi/g}$$

$$E = 0.0538 \text{ (MeV/dis)} \cdot \text{(rem/rad)},$$

The factor 0.0187 is derived from the product of (0.037 dis/sec per pCi) (3.156×10^{7} sec/yr) (1.602×10^{-8} g · rad/MeV).
Therefore

$$DR = (0.0187)\ (1.12 \times 10^{-5})\ (0.0538)$$

$$= 1.13 \times 10^{-8} \text{ rem/yr per person}$$

For 6.4×10^{9} persons, the worldwide dose rate factor thus becomes 72.1 man-rem/yr after the release of 1 Ci/yr for 30 years.

The 70-year dose commitment (DC) factor, which is the sum of the dose during release and the dose after release has stopped, is calculated as follows:

$$DC = \left[(0 + 72.1 \text{ man-rem/yr})/2\right] (30 \text{ yr}) + \left[(72.1 \text{ man-rem/yr})\ (40 \text{ yr})\right]$$

$$= 3970 \text{ man-rem per 1 Ci/yr released for 30 years.}$$

These dose factors are summarized in Table D.2.1.

D.2.3 Krypton-85

When krypton-85 is released to the atmosphere it will mix rapidly with the atmosphere in the hemisphere in which it is released. After about 2 years it will also be fairly well mixed throughout the world's atmosphere. For purposes of this analysis, therefore, simple uniform worldwide mixing of ^{85}Kr in the world's atmosphere has been assumed. Similar assumptions have been used by the NRC in its testimony for the AGNS fuel reprocessing facility at Barnwell (Eckerman and Congel 1974) and the EPA in its projections of population dose commitments from the nuclear industry (EPA 1973 and 1974).

The National Council on radiation Protection and Measurements has published a discussion of the behavior and significance of ^{85}Kr in the atmosphere (NCRP 1975). In that report a comparison was made between the population exposure estimates made by detailed modeling of ^{85}Kr dispersion and estimates assuming uniform mixing in the world's atmosphere.

The model used in this analysis ignores the higher concentrations near the source and during the first pass through the latitudinal band where the release occurs. As a result, the model underestimates the local and regional dose at short times after the release. However, the net effect on the worldwide dose from long-term accumulated dose commitment exposure is small--about 10 to 20%, depending on whether the nuclear facility is sited in the Midwest or on the East Coast. The rapid mixing across the equator makes separate accounting of the northern and southern hemisphere population doses unnecessary.

D.2.3.1 Dose Conversion Factors for Krypton-85

The world's atmosphere contains 3.96 x 10^{18} m^3 of air at standard temperature and pressure (NCRP 1975). The concentration of ^{85}Kr at any time is simply the cumulative amount released (corrected for radioactive decay) divided by the volume of the atmosphere. For a continuous uniform release rate of 1 Ci/yr, the concentration (C_t) of krypton becomes

$$\begin{aligned} C_t &= \left[(1\ \mathrm{Ci/yr})\ (10^{12}\ \mathrm{pCi/Ci})/(3.96 \times 10^{18}\ \mathrm{m}^3)\right] \left[1 - \exp(-\lambda t)\right]/\lambda \\ &= (2.53 \times 10^{-7}) \left\{\left[1 - \exp(-\lambda t)\right]/\lambda\right\}\ \mathrm{pCi/m^3\ per\ Ci/yr\ released} \end{aligned}$$

where

λ = radiological decay constant for ^{85}Kr of 0.0648 per year

t = years since start of release.

For 30 years of continuous release at 1 Ci/yr the expression $\left[1 - \exp(-\lambda t)\right]/\lambda$ becomes 13.2. This indicates that after 30 years 13.2 Ci remain in the environment out of the total of 30 Ci released. The concentration (C_{30}) then becomes

$$C_{30} = 2.53 \times 10^{-7}\ (13.2) = 3.34 \times 10^{-6}\ \mathrm{pCi/m^3\ per\ Ci/yr.}$$

The concentration during the next 40 years after the release has stopped is this 30th year concentration corrected for decay. Thus the total time-integrated concentration (TIC) is the sum of the combined expressions for concentration during the two time periods (0 to 30 years and 30 to 70 years). This yields the following equation:

$$TIC = (2.53 \times 10^{-7})\ (1/\lambda^2)\ \left[\lambda t_1 + \exp\ (-\lambda t_2) - \exp(-\lambda \Delta t)\right]\ (\text{pCi}\cdot\text{yr/m}^3) \text{ per Ci/yr released}$$

where

t_1 = time over which release occurs,

t_2 = time over which dose is calculated,

$\Delta t = t_2 - t_1$.

For t_1 = 30 years and t_2 = 70 years the expression within brackets becomes 448, which yields a time-integrated concentration of

$$1.13 \times 10^{-4} \text{ pCi}\cdot\text{yr/m}^3 \text{ per Ci/yr.}$$

Unlike ^3H and ^{14}C, which emit only low-energy beta particles during their radioactive decay, ^{85}Kr emits a gamma photon in a small percentage of its decays. These photons plus a small contribution from bremsstrahlung associated with the beta decay are capable of irradiating the whole body(a) during external exposure to ^{85}Kr dispersed in air. Krypton-85 is not significantly absorbed into the body during inhalation, and this pathway makes a negligible contribution to the whole-body dose (NCRP 1975).

Soldat et al. (1973) have calculated the whole-body dose factor for a person immersed in a half-infinite cloud of ^{85}Kr to be 2.2×10^{-3} mrem/hr per Ci/m^3 (1.9×10^{-8} rem/yr per pCi/m^3). Combining this dose factor and a constant world population of 6.4×10^9 persons with the expression for concentration (C_{30}) yields the world population whole-body dose rate in the 30th year as follows:

$$\left[3.34 \times 10^{-6} \ (\text{pCi/m}^3) \text{ per } (\text{Ci/yr})\right]\ (6.4 \times 10^9 \text{ persons})\ \left[1.9 \times 10^{-8} \ (\text{rem/yr}) \text{ per } (\text{pCi/m}^3)\right]$$

$$= 4.08 \times 10^{-4} \text{ man-rem/yr per Ci/yr released for 30 years.}$$

The accumulated 70-year dose is

$$\left[1.13 \times 10^{-4} \ (\text{pCi}\cdot\text{yr/m}^3) \text{ per } (\text{Ci/yr})\right]\ (6.4 \times 10^9 \text{ persons})\ \left[1.9 \times 10^{-8} \ (\text{rem/yr}) \text{ per } (\text{pCi/m}^3)\right]$$

$$= 1.38 \times 10^{-2} \text{ man-rem/70 years per Ci/yr released for 30 years.}$$

These factors are summarized in Table D.2.1.

(a) Defined as the layer of tissue lying 5 cm below the surface of the skin.

D.2.4 Dose Conversion Factors for System Analysis

The nuclear fuel cycle facilities in place and operating will change year by year. To obtain a realistic assessment of the long-term population dose commitments, calculation of the dose commitment from each year's operation followed by a summation of these yearly values is necessary. This can best be assessed by deriving population dose commitment factors for a one-year unit release.

Because of the nature of the three radionuclides involved in the world population dose estimates (^{3}H, ^{14}C, and ^{85}Kr), there is no long-term accumulation in the body. Hence, each year's release and resulting dose commitment can be treated independently of the others.

The following expression relates the 70-year dose commitment (from a 1-year chronic release) to the dose in the first year.

$$R = (1/\lambda^2) \left[\lambda t_1 + \exp(-\lambda t_2) - \exp(-\lambda \Delta t)\right] (\mathrm{yr})^2$$

where

t_1 = 1 year,
t_2 = 70 years,
$t = t_2 - t_1$ = 69 years,
λ = radioactive decay constant (ln2/half-life).

The values of this ratio for ^{3}H, ^{14}C, and ^{85}Kr are given in Table D.2. Table D.2.2 also includes the dose commitment factors per unit release obtained when these ratios are applied to the first-year dose (item 1/1 from Table D.2.1).

Using these dose factors and annual releases of ^{3}H, ^{14}C, and ^{85}Kr from waste management facilities, estimates of worldwide population dose can be obtained for the evolving cycle systems.

TABLE D.2.2 70-Year World Population Dose Commitment from a 1-Year Chronic Release, man-rem/70 years per Ci/yr released

Radionuclide	Ratio[a]	Dose Commitment Factor[b]
^{3}H	17	8.2×10^{-3}
^{14}C	69	1.7×10^{2}
^{85}Kr	15	4.7×10^{-4}

(a) Ratio of 70-year dose commitment from a 1-year chronic release to the dose in the year of release.
(b) Seventy-year dose commitment to the world population from a 1-year release of 1 Ci to the environment plus continued exposure to the residual environmental contamination.

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APPENDIX E

RADIOLOGICALLY RELATED HEALTH EFFECTS

The radiation dose to man from ingestion, inhalation, or external exposure to specified quantities of radionuclides can be calculated with reasonable confidence. Estimates of the amounts of radioactive material that may be released from Commercial Waste Management (CWM) operations, however, and fractions reaching man via various environmental pathways are not as well defined. The relationship of dose to so-called "health effects" is even less well defined. Thus, estimates of "health effects" that may result from radiation exposure consequent to CWM activities can derive only from a chain of estimates of varying uncertainty. The usual practice in making these estimates is that if an error is to be made, it will be made in a way intended to overprotect the individual. As a result, if the chain of estimates is long, there may be considerable conservatism in the final value.

Because expected releases of radioactive materials are small, and the radiation dose to any individual is small, the effects considered are long-delayed somatic and genetic effects; these will occur, if at all, in a very small fraction of the persons exposed. Except as a consequence of the unusually severe accident involving larger doses, no possibility exists for an acute radiation effect. The effects that must be considered are 1) cancers that may result from whole body exposures, and more specifically, from radioactive materials deposited in lung, bone, and thyroid; and 2) genetic effects that are reflected in future generations because of exposure of the germ cells.

Knowledge of these delayed effects of low doses of radiation is necessarily indirect. This is because their incidence is too low to be observed against the much higher background incidence of similar effects from other causes. Thus, for example, it is not possible to attribute any specific number of human lung cancers to the plutonium present in everyone's lungs from weapons-test fallout, because lung cancers are known to be caused by other materials present in much more hazardous concentrations, and because lung cancers occurred before there was any plutonium. Even in controlled studies with experimental animals, one reaches a low incidence of effect that cannot be distinguished from the level of effect in unexposed animals, at exposure levels far higher than those predicted to result from CWM activities. Hence, one can only estimate a relationship between health effect and radiation dose, basing this estimate upon observations made at very much higher exposure levels, where effects have been observed in man, and carefully studied animal experiments. In this context the National Council on Radiation Protection and Measurements has said (NCRP 1975): "The NCRP wishes to caution governmental policy-making agencies of the unreasonableness of interpreting or assuming 'upper limit' estimates of carcinogenic risks at low radiation levels derived by linear extrapolation from data obtained at high doses and dose rates, as actual risks, and of basing unduly restrictive policies on such interpretation or assumption" (NCRP 1975, p. 4).(a)

An alternative approach involves direct comparison of the estimated radiation doses from CWM activities with the more accurately known radiation doses from other sources. This avoids the most uncertain step in estimating health effects (the dose-effect relationship) and provides a comparison with firmly established data on human exposure (i.e., the exposure to naturally occurring radiation and radioactive materials). Some people prefer to judge a risk's acceptability on knowledge that that risk is some certain fraction of an unquantifiable, but unavoidable, natural risk, than to base this judgement on an absolute estimate of future deaths that might be too high or too low by a large factor. Because of these judgmental problems it is the practice in this Statement to compare estimated radiation exposure from CWM activities with naturally occurring radiation exposure as well as to indicate estimates of cancer deaths and genetic effects.

E.1 LATE SOMATIC EFFECTS

Recently much literature has dealt with the prediction of late somatic effects of very low-level irradiation. This literature is not reviewed in detail here because it is recent and readily available. Instead, the various dose-effect relationships that have been proposed are briefly considered and justification is given for the range of values employed in this Statement.

Two publications have served as the basis for most recent efforts to quantify late somatic effects of irradiation. These are the so-called BEIR Report, issued in 1972(b) by the National Academy of Sciences as a report of its Advisory Committee on the Biological Effects of Ionizing Radiations (NAS-NRC 1972); and the so-called UNSCEAR Report, a report to the General Asembly by the United Nations Scientific Committee on the Effects of Atomic Radiation, most recently revised in 1977 (UNSCEAR 1977).

Both the BEIR and UNSCEAR Reports draw their conclusions from human effects data derived from medical, occupational, accidental, or wartime exposures to a variety of radiation sources: external x-irradiation, atomic bomb gamma and neutron radiation, radium, radon and radon daughters, etc. These observations on humans were, of course, the result of exposures to relatively large total doses of radiation at relatively high dose rates. Their extrapolation to the low doses and dose rates of concern to us is acknowledged by the BEIR Report as "fraught with uncertainty" (p. 7). The BEIR Report concludes, however, that the assumption of a linear relationship between dose and effect, extending to zero dose with no threshold dose below which no effects are predicted, "in view of its more conservative implications,...

(a) EPA commented that this paragraph reflects a bias on the part of the authors. However, the NRCP quotation was chosen because it represented the negative point of view, and it was the purpose of this paragraph to reflect that point of view.

(b) A version of this report is in progress.

warrants use in determining public policy on radiation protection." But it further cautions that "explicit explanation and qualification of the assumptions and procedures involved in such risk estimates are called for to prevent their acceptance as scientific dogma" (p. 97).

The BEIR Report makes estimates of both absolute risk (cancer deaths per unit of radiation exposure) and relative risk (percentage increase above normal incidence of cancer deaths per unit of radiation exposure). And for each of these approaches it assumes either a 30-year or a duration-of-life interval following the latent period, during which risk remains elevated for non-leukemic cancer. Separate risk estimates are derived for the in utero, 0-9 years, and 10+ years age periods, reflecting presumed age differences in the sensitivity to radiation. The derivation of these risk estimates and their application to the U.S. population is summarized in the BEIR Report (p. 169) where the number of excess cancer deaths per year in the U.S. population, because of continual exposure at a rate of 0.1 rem/yr, is estimated as:

- 1726 for the absolute risk model with 30-year risk plateau
- 2001 for the absolute risk model with duration-of-life risk plateau
- 3174 for the relative risk model with 30-year risk plateau
- 9078 for the relative risk model with duration-of-life risk plateau.

The exposure rate of 0.1 rem/yr employed in these estimates is in the range of doses received from naturally occurring radiation sources in the continental U.S.

The BEIR Report risk estimates are shown in Table E.1.1, converted to a man-rem basis. This conversion involved dividing the risk estimates of Table 3-1, page 169, of the BEIR Report, by 20,000,000, since the U.S. population, taken as 200,000,000, if exposed to 0.1 rem/yr, receives a total annual exposure of 20,000,000 man-rem. The BEIR Report provides estimates for leukemia and for "all other cancers"; the "all other cancers" category is further subdivided for the absolute risk model as applied to those aged 10 or more. Values for bone and lung cancer are shown in Table E.1.1 as though the apportionment applied to the total population. It is important to note that the approximately five-fold range of values for total cancer deaths predicted by the four different BEIR Report models do not define a range between maximum and minimum possible values. They are merely four estimates, based on different assumptions, between which it is not possible to make a confident choice based on present knowledge.

The Environmental Protection Agency (EPA) in its Environmental Analyses of the Uranium Fuel Cycle (EPA 1973, 1976) chose single risk estimates, based on the BEIR Report, which it considered" the best available for the purpose of risk-cost benefit analyses, [while cautioning that] they cannot be used to accurately predict the number of casualties" (EPA 1973, p. C-14). These EPA risk estimates, expressed as cancer deaths per million man-rem, are also listed in Table E.1.1. The derivation of these numbers is not detailed in the EPA publications, but they continue to be used by the EPA and have been adopted by others.

TABLE E.1.1. Comparison of Various Estimates of Cancer Deaths per Million Man-Rem

	BEIR Report (NAS-NRC 1972)					Reactor Safety Study (NRC 1975)				
	Absolute Risk Model		Relative Risk Model							
Type of Cancer	30-Year Plateau	Life Plateau	30-Year Plateau	Life Plateau	Environmental Protection Agency	Upper Bound	Central Estimate[b]	Lower Bound[b]	UNSCEAR Report(2)	ICRP-26(10)
Leukemia	-26-[a]		-37-[a]		54 (1973a)	28	5.6	0	15-25	20
Non-leukemic	60	74	122	417		106	42	0		
Lung	16	19			60 (1973b)	22	4.4	0	25-50	20
Bone	2.4	3.0			16 (1973a)	7	1.4	0	2-5	5
Thyroid						13	2.6	0	5-15	5
Total	86	100	159	454	200 (1973b)	134	48	0	100	100

(a) 10-year risk plateau following in utero exposure, otherwise 25 years.
(b) Calculated on the assumption that no individual dose will exceed 10 rem.
NOTE: The term "health effects" is sometimes used to include sublethal cancers and less serious genetic defects. However, the estimates made in this statement are for cancer deaths and serious genetic effects.

The Reactor Safety Study[a] (RSS) of the Nuclear Regulatory Commission (1975; this is commonly known as the Rasmussen Report) included an effort by an Advisory Group on Health effects to update and extend the conclusions of the BEIR Report (NRC 1975). Among the 17 members of this Advisory Group were five who also had served on the BEIR Committee. The RSS derived three classes of risk estimates: an "upper-bound estimate," a "central estimate," and a "lower-bound estimate." In contrast to the different BEIR Report risk estimates, the RSS estimates purport to establish a range within which the true value should be found. The RSS risk estimates for organs of interest to this Statement, and as applied to low-dose exposure, are listed in Table E.1.1. The details of the temporal exposure patterns, age distributions, and computational approaches employed in the BEIR and RSS Reports are not identical, and the risk estimates are therefore not strictly comparable; but errors from this source are negligible in comparison to the other uncertainties involved.

In arriving at upper-bound estimates, the RSS made two significant changes in BEIR assumptions and modified several numerical values on the basis of newer data. The "relative risk model" of the BEIR Report was eliminated and all estimates were based on the "absolute-risk model" and the plateau period for expression of non-leukemic cancer following postnatal exposure was taken as 30 years; the duration-of-life plateau option of the BEIR Report was dropped. The rationale for these changes is presented in the RSS Report. The major change resulting from new data was a 40% reduction in the leukemia risk of in-utero exposure; this was based upon revised dosimetry provided by the authors of the publication from which the BEIR risk estimate was primarily derived. The upper-bound estimates shown in Table E.1.1 are taken directly from Table VI 904, p. 9-33, of the RSS Report (NRC 1975), except for the thyroid cancer risk; this is derived from a "case" estimate of 134 per million man-rem modified by a mortality estimate of 10% (NRC 1975, p. 3-26 and 9-27).

The RSS central estimate "modifies the upper-bound estimate by correcting for risk reduction caused by both the ameliorating effects of dose protraction and the lesser effectiveness of very small acute doses" (NRC 1975, p. G-7). This correction acknowledges the preponderance of data from experimental studies, which indicate that the dose-effect relationship is not linear and that low doses of low LET (linear energy transfer) radiation delivered at low dose rates afford a significant opportunity for repair of radiation damage. The RSS discusses and references the extensive radiobiological literature on this subject and concludes that at doses below 10 rem, or at dose rates below 1 rem/day, a "dose-effectiveness factor" of 0.2 is justified (i.e., for a given total dose the dose efectiveness in producing a "health effect" is less at smaller dose rates). This was still considered a conservative position, the RSS Advisory Group on Health Effects was "of the unanimous opinion that the dose effectiveness factors they recommended probably overestimate the central estimate" (NRC 1975, p. 9-22). It should be recognized that some may not agree in applying such a factor in the human case, where the very limited data do not entirely

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a) Since the Reactor Safety Study (RSS) represents the conclusions of a respected body of scientists, many of whom were also members of the BEIR Committee, the values reported in the RSS were not adopted but rather were considered when the values in Table E.1.2 were derived.

support the RSS position (Brown 1976). The EPA, in its formal review of the RSS study, disagreed with several aspects of the RSS health effects model, including the 0.2 dose rate effectiveness factor, and concluded that the RSS central estimate of late somatic effects "may be underestimated by a factor of 2 to 10" (EPA 1976).

Finally, the RSS acknowledges in its lower-bound estimate the possibility that a threshold for cancer induction may exist. While a threshold for primary radiation effects at the molecular level is considered unlikely on theoretical grounds, the mechanisms by which such effects become expressed as cancers are not understood, and available data in no way preclude the possibility of a threshold for these expressed effects. The RSS calculates its lower-bound estimate assuming a 10- or 25-rem threshold dose, either of which is larger than most doses predicted to occur to an individual from CWM activities.

The most recent and most thoroughly documented estimates of cancer risk from radiation exposure are those contained in the 1977 UNSCEAR Report. These values are listed in Table E.1.1. The UNSCEAR Report cautions that these values are". . . derived essentially from mortalities induced at doses in excess of 100 rad. The value appropriate to the much lower dose levels involved in occupational exposure, and even more so in environmental exposures to radiation, may well be substantially less; . . ." (p. 414). Also shown in Table E.1.1 are the risk estimates adopted in the 1977 Recommendations of the International Commission on Radiological Protection (ICRP 1977), which were based primarily on the UNSCEAR Report.

E.2 GENETIC EFFECTS

It is known that genetic effects result from alterations within genes, called mutations, or from rearrangements of genes within chromosomes. There is no radiation-dose threshold for the production of mutations, but repair of damage to genetic material can occur during exposure at low dose rates. This information is reviewed and discussed at length in the 1977 UNSCEAR Report.

The conventional approach to this problem has been to estimate a "mutation doubling dose," i.e., the radiation dose required to double the existing mutation rate. The BEIR Report concludes that this doubling dose for humans lies in the range of 20 to 200 rem. The UNSCEAR Report considers additional experimental data and opts for a single value of 100 rem. Given a number for the doubling dose, if one can assume that radiation-induced mutations have the same effect on health as normally occurring mutations and if one knows the burden of human ill health attributable to such normally occurring mutations, one can directly estimate the genetic effect of any given radiation dose. Unfortunately, it is not clear that radiation-induced mutations are equivalent in effect to normally occurring mutations. Nor is there any confidently accepted quantification of the human ill health attributable to these normally occurring mutations.

Four kinds of specifically recognized genetically associated diseases are usually distinguished.

1. Autosomal dominant disorders are those caused by the presence of a single gene. The most common examples are: chondrodystrophy (abnormal cartilage development), osteogenesis imperfecta (abnormally brittle bones), neurofibromatosis (disease characterized by multiple soft tumors), eye anomalies including congenital cataract, and polydactylism (more than 10 fingers or toes) (Trimble and Doughty 1974). It is generally agreed that these disorders will double in frequency if the mutation rate is doubled (NAS-NRC 1972 and UNSCEAR 1977). There is some disagreement on their normal frequency of occurrence: the earlier data (Stevenson 1959) employed in the BEIR Report indicate a 1% normal incidence, while a more recent study of and Trimble and Doughty 1974), indicates an incidence of something less than 0.1%. These new data have not been fully accepted, however, and the 1977 UNSCEAR Report continues to employ the 1% normal incidence figures.
2. Multifactorial (irregularly inherited) disorders have a more complex and ill-defined pattern of inheritance. These diseases include a wide variety of congenital malformations and constitutional and degenerative diseases. Their normal incidence in the population was estimated in the BEIR Report to be about 4% (NAS-NRC 1972); however, the newer data of Doughty and Trimble suggest an incidence as high as 9-10% (UNSCEAR 1977). The BEIR Report states that, "The extent to which the incidence of these diseases depends on mutation is not known" but assumes a "mutational component" of 5 to 50% (p. 56). The 1977 UNSCEAR Report employs a single figure of 5% and considers 10% to be an upper limit (p. 429). Newcombe has argued that "the bulk of the most directly pertinent experimental studies thus

fail to demonstrate any important effect of irradiation on the irregularly inherited diseases, or on general health and well being," and concludes that "the collectively numerous irregularly inherited diseases of man are unlikely to be substantially increased in frequency by exposure of his germ plasm to radiation" (Newcombe 1975).

3. Disorders due to chromosomal aberrations include diseases characterized by changes in the number of chromosomes, or in the structural sequence within chromosomes. It is generally agreed that these diseases will show little increase as a result of low-level, low-LET irradiation, and they were not quantified in the BEIR Report. The 1977 UNSCEAR Report includes a numerical estimate for such effects.

4. Spontaneous abortions are known to occur as a result of chromosomal effects, often so early in pregnancy as to be undetectable. Such effects have been generally excluded as not a relevant health effect (NAS-NRC 1972).

In addition to the above specifically identifiable genetic effects, there may well be genetic influence on other unquantifiable aspects of physical and mental ill health. The BEIR Report assumed that two-tenths of this "ill health" was due to genetic factors related to mutation, acknowledging that "it may well be less, but few would argue that it is much higher" (p. 57). Using this factor and a mutation doubling dose of 100 rem, one calculates an eventual 0.2% increase in "ill-health" as a consequence of continual exposure to 1 rem per generation. Such ill-defined effects cannot be quantitatively compared to specific genetic effects, or carcinogenic effects, not can they be stated on a man-rem basis.

Table E.2.1 summarizes the BEIR Report and UNSCEAR Report genetic risk estimates. The EPA has employed an estimate of 300 genetic effects per million man-rem (EPA 1973, Part III), as has also the Medical Research Council in England (MRC 1975). The newer data on the normal frequency of autosomal dominant disorders (Trimble and Doughty 1974), and Newcombe's (1975) evaluation of the significance of multifactoria disorders, lead to an estimate for total genetic effects of only 10 per million man-rem. All of these estimates are for total effects, to be experienced over all future generations.

TABLE E.2.1. Estimates of Genetic Effects of Radiation Over All Generations

Type of Effect	BEIR Report (1972)	UNSCEAR Report (1977)	EPA (1973)	Newcombe (1975)
Autosomal Dominant Disorders	50-500	100		10
Chromosomal Disorders		40		
Multifactorial Disorders	10-1000	45		
Total	60-1500	185	300	10

E.3 CONCLUSIONS

For this Statement a range encompassing commonly used cancer risk factors has been employed, as indicated in Table E.3.1. At the same time the possibility of zero risk at very low exposure levels is not excluded by the available data. The lower range of risk estimates in Table E.3.1. may be considerd more appropriate for comparison with the estimated risks of other energy technologies. The upper part of the range may be more appropriate for radiation protection considerations.

A range of 50 to 300 specific genetic effects to all generations per million man-rem was employed in this Statement. The lower value recommended by Newcombe has not been generally accepted and the upper end of the BEIR Report range seems too high in the light of newer evidence discussed in the 1977 UNSCEAR Report. As in the case of the somatic risk estimates, the lower end of the range may be considered more appropriate for comparative risk evaluations, while the upper end of the range may be appropriate to radiation protection considerations.

All estimates of health effects, as quoted elsewhere in this Statement, employ the risk factors summarized in Table E.3.1. No special risks are considered to be associated with any specific radionuclide except as reflected in the calculation of their dose equivalent (in rems) in the various tissues of concern. However, because of their particular significance, *effects attributable to certain radionuclides* (^{3}H, ^{14}C, ^{85}K, *and plutonium*) are discussed separately on the following pages.

TABLE E.3.1. Health Effects Risk Factors Employed in This Statement

Type of Risk	Predicted Incidence per 10^6 man-rem
Fatal cancers from:	
Total body exposure	50 to 500
Lung exposure	5 to 50
Bone exposure	2 to 10
Thyroid exposure	3 to 15
Specific genetic effects to all generations from total body exposure	50 to 300
Total	100 to 800

E.4 SPECIFIC CONSIDERATION OF HEALTH EFFECTS FROM TRANSURANICS

Data relevant for predicting specific health effects from transuranics have been considered elsewhere, in great detail (USAEC 1974, Bair 1974 and MRC 1975). Only the kinds of data available and the approaches that might be taken if specific transuranic health effect predictions were desired are considered here.

E.4.1 Experience with Transuranic Elements in Man

No serious health effects attributable to transuranic elements have been reported in man. There are extensive data, however, on exposure of man to transuranic elements. Such exposures arise from two main sources: the worldwide plutonium fallout from atmospheric testing of nuclear weapons and other devices, and the accidental exposure of persons working with transuranics. Since these exposures have produced no effects distinguishable from effects caused by other causes, the information is useful in health effects prediction only as an indication that unusual or unexpectedly severe effects are not to be anticipated; i.e., such negative data can be used only to set an upper limit on possible effects.

E.4.2 Experience with Natural Radiation in Man

Alpha-emitting elements are a natural part of the human environment. Humans have lived with these internally deposited radioelements and with radiation from other natural sources throughout the history of the species. It is of some relevance to note that inhaled naturally occuring alpha-emitting radionuclides contribute an average annual dose of about 0.1 rem to the lung, and that naturally occurring alpha emitters in bone contribute an average annual dose at bone surfaces of about 0.04 rem (NCRP 1975). While these doses cannot be related to any measure of specific effects, they have been at least "tolerable" on the evolutionary scale, and therefore slight increases can hardly have catastrophic effects.

E.4.3 Data from Experiments with Animals

Direct information on the toxicity of transuranic elements is available only from studies in experimental animals. The radiobiological literature suggests that the biological effects observed in such animal experiments will at least qualitatively approximate those that would occur in man exposed under the same conditions. Based on extensive data from several animal species, it is concluded that the most probable serious effects of long-term, low-level exposure to transuranics are lung, bone, and possibly liver tumors. Most of these data are from experiments with plutonium, but can probably be applied to other transuranics with less error than is involved in many other necessary assumptions. While quantitative extrapolation from animal to man involves considerable uncertainty, the animal data suggest tumor risks per million organ-rem of 60 to 200 for lung (Bair and Thomas 1976), and 10 to 100 for bone (Bair 1974, Mays et al. 1976). These estimates are compared with others in Table E.4.1.

TABLE E.4.1. Comparison of Transuranic Health Risk Estimates (Tumor deaths per million organ-rem)

	BEIR (1972)				
	High[a]	Low[b]	MRC (1975)	Mays et al. (1976)	Risk Estimates Based on Data from Animals
Lung tumors	100	16	25		60-200[c]
Bone tumors	17	2	5	4	10-100[d]
Liver tumors			20		

(a) Relative risk model with lifetime plateau (Newcombe 1975).
(b) Absolute risk model with 30-year plateau (Necombe 1975).
(c) Data from Bair and Thomas (1976).
(d) Data from Bair (1974) and Mays et al. (1976).

E.4.4 Data on Effects of Other Types of Radiation on Man

Inferences concerning the effects of transuranic elements in man may be drawn from information available on the effects of other forms of ionizing radiation in man; e.g., data derived from medical, occupational, accidental, or wartime exposure of humans to different radiation sources, including external x-radition, atomic bomb gamma and neutron radiation, radium, radon and short-lived radon decay products. Such information has been summarized in the BEIR and UNSCEAR Reports, as previously described. England's Medical Research Council (1975), considering much the same information covered in the BEIR and UNSCEAR Reports, derived risk estimates specifically applicable to plutonium.

Also of interest are recently accumulated data on the carcinogenicity of ^{224}Ra in human bone (Spiess and Mays 1971, 1972). These data are particularly relevant to risks from plutonium, since ^{224}Ra is predominantly an alpha emitter and, because of its very short half-life (3.64 days), irradiates only the surface layer of bone, in much the same manner as plutonium does. From these ^{224}Ra data, Mays et al. (1976) have estimated a bone cancer risk of 4 per million bone-rem.

Table E.4.1 compares tumor risk estimates from these several sources. Quantitative application of these data to the very low exposure levels involved in population exposure resulting from commercial waste management practices is uncertain; however, the kinds of data presented in Table E.4.1 are reassuring because of their general agreement, and because they predict no unusual incidence of effects not contemplated in the selection of the general risk estimates used in this Statement.

E.5 SPECIFIC CONSIDERATION OF HEALTH EFFECTS FROM KRYPTON-85

The radiological significance of ^{85}Kr was reviewed in a recent report of the National Council on Radiation Protection and Measurements (NCRP 1975). Most of the discussion in this appendix derives from that report, which should be consulted for details or for more extensive citation of the literature.

Because krypton is virtually inert chemically, it is not metabolized. Exposure of humans results from ^{85}Kr in the atmosphere external to the body, from ^{85}Kr inhaled into the lung, and to a much smaller degree from ^{85}Kr dissolved in body fluids and tissues. Over 99% of the decay energy of ^{85}Kr is in the form of a relatively weak beta ray (mean energy, 0.25 MEV) which limits the hazard from external exposure. There is general agreement that the dose to the sensitive cells of the skin from external exposure is about 100 times larger than the dose to the lung or any other internal organ (NCRP 1975, Kirk 1972, Soldat et al. 1975, Snyder et al. 1975).

The NCRP Report (1975) considers four categories of delayed effects from long-term exposure to low-level environmental concentrations of ^{85}Kr. These are: 1) genetic effects, 2) overall carcinogenic effects, 3) carcinogenic effects on skin, and 4) possible interaction of ionizing and ultraviolet radiation.

Estimation of genetic and overall carcinogenic effects of ^{85}Kr exposure involves no unusual features. Doses to gonads and to total body have been considered essentially identical by all who have considered the problem (NCRP 1975, Kirk 1972, Soldat et al. 1975). Genetic and carcinogenic risk factors chosen for general applicaion in this Statement (Table E.1.2) should be appropriate to ^{85}Kr.

Carcinogenic effects on skin do constitute a unique problem, however, since the human exposure dose from ^{85}Kr is 100 times higher to the skin than to any other tissue. Dose-response data on radiation-induced skin cancer are limited, but suggest a threshold-type response; certainly the skin is less susceptible to radiation carcinogenesis than are many other tissues. The BEIR Report (Weston 1973), after review of the available data, concludes that "numerical estimates of risk at low dose levels would not seem to be warranted."

As a consequence, neither dose to skin nor estimated health effects that might result from low-level skin irradiation are presented in this Statement. (Skin cancer is perhaps the most easily controlled of all malignancies and is rarely fatal.)

The possibility of interaction between the radiation from ^{85}Kr and solar ultraviolet radiation, the latter of which is considered to be responsible for most human skin cancer, was raised in the NCRP Report (NCRP 1975). There is no direct evidence for such interaction, but the possibility was thought to justify further epidemiological and laboratory studies.

E.6 SPECIFIC CONSIDERATION OF HEALTH EFFECTS FROM TRITIUM

Although tritium is subject to the uncertainties involved in any prediction of effects at dose levels far below those for which there are experimental data, the relatively uniform distribution of hydrogen throughout the body and our understanding of the metabolism of hydrogen and water by the body do provide more confident dosimetry than is available for most other radionuclides. If there is special concern about tritium effects, it relates primarily to the difficulties of preventing its release to the environment, and to its worldwide distribution and availability to man following release. Many aspects of the biological concerns for tritium in the biosphere are reviewed in the Proceedings of a symposium on the subject, held in 1972 (Moghissi and Carter 1973).

There has been some concern that tritium incorporated in organic compounds, either before or following ingestion by man, might present a substantially increased hazard. Such an increased hazard might be due to: a) prolonged retention of the tritium-containing compound, b) enhanced biological effectiveness of the radioactive disintegration due to conversion of the hydrogen atom in a vital molecule to a helium atom (transmutation effect), or c) an enhanced radiation effect due to origin of the beta ray within a vital molecule. If the hydrogen of all molecules in the body were uniformly labeled with tritium, this would add perhaps 50% to the whole body radiation dose from body water alone. Any larger increased radiation dose from organically bound tritium could occur only if tritium were preferentially incorporated or retained, in comparison with ordinary hydrogen. This possibility was reviewed by Weston (1973) who concluded that, "it is apparent that large kinetic isotope effects are often found for tritium-labeled compounds. In tracer experiments utilizing tritium, observed rate constants could easily differ by an order of magnitude from those for the analogous unlabeled compound. If tritium from a source of HTO at constant specific activity is incorporated into a biological system by irreversible chemical reactions, it will be discriminated against; and the tritium level in the biological system will remain lower than that of the source. Conversely, kinetic isotope effects in the back exchange to remove tritium after incorporation will favor retention of tritium in the biological system."

Although rather large isotope effects occur in individual chemical reactions, the overall effects in biological organisms seem relatively small, as discussed by Shtukkenberg (1968). Thompson and Ballou (1954) compared tritium and deuterium in rats, as did Glasscock and Duncombe (1954). The effects were small, as they were in a study of algae (Crespi et al. 1972). It therefore seems reasonable to assume, as was done in the dosimetric calculations for this Statement, that tritium will behave like ordinary hydrogen; any error introduced by such an assumption will probably overestimate the effects of tritium.

The significance of transmutation effects has been a controversial subject, but there now appears to be agreement on the following conclusions, as expressed by Feinendegen and Bond (1973): "The effects of intracellular tritium are overwhelmingly due to beta irradiation of the nucleus. Transmutation effects do not produce a measurably increased effect under most conditions and are detectable only, if at all, under highly specialized laboratory conditions. The origin of tritium beta tracks in, or their close juxtaposition to, the

DNA molecule does not appear to enhance the degree of somatic effects." Studies of the induction of gene mutations in mice also indicate no substantial transmutation effect (Cumming et al. 1974).

Concern has been expressed for the case in which a developing female fetus is exposed to elevated body water levels during oocyte formation; tritium corporated in these germ cells would be retained until ovulation, and this might constitute a special genetic hazard (Radford 1969). Osborne (1972), however, has estimated that in such a circumstance, less than 0.2% of the initial dose rate to the nucleus originates from tritium incorporated in DNA, and that it would be 30 years before the initial dose from body water was equaled by the cumulative dose from DNA-incorporated tritium.

It would thus appear quite certain that tritium incorporated into organic compounds poses no substantially increased hazard beyond that accounted for by its contribution to whole body dose.

Tritium is a pure beta emitter of very weak energy--18.6 keV maximum. The linear energy transfer (LET) of such a weak beta is higher than that of more energetic beta, x-, or gamma radiation, and much experimental effort has been devoted to determining whether this higher LET is reflected in an increased relative biological effectiveness (RBE). The International Commission on Radiological Protection in its report on Permissible Dose for Internal Radiation (ICRP 1959) used a quality factor of 1.7 for tritium, the value employed in the dosimetric calculations for this Statement. RBE studies were reviewed by Vennart (1968), who concluded "that a value of QF different from unity of either tritium or other β-emitters is hardly justified, and the ICRP reduced the tritium quality factor to unity in 1969, an action concurred in by the National Council on Radiation Protection and Measurements" (1971). More recently, further evidence has been presented to justify a value higher than unity (Johnson 1973 and Moskalev et al. 1973). Of particular interest are studies of Dobson et al. (1974, 1975) on the survival of female germ cells in young mice exposed to a continuously maintained level of tritium oxide in body water. These studies seem to indicate an increasing RBE with protraction of exposure, with the suggestion of a limiting RBE value of about 4 at very low doses. It is important to note, however, that an increasing RBE at very low doses for the relatively high-LET beta radiation from tritium, is (on theoretical grounds, at least) more likely due to a decreased biological effectiveness of the reference, low-LET radiation, than to an absolute increase in tritium effectiveness.

With specific regard to the RBE for genetic effects, the induction of mutations by tritium in mice has been recently studied at Oak Ridge National Laboratory (Cumming et al. 1974). The report of these studies presents the following conclusion: "Thus, if absorbed dose to the testis is accepted as meaningful for purposes of comparison with gamma or X-rays, the . . . point estimate of relative biological effectiveness (RBE) for postspermatogonial germ-cell stages is close to 1, with fairly wide confidence intervals. The point estimate of RBE for spermatogonia is slightly above 2, with confidence intervals which include 1, and there remains the suggestion that the distribution of mutants among the seven loci may differ from that produced by gamma rays" (Cumming et al. 1974).

In summary, it may be concluded that research on both somatic and genetic effects attributed to tritium has failed to produce results markedly different from those which would have been predicted from a general knowledge of ionizing radiation. It may then be assumed that the conventional methods of estimating radiation dose and biological effect, as employed in this Statement, are applicable to tritium.

E.7 SPECIFIC CONSIDERATION OF HEALTH EFFECTS FROM CARBON-14

The radiological signficance of ^{14}C has received much attention because 1) carbon occurs everywhere in nature, including man; 2) ^{14}C has a long half-life, 5730 years; and 3) weapons tests have significantly increased global ^{14}C levels (UNSCEAR 1977, pp. 41-42). Only recently has attention been directed to the considerably smaller ^{14}C releases that may be expected from the nuclear fuel cycle (ERDA 1975, Hayes 1977).

As with tritium, there is concern that transmutation effects (i.e., effects resulting from the conversion of a carbon atom to a nitrogen atom in a vital molecule) may increase the health risk from ^{14}C beyond that attributable to the beta-radiation dose. This is of particular concern with regard to genetic effects. Direct experimental data to settle this question are not available. In his original article (1958) calling attention to health risks from ^{14}C, Pauling concluded "that the special mechanism involving ^{14}C atoms in the genes themselves is less important than irradiation in causing genetic damage." Totter, Zelle and Hollister (1958), reviewing the then available data, concluded that "subject to large uncertainty, the transmutation effect of ^{14}C atoms contained in the genetic material of the human body could lead to about the same number of genetic mutations as the radiation effect from ^{14}C."

The general problem of transmutation effects has received much recent study, and the occurrence and importance of such effects has been clearly demonstrated for ^{32}P (Krisch and Zelle 1969). Less work has been done with ^{14}C, and reported results are not entirely consistent. In studies with Drosophila (fruit flies), Lee and Sega observed little, if any, mutagenic effect from ^{14}C-thymidine incorporated in sperm. They concluded that "if transmutation of ^{14}C is mutagenic at all, it is less effective than ^{32}P (in similar experiments) by two orders of magnitude;" and that, "for practical purposes in considering mutagenic hazards or toxicity effects due to chromosome breakage, only the beta radiation of ^{14}C needs to be considered."

On the other hand, McQuade and Friedkin (1960) observed twice the frequency of chromosome breakage in onion root tips after administering thymidine with ^{14}C-labeling in the methyl group, as with ^{14}C-labeling in the 2 position. This seems to imply a differential transmutation effect, since the labeling position should not influence beta-radiation-induced effects. There is, in any case, no experimental evidence for a transmutation effect that is many times larger than the radiation effect, although such claims have been made on theoretical grounds (Golenetskii et al. 1976). Therefore, based on what appears a preponderance of informed opinion (Krisch and Zelle 1969, and Lee and Sega 1973), this report does not consider the possibility of ^{14}C transmutation effects.

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APPENDIX F

REFERENCE ENVIRONMENT FOR ASSESSING ENVIRONMENTAL IMPACTS

The following reference environment was developed as an aid in assessing environmental impacts associated with construction and operation of waste treatment, interim storage and/or final disposition facilities. The reference environment concept is used to replace, where appropriate, the criteria-type approach to generic environmental assessment.

The reference environment was developed primarily from data on existing plant sites in the midwestern United States. There is, however, no intent to endorse this area or type of environment for any nuclear fuel cycle facility. Since the reference environment is to be used in a generic or hypothetical sense, references supporting the descriptive material were not considered necessary and are not included. The reference environment is representative of the surface geology only and has nothing to do with the deep geology as may be appicable to siting to waste repositories in geologic media.

For assessment of environmental effects, it is assumed that each waste management facility is located (independently, not collocated) within the reference environment. Although an artificiality, analysis of impacts from waste management facilities centered at the same location simplifies calculations and permits direct comparison of impacts among facilities on the same environmental features.

F.1 LOCATION OF SITE

Regardless of the size of the site or purpose to which it is to be put, the center of the site is assumed to be located 8 km west of the R River, about 13 km northwest of Town A in county A, and 50 km northwest of a major metropolitan area (City G) in a midwestern state.

F.2 REGIONAL DEMOGRAPHY AND LAND USE

The reference environment is located in a region that is mainly rural; the land is used chiefly for farming. The nearest communities are A, about 13 km southeast of the site, with a population(a) of about 2,000; B (population 400) about 6 km northwest; C (population about 1,000) about 8 km east; D (population 1,100) about 16 km southwest; and E (population 3,000) about 16 km south. The closest large cities are F (population 40,000) about 32 km northwest and G (population 1,800,000) about 50 km southeast.

The population within a 1-km radius (300 km^2) of the site is about 12,000. Within an 80-km radius of the site (20,000 km^2) the population is about 2,000,000, of which about 93% resides in the G metropolitan area (see Table F.2.1).

In County A, and in County B just across the R River to the northeast, about 82% of the land is used for farming. The main crops in these two counties, which include all land

TABLE F.2.1. Projected Year 2000 Population in Reference Environment

RANGE, km	1.6	3.2	4.8	6.4	8.0	16	32	48	64	80	TOTALS
N	0	4	4	18	160	210	1,115	3,641	2,137	1,209	8,498
NNE	0	4	4	14	26	157	986	3,350	4,185	1,872	10,598
NE	0	6	18	72	109	232	1,306	4,897	2,848	6,371	15,859
ENE	0	4	12	72	145	333	2,025	2,677	8,743	6,209	20,220
E	0	4	12	145	537	993	1,321	9,094	6,344	14,195	32,645
ESE	0	4	20	353	118	610	3,400	50,482	123,104	163,155	341,246
SE	0	25	245	1,069	194	632	5,063	46,789	581,389	579,114	1,214,520
SSE	0	4	18	45	157	374	3,466	18,642	59,435	32,445	114,586
S	0	4	41	67	112	1,097	5,438	5,844	10,131	7,334	30,068
SSW	0	15	26	67	126	571	3,177	4,809	6,411	7,317	22,523
SW	0	30	65	58	50	423	1,835	4,656	6,106	6,856	20,079
WSW	0	6	55	93	65	414	3,007	1,901	7,515	4,442	17,498
W	0	9	31	78	73	379	1,730	3,600	3,326	4,805	14,031
WNW	4	8	8	44	29	332	1,662	6,495	6,493	5,984	21,059
NW	0	6	9	21	44	293	5,277	47,196	4,061	4,501	61,408
NNW	0	8	15	55	181	165	1,204	2,753	2,480	4,533	11,394
TOTALS	8	141	583	2,271	2,126	7,215	42,012	216,826	834,708	850,342	1,956,232
CUM TOTAL (rounded)	8	150	730	3,000	5,100	12,000	54,000	270,000	1,100,000	2,000,000	2,000,000

(a) Populations are assumed to be those for the year 2000.

within 16 km of the site, are soybeans, corn, oats, and hay. It is expected that these two counties will remain largely agricultural and that the population distribution will not change significantly with time.

A wildlife refuge is located about 14 km northeast to 19 km north of the site. A state park is located about 10 km west-southwest of the site, and a state forest and campground are about 14 km northeast of the site.

F.3 GEOLOGY

The area in which the reference sites are situated is assumed to occupy a terrace at an elevation of 300 m above sea level (MSL). Several flat alluvial terraces comprise the main topographic features in the vicinity. Many of these terraces are lower than that at the site and lie at an average elevation of 280 m above sea level and, in general, slope away from the river at grades of 2 or 3%. The topography in the area of the site is essentially typical of that in the region.

The rocks that underlie this region are classified as pre-Cambrian and are very old. Glaciation probably less than 1,000,000 years in age, as well as recent alluvial deposition, has mantled the older basement rocks with a variety of unconsolidated materials in the form of glacial moraines, glacial outwash plains, glacial till and river bed sediments. This cover of young soils rests upon a surface of glacially carved deeper rock consisting sequentially in depth of sandstone, shale and granitic rocks. The upper surface of underlying rock can support unit foundation loads up to 73,000 kg/m^2. The bedrock surface is irregular and slopes generally to the east or southeast.

The nearest known or inferred fault is 37 km southeast of the site. There is no indication that faulting has affected the area of the site in the last few million years. Within the last 100 years, only two earthquakes were recorded as having occurred within 160 km of the site. The first occurred in 1917 and had an intensity of VI on the modified Mercalli scale. The epicenter was located about 100 km northwest of the site. The second occurred in 1950; it had an estimated intensity of V to VI and the epicenter was located about 130 km north-northwest of the site. For construction of facilities in this area the design basis earthquake relates to a horizontal acceleration of 0.1 g.

F.4 HYDROLOGY

Large supplies of ground water are available from the R River outwash plain alluvium, glacial moraine, and from underlying sandstones in the area. The general course of deep ground-water flow is to the southeast. The regional gradient broadly parallels the trend of the topography and the surface drainage. The natural surface drainage of the immediate site area is mainly to the southeast, toward the river.

The R River tributaries close to the site area are S Creek, 8 km northwest, and T Creek, 5 km southwest. The B River flows parallel to and east of the R River, joining the R 24 km downstream from the site area.

The ground-water levels near the site are relatively flat and slope toward the river during normal river stages. During periods of high river flow, there may be some reversal of ground-water flow near the river. These reversals would be of short duration and infiltration of water from the river would be limited. The gradient toward the river is re-established after the high water recedes.

River flow information based on data from the R River gaging station is as follows:

Number of years of record	40
Average annual flow, ℓ/sec	120,000
Minimum recorded flow, ℓ/sec	6,200
Maximum recorded flow, ℓ/sec	1,300,000

River flow and temperature data pertinent to the reference site are shown in Figures F.4.1 and F.4.2, respectively.

Flow duration data for the R River calculated in the vicinity of the reference site are shown in Figure F.4.3. Based on these data, the flow is expected to exceed 50,000 ℓ/sec 90% of the time and 27,000 ℓ/sec 99% of the time.

The average river velocity at the site varies between 0.5 and 0.8 m/sec for flows below 280,000 ℓ/sec. The river drops about 3 m from 2.4 km upstream to 2.4 km downstream of the site. Rapids frequently occur in this stretch of the river.

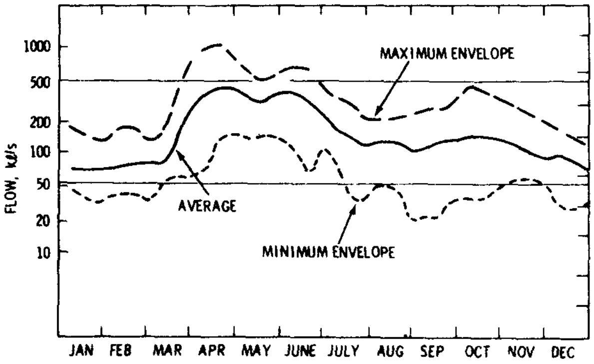

FIGURE F.4.1. Daily Average and Extreme River Flows at the Reference Site

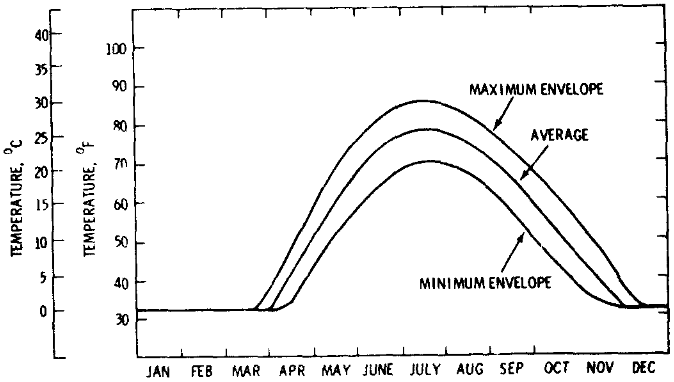

FIGURE F.4.2. Daily Average and Extreme Water Temperatures at the Reference Site

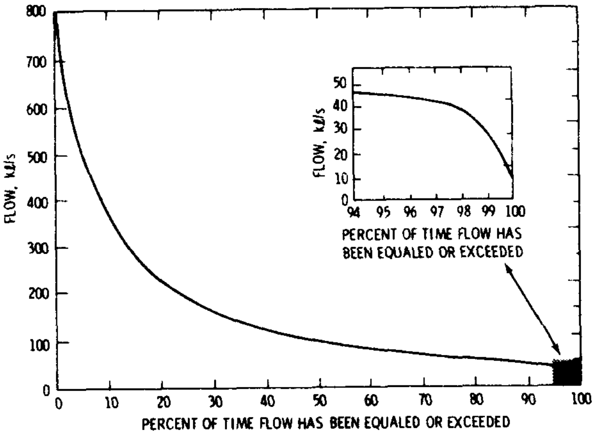

FIGURE F.4.3. River Flow Duration Data for R River at the Reference Site

The 1-in-1000-year flood is expected to reach 281 m MSL (mean sea level), and the maximum flow of record (1965) is estimated to have reached 279 m MSl. Normal river stage in the vicinity of the site is about 276 m MSL, and the site grade is 300 m MSL.

A study was conducted to determine the predicted flood discharge flow and water level at the site resulting from the "maximum probable flood" as defined by the U.S. Army Corps of Engineers. The "maximum probable flood" was estimated as 10 million ℓ/sec with a corresponding peak stage of elevation 286 m MSL at the reference site. The peak level at the site would be reached in about 12 days from the onset of the worst combination of conditions resulting in the "maximum probable flood."

The R River water's chemical characteristics are given in Table F.4.1.

The nearest domestic water supply reservoir is the G Water Works Reservoir. This reservoir is located in northern G and is fed by the R River from an intake about 64 km downstream from the reference site area. (This water supply serves about 1.8 million people)

The ground-water table under normal conditions is higher than the river; thus ground water and runoff drain to the river. There are numerous shallow wells supplying residences and farms along the river terrace. The closest public water supply well is the A city well, which obtains water 72 m below ground level.

TABLE F.4.1 R River Water Chemistry Summary of 12 Monthly Samples

	Minimum	Maximum	Average	Std. Dev.	No.
Solids-mg/ℓ					
Total	143	216	185	23.2	12
Dissolved	125	208	178	27.8	12
Suspended	1.2	18.4	7.5	6.2	12
Hardness-mg/ℓ (As $CaCO_3$)					
Total	98	174	147	24.8	12
Calcium	70	120	99	15.6	12
Magensium	28	58	48	9.9	12
Alkalinity-mg/ℓ (As $CaCO_3$)					
Total	91	165	140	24.3	12
Phenolphthalein	0	12	1.8	4.1	12
Gases-mg/ℓ					
Free carbon dioxide	--	--	--	--	--
Ammonia-nitrogen (N)	0.0	0.09	0.02	0.03	12
Anions-mg/ℓ					
Carbonate (CO_3)	0.0	14.4	2.10	4.96	12
Bicarbonate (HCO_3)	111	201	166	29.1	12
Hydroxide (OH)	--	--	--	--	--
Chloride (Cl)	0.30	5.00	1.43	1.48	12
Nitrate-nitrogen (N)	0.07	0.55	0.26	0.15	12
Sulfate (SO_4)	6.3	13.5	9.5	2.2	12
Phosphorus-soluble (P)	0.012	0.057	0.030	0.012	12
Silica (SiO_2)	3.2	12.5	7.7	3.3	12
Cations-mg/ℓ					
Calcium (Ca)	28.0	48.1	39.7	6.28	12
Magneisum (Mg)	6.8	14.1	11.6	2.4	12
Sodium (Na)	2.8	6.4	5.0	1.1	12
Total iron (Fe)	0.04	0.52	0.23	0.13	12
Total manganese (Mn)	--	--	--	--	--
Potassium (K)	--	--	--	--	--
Miscellaneous					
Color (APHA units)	20	80	39	22	12
Turbidity (JTU)	1.00	4.50	2.53	1.48	12
Ryznar index (AT 77°F)	6.64	7.86	7.21	0.377	12
Conductivity (mmho)	192	350	292	49.8	12
pH	7.40	8.60	8.15	0.308	12
BOD (mg/ℓ)	0.9	2.5	1.4	0.58	12
Dissolved oxygen (mg/ℓ)	8.0	15.0	10.6	2.1	11
Temp. (DEG. C)	0.0	23.0	9.69	9.03	12

F.5 METEOROLOGY

The general climatic regime of the site is that of a marked continental type characterized by wide variations in temperature, scanty winter precipitation, normally ample summer rainfall, and a general tendency to extremes in all climatic features. Temperature data, obtained by adjusting 54-year climatological summaries for G and B, indicate that January is the coldest month, with average daily maximum, mean and minimum temperatures of -6, -11 and -16°C, respectively. July is the warmest month, with corresponding temperatures of 28, 22, and 16°C. Table F.5.1 shows monthly statistics.

The number of days with maximum temperatures of 32°C and above is estimated to be 12. The numbers of days with a minimum temperature of 0°C or below and -18°C or below are estimated to be 168 and 40, respectively. The January relative humidities at 7:00 a.m., 1:00 p.m., and 7:00 p.m., EST, are estimated to be 76, 68, 70%, respectively. The corresponding humidities for July are 86, 55, and 55%. Monthly average humidities are shown in Table F.5.2.

The annual average rainfall is about 76 cm. The maximum 24-hr total rainfall for the period 1894-1965 for B was 13 cm and occurred in May. Thunderstorms have an annual frequency of 36 and are the chief source of rain from May through September. Snowfall in the area has an annual average of 110 cm, with occurrences recorded in all months except June, July and August. The extremes in annual snowfall of record are a 15-cm minimum and a 220-cm maximum.

Annually, the winds are predominantly from the northwest or from the south through southeast. This bimodal distribution is characteristic of the seasonal wind distributions as well. The average windspeed for spring is 11 km/hr and for the other seasons about 16 km/hr. The maximum reported windspeed of 160 km/hr, reported in July 1951, was associated with a tornado. Tornadoes and other severe storms occur occasionally. Eight tornadoes were reported in the period 1916 to 1967 in county A. The theoretical expected frequency of a tornado striking a given point in this area is 5 x 10^{-4} per year. For design purposes a maximum windspeed of 580 km/hr is assumed to be associated with tornadoes.

TABLE F.5.1. Monthly Temperature Statistics (°C)

	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Maximum	-6.1	-4.4	3.3	12.8	20.0	25.0	28.3	26.7	22.2	15.0	4.4	-3.3
Minimum	-16.1	-14.4	-6.7	1.7	7.8	13.3	16.1	15.0	10.0	3.9	-4.4	-12.2
Mean	-11.1	-9.4	-1.7	7.2	13.9	18.9	22.2	21.1	16.1	9.4	0.0	-7.8
Extreme Max	15.0	16.1	27.8	32.8	40.6	39.4	41.7	40.0	40.6	32.2	23.9	17.2
Extreme Min	-38.9	-36.7	-34.4	-15.6	-5.7	6.0	5.6	3.3	-5.6	-13.3	-27.8	-33.9

TABLE F.5.2. Mean Monthly Relative Humidity percent

Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
74	75	73	66	62	66	68	70	70	66	73	78

It is estimated that natural fog restricting visibility to 0.4 km or less occurs about 30 hr/year. Icing due to freezing rain can occur between October and April, with an average of one to two storms per year. The mean duration of icing on utility lines is 36 hr.

Diffusion climatology comparisons with other locations indicate that the site is typical of the region, with relatively favorable atmospheric dilution conditions prevailing.(a) Frequency of thermal inversion is expected to be about 32% of the year, and the frequency of thermal stabilities is 19% slightly stable, 27% stable, 20% neutral, and 34% unstable. The joint distribution of windspeed, direction, and stability is given in Table F.5.3.

TABLE F.5.3 Annual Average Joint Frequency Distribution, Percent of Occurrence

WIND SPEED(M/S)	STABILITY TYPE							WIND DIRECTION								
		NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
1.10	A	.02	0.00	.01	0.00	.01	.01	0.00	.02	.02	0.00	0.00	.01	.02	0.00	0.00
2.50	A	.10	.11	.17	.12	.07	.15	.11	.15	.25	.21	.31	.35	.32	.37	.19
4.30	A	.27	.31	.21	.22	.22	.30	.47	.58	.40	.58	.42	.41	.62	.77	.62
6.50	A	.06	.07	.01	.06	.25	.72	.73	1.38	.62	.16	.15	.09	.51	.64	.59
9.10	A	0.00	0.00	0.00	0.00	0.00	.02	.32	.31	.07	0.00	.04	.04	.10	.17	.14
12.20	A	0.00	0.00	0.00	0.00	0.00	0.00	.02	.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.10	B	.02	.02	.02	.04	.02	.02	.02	.06	.01	.04	.04	.01	0.00	.01	0.00
2.50	B	.09	.04	.16	.05	.12	.09	.06	.15	.11	.14	.12	.16	.14	.16	.10
4.30	B	.19	.14	.05	.14	.05	.09	.14	.23	.21	.19	.07	.25	.16	.22	.22
6.50	B	.01	.01	.02	.01	.07	.07	.05	.07	.02	0.00	0.00	.06	.21	.21	.17
9.10	B	0.00	0.00	0.00	0.00	.01	0.00	.01	.02	.01	0.00	0.00	.01	0.00	.11	.01
12.20	B	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.10	C	.02	.01	.04	0.00	0.00	.01	.01	.01	.01	0.00	.05	.01	.02	0.00	0.00
2.50	C	.05	.10	.04	.06	.07	.07	.06	.06	.12	.06	.09	.10	.07	.09	.09
4.30	C	.11	.04	.07	.04	.07	.05	.17	.12	.05	.04	.02	.16	.17	.22	.14
6.50	C	.02	.01	.04	.01	.04	.05	.04	.07	.01	.01	.02	0.00	.17	.15	.07
9.10	C	.05	0.00	0.00	0.00	0.00	0.00	0.00	.02	0.00	0.00	.01	.02	.02	.07	0.00
12.20	C	.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.10	D	.19	.16	.22	.04	.07	.09	.07	.10	.10	.14	.10	.11	.07	.10	.09
2.50	D	.54	.61	.85	.82	.47	.46	.47	.53	.32	.32	.41	.67	.47	.99	.90
4.30	D	.73	.60	.62	1.03	.94	1.17	.90	.66	.49	.36	.36	.72	1.30	1.65	1.30
6.50	D	.21	.27	.19	.46	.61	.61	.37	.35	.20	.22	.10	.38	1.24	1.40	.78
9.10	D	.10	.04	0.00	0.00	.01	.04	.07	.05	.02	.01	.01	.16	.07	.21	.10
12.20	D	.02	0.00	0.00	0.00	0.00	0.00	0.00	.02	0.00	0.00	0.00	0.00	0.00	.01	0.00
1.10	E	.06	.02	.11	.15	.07	.20	.09	.14	.11	.10	.10	.12	.05	.17	.06
2.50	E	.51	.35	.25	.61	.57	.72	.33	.30	.21	.42	.52	.65	.49	.75	.48
4.30	E	[illegible]	.10	.06	.38	.26	.91	.69	1.16	.57	.49	.30	.67	.64	.78	.35
6.50	E	.01	0.00	0.00	.11	.01	.15	.30	.56	.30	.10	.06	.05	.22	.09	.02
9.10	E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.20	E	0.00	0.00	0.00	0.00	0.00	0.00	0.00	.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.10	F	.07	.11	.11	.10	.12	.06	.12	.19	.10	.15	.15	.21	.09	.10	.20
2.50	F	.14	.22	.15	.42	.40	.46	.58	.65	.32	.35	.35	.63	.37	.67	.36
4.30	F	0.00	.01	0.00	.02	.05	.20	.30	.48	.27	.14	.05	.10	.04	.17	.14
6.50	F	0.00	0.00	0.00	0.00	0.00	0.00	.04	.01	.05	0.00	0.00	.01	0.00	0.00	0.00
9.10	F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.20	F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.10	G	.09	.04	.12	.20	.11	.19	.32	.31	.17	.31	.46	.33	.22	.20	.12
2.50	G	.05	.05	.07	.14	.17	.32	.65	.74	.21	.23	.28	.28	.15	.35	.36
4.30	G	.01	.01	0.00	[illegible]	.01	.01	.02	.10	.02	0.00	.02	.01	0.00	.12	.04
6.50	G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.10	G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.20	G	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

SUMMARY DATA, FOR STABILITY-TYPE	A	B	C	D	E	F	G
TOTAL PERCENT FOR STABILITY IS	17.85	5.90	4.00	34.37	19.46	10.44	7.94

(a) An investigation of the variations in atmospheric dispersion among a number of sites around the nation was made to determine differences to be expected in radiation dose calculations based on atmospheric dispersion because of different synoptic conditions for different locations. For five of the eight sites studied it was determined that the maximum atmospheric dispersion coefficient at 1100 m and at 72 km from the point of release was not greater by more than a factor of two over that of the reference site. It was no greater than a factor of six for any of the other three sites studied.

F.6 PATHWAY PARAMETERS RELEVANT TO RADIOLOGICAL DOSE CALCULATIONS

Radiation exposure of man via airborne pathways may include that from radiation emitted from overhead plumes and ground-level clouds; direct radiation from radionuclides deposited on the ground; inhalation of radionuclides released to the atmosphere; and consumption of foods produced from vegetation upon which radionuclides have been deposited or which have been grown in soils on which deposition has accumulated. Such foods may include vegetables from local gardens; milk from cows foraging on pasture grass; or meat from animals raised on pasture and feed grown in the vicinity of the plant. These pathways are illustrated in Figure F.6.1.

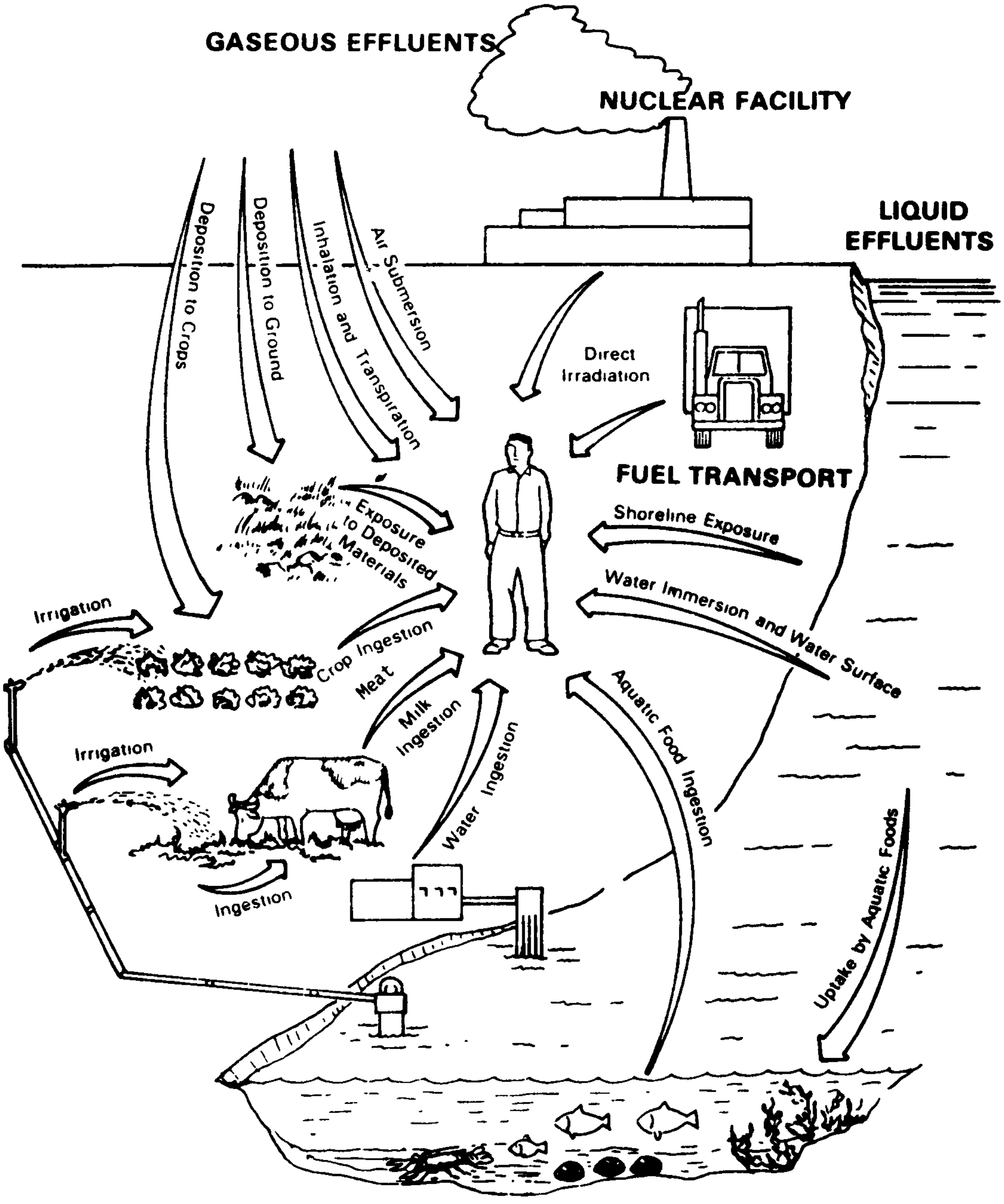

FIGURE F.6.1. Pathways for Radiation Exposure of Man

Also, as illustrated in Figure F.6.1, radiation exposure of man via surface water pathways may include that from ingesting radionuclides with drinking water, consumption of aquatic foods, and direct radiation from surface waters received through shoreline activities or swimming or boating.

For the milk and home garden pathways, the nearest dwelling is assumed to be a farmhouse adjacent to the site boundary southeast of the main plant where the maximum ground-level atmospheric dispersion factor ($\bar{X}/Q'$) is about 3×10^{-7} sec/m^3 for ground-level releases and 1.5×10^{-8} sec/m^3 for tall stack releases. A milk cow is assumed to be kept at this farm and maintained on fresh pasture 7 months of the year. It is assumed that a garden is kept for vegetables; however, there are no large truck gardens in the area.

For the farm-crop-irrigation pathway, it is assumed that about 82% of land in the vicinity of the site is farmed. Production is essentially 60% soybeans (0.7 kg wet weight/m^2) 30% corn, oats and other grain (0.35 kg wet weight/m^2) and 10% hay (1.5 kg wet weight/m^2). For dose calculation purposes, it is assumed that 10% of the average flow rate ($\sim$12,000 ℓ/sec) of the R River in the vicinity of the plant site is drawn from the river during June, July and August for irrigation of 250 km^2.

For the recreational and aquatic food pathways, it is assumed that in the vicinity of the plant a "maximum-exposed individual"(a) may spend 100 hr/yr swimming or boating and may spend 500 hr/yr obtaining 10 kg of fish and 10 kg of fresh water mollusca. Aquatic foods are assumed to be consumed within 24 hours of the time they are harvested.

For pathways to the population, it is assumed that 85% of the 2 million residents within 80 km of the site obtain their drinking water from the R River. Travel time to the consumer from a point on the river nearest the site is taken to be 48 hours. It is assumed that on the average each person will spend 5 hr/yr swimming and 10 hr/yr boating or fishing downstream from the site. The average per capita fish consumption for this area has been estimated to be 1.1 kg/yr. It is assumed that 10% of this consumption is from fish obtained downstream from the site.

(a) A "maximum-exposed individual" is an individual whose habits tend to maximize his or her dose.

F. 12

APPENDIX G

REFERENCE SITES FOR ASSESSING SOCIAL AND ECONOMIC IMPACTS

A generic assessment of socioeconomic impacts incorporates the assumption that various sites may be under consideration for development of nuclear waste management facilities. Since the potential sites may differ considerably in their distinguishing characteristics (e.g., population size, composition, and distribution; industrial composition of the labor force; and availability of social services) it is necessary to examine the potential effects of energy facilities on several alternative sites. For example, it is reasonable to assume that a highly urbanized community offering a wide range of services to residents will experience fewer negative effects from the construction and operation of a project than will a sparsely populated rural community. In the latter, even a relatively small project could produce disruptive effects.

In addition to considering alternative reference sites, it is also necessary to assess the effects of several types of nuclear waste management facilities. These facilities differ substantially in terms of the length of time and the number of workers needed for construction, the number of workers required for planned operation, the potential hazards created through storage and transportation of noxious materials, and the amount of land occupied. Thus, it is reasonable to expect that the variety and degree of socioeconomic impacts will differ according to the facility in question.

Each of the three reference sites utilized in the assessment of social and economic impacts is based on realistic conditions chosen on the basis of criteria listed below. They should not be construed to represent an endorsement of any specific site for facility location. Since the reference sites are to be used in a generic or hypothetical sense, source references supporting the descriptive material are presented in terms of their broad, general areas rather than in specific terms (see Table G.2.1). One of the three reference sites coincides with the reference environment described to in Appendix F.

G.1 CRITERIA FOR REFERENCE SITE SELECTION

To permit an assessment of a wide range of variation in impacts, three reference sites were selected for analysis from a larger number of possible locations for nuclear waste facilities on the basis of two criteria:

- population size. The three sites vary markedly in terms of the total number of inhabitants at the site and in the surrounding region.
- population distribution. The three sites exhibit variations in population density and degree of urbanization.

G.2 CHARACTERISTICS OF REFERENCE SITES

To emphasize that the reference sites are hypothetical, they are simply labeled Midwest, Southeast, and Southwest. Each reference site consists of a single county. The region within which the county is located is defined as the aggregation of all counties falling substantially within a 50-mile radius of the facility. If more than half of a county is included within that 50-mile radius, it is included in the region.

Regional populations are important for assessing site impacts because a sizable portion of the site labor force may commute to work from regional localities. Fifty miles represents the maximum commuting distance that most workers are willing to undertake. Furthermore, population redistribution within the region may result in project-related impacts.

Table G.2.1(a) summarizes data for the site counties and surrounding regions. Two types of comparisons can aid in the interpretation of these data. First, there are marked differences among the sites, whether based on county or regional comparisons. Second, there are important differences between the county and the region for each site. From the population data it is evident that the Southeast and Midwest regions are highly urbanized when compared with the Southwest region. Differences among the three counties are even greater. While the Midwest site falls within the most urbanized region, the county containing that site has the smallest urban component. In fact, each site county is less urbanized than its corresponding region, reflecting the likelihood that waste repositories will be situated away from urban centers and densely settled areas. The density figures also support this observation.

The sites vary dramatically in terms of population change over the 1965 to 1970 period, with the Southwest site showing a marked decline, the Midwest site a comparable increase, and the Southeast site remaining relatively stable. From 1970 to 1975 all sites gained population, and the differences among the rates of change are smaller than in the preceding 5-year period. These changes over the decade can be attributed to two components: natural change and net migration. Natural change is the difference between births and deaths. Net migration is the difference between the number of persons moving into an area and the number moving out. Each site has experienced an excess of births over deaths, thus serving to moderate the population loss due to emigration from the Southwest and Southeast sites over this period while increasing the growth experienced by the Midwest site. Population change has important consequences in the capacity of a site to absorb impacts. Counties that are experiencing rapid population growth may be more likely to plan to accommodate further demand on local services than counties that are not growing. On the other hand, counties that are losing population may have under-utilized service sectors, which would then be available to serve the needs of project-related immigrants.

While the Southeast county has a high urban component compared with the Midwest county, the Southeast county is only one-fifth as densely populated as the Midwest county. In the

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(a) The population data used here are based on realistic locations covering the period 1970 to 1975. Analyses of future impacts are based on projections of these data to the year 1980 and beyond.

Table G.2.1 Selected Data characteristics of Three Reference Sites, Socioeconomic Impact Analysis (a)

Characteristic	Southwest Site		Midwest Site		Southeast Site	
	County	Region	County	Region	County	Region
Population						
Estimated total population 1975	42,000	142,000	47,000	2,154,000	17,000	487,000
% Change 1965-1970	-8.5	-8.6	15.0	11.1	-1.4	4.2
% Change 1970-1975	3.2	5.8	24.9	3.8	11.9	2.6
Unemployed construction labor force, 1980	--	390	--	10,660	---	2,420
Net migration rate 1965-1970	-14.9	-14.6	7.4	3.0	-6.6	-2.4
Net migration rate 1970-1975	-0.9	0.5	18.4	-0.7	6.1	-2.2
% Urban 1970	76.9	78.9	8.4	85.1	40.9	50.1
Density 1970 (persons per sq. mi.)	9.9	9.2	57.8	246.8	31.1	60.1
% Nonwhite 1970	2.9	5.0	0.3	2.4	41.3	38.3
% Families with children under 18, 1970	56.8	59.3	59.4	59.7	57.6	57.6
Median age 1970	27.2	26.3	25.6	25.6	24.9	24.5
Employment						
Nonworker to worker ratio	1.7	1.7	1.6	1.3	1.4	1.5
% Employed in farming	5.7	5.8	13.6	2.2	8.5	4.9
% Employed in construction	7.7	5.6	6.0	3.7	5.2	5.8
% Unemployed	5.1	5.1	4.5	3.3	4.6	4.3
% Below poverty level	17.8	16.6	10.8	5.5	24.6	22.3
Median family income	7,870	7,965	8,936	11,242	6,997	7,166
Education						
Median years school completed	11.9	12.0	12.2	12.3	9.8	10.6
% High school graduates	49.3	51.3	56.0	64.5	29.8	37.0
Housing						
% Housing units renter occupied	25.9	25.7	15.8	31.5	33.4	33.2
% Units vacant	16.1	18.2	6.4	3.4	9.4	8.3
Trailers as % of housing units	2.5	3.3	6.5	1.8	7.2	5.8
% Units lacking plumbing	5.0	3.6	8.7	4.0	29.3	19.7
% Units built 1939 or earlier	19.2	17.6	53.3	41.1	36.8	30.6
% Units with 1+ persons per room	11.7	11.6	9.5	6.9	15.1	13.1
% Units using public sewer service	77.8	82.1	39.3	82.7	45.8	46.3

(a) These data were developed from standard sources, but since sites are generic, no identifying information is given.

Southwest region most people live in towns just large enough to qualify as urban by the U.S. Census Bureau (2500 or more). The nearest metropolitan center (population 50,000/year or more) is over 100 miles from any part of the Southwest region. The Midwest region, however, contains a very large metropolitan center, though the site itself is primarily rural.

Looking briefly at the data related to employment, it is apparent that the Midwest site residents enjoy the highest standard of living. This is true for both the county and the region and is reflected by relatively high family income, low percent unemployed, and low percent below the poverty level, defined for 1975 by the U.S. Census Bureau as $5500 for a nonfarm family of four. In contrast, almost one-quarter of the Southeast site residents are below the poverty level, and the median income for the Southeast region is less than two-thirds that for the Midwest region. Similar regional differences are reflected in the data presented on education. The Southeast site residents are substantially less educated than residents from the other two sites, a condition to be expected from the more rural character of the Southeast site.

Housing variables are critical because they reflect the ability of a community to adequately accommodate a substantial population influx. Vacancy rates coupled with the condition of housing determine the ease with which the incoming labor force can find adequate, affordable living space. In this regard, the Southwest site is apparently best situated to accommodate a population influx. It has a higher vacancy rate and substantially newer housing units in better condition when compared with the other two sites. In addition, a very high proportion of the Southwest site's housing facilities are connected to a public sewer service.

The three reference sites selected are each distinct in terms of demographic, economic, and social service characteristics. The relative size and significance of socioeconomic impacts that might accrue from the construction and operation of waste management facilities will be conditioned in large part by these characteristics of the reference site.

APPENDIX H

HAZARD INDICES

The total quantity of radioactive material to be isolated can be compared to the isotope quantities that naturally occur in the earth's crust (Winegardner and Jansen 1974, Smith 1975). This comparison can be used to indicate the relative hazard that may result from the burial of radioactive waste (i.e., geologic isolation). Early efforts to develop safety perspectives on geologic isolation led to the development of hazard indices. These indices attempted to combine those parameters that characterize waste isolation into an index on public health and safety. The indices use one or more of the following parameters: quantity of radioactive material, specific activity, decay properties, chemical and physical form, packaging, toxicity, time behavior, and pathways.

Some hazard indices that have been developed are listed and defined in Table H.0.1. Studies in which they have been used include: the comparison of the toxic content of high-level waste to the toxic content of the uranium ore and tailings from which it came (Cohen 1976, 1977); the comparison of the toxic level of Pu sent to high-level waste against the toxic level of lead sent to waste (Cohen 1975); The Reactor Safety Study (NRC 1975) (risk of nuclear plant accidents compared to risk of natural disasters); risk of plutonium shipments (Hall et al. 1977); risk of natural and man-caused radioactivity (Turnage 1976); the relevance of nuclide migration at Oklo (Walton and Cowan 1975); underground testing of nuclear devices (Teller et al. 1968); direct impact of disruptive events (Starr 1970); and risk comparisons to alternative energy resources (Grahn 1976, pp. 371-387; Straker and Grady 1977; Cottrell 1976; Blot et al 1.977; Starr et al. 1972; Petrikova 1970; McBride et al. 1977).

The various hazard indices attempt to incorporate additional considerations (such as the concentration of the waste material and the pathways for the nuclear material to enter the biosphere) into the comparison between nuclear waste and naturally occuring radioactive materials. As can be seen in Table H.0.1, the total quantity of radioactive material (Q), the maximum permissible concentration (MPC), and the maximum permissible intake (MPI) give measures of the toxicity of the waste material. A better index of the toxicity of the material is the hazard measure (HM) (Walton and Cowan 1975), which is the quantity of water required to dilute the material to its acceptable maximum permissible (non-toxic) concentration. Thus, the HM is a number that is proportional to the toxicity of the waste material. The "first modified hazard measure" (HM1) (Walsh et al. 1977) compares the anticipated exposure (or dose) to an allowable limit. It was introduced to evaluate the effect of environmental pathways on hazards from a variety of environmental pollutants including nuclear wastes. The second modified hazard measure (HM2) (McGrath 1974) is a measure of the potential hazard of radioisotope releases in air and water. It is a number proportional to such hazard. The third modified hazard measure (HM3) (Petrikova 1970) is a quantity to assess the radioactive risk to future generations from future releases of radioisotopes. It is the

TABLE H.1. Hazard Indices(a)

Hazard Index	Definition and Inputs	Interpretation (for Nuclear Waste Isolation)(b)
Quantity of Radioactive Material (Q)	Waste Inventory (or waste released)	Comparison of waste inventories to natural radionuclides (or for use below) (Winegardner and Jansen 1974).
Maximum Permissible Concentration (MPC)	10 CFR 20	Relative hazards of radioactive species (or for use below).
Maximum Permissible Intake (MPI)	$MPI_{air} = (7300\ m^3/yr)\ (MPC_{air})$ $MPI_{water} = (0.8\ m^3/yr)\ (MPC_{water})$	Same as MPC.
Hazard Measure (HM)	$HM = Q/MPC$	Volume of air or water to dilute Q radionuclides to one MPC. (Winegardner and Jansen 1974, Smith 1975)
Modified Hazard Measure (HM1) (Walsh et al. 1977)	$HM1 = D/D_2$ D = exposure D_2 = exposure limit	Ratio of anticipated exposure to allowable limit.
Modified Hazard Measure (HM2) (McGrath 1974)	$HM2 = Q(a/MPI_{H_2O} + b/MPI_{air})$ a,b = fractions of Q released to water and air	$HM2 = Q(a/MPI_{H_2O} + b/MPI_{air})$
Modified Hazard Measure (HM3) (Smith and Kastenberg 1976)	$HM3 = \int_t^{t+d} (Q(t')/MPI)dt'$	Number of MPI in the environment versus time.
Potential Hazard Measure (PHM) (Gera and Jacobs 1972)	$PHM = P \frac{Q}{MPI} \frac{1}{\lambda}$ P = probability of reaching man λ = decay constant	Risk of releasing Q versus time.
Hazard Index (HI) (Claiborne 1975, Haug 1977)	$HI = \frac{Q}{MPC(V)}$ V = entrained volume	Number of MPCs per unit volume.
Hazards Available Index (HA) (Bruns 1976)	$HA = \log_{10}HI + \log_{10}TF$ TF = transport factors	HI with pathway transport efficiency included.
Isolation Time (T) (Voss and Post 1976)	$T = -\frac{1}{\lambda} \ln \frac{MPC\ V_f\ D}{A\ L}$ V_f = groundwater volume flow rate D = dilution factor A = waste leach area L = leach rate	Time which nuclides must be held to reduce concentration to one MPC.
Relative Toxicity Index (RTI) (Haug 1977, Hamstra 1975, Haug 1976, Cohen and Tonnessen 1977, Roching 1977)	$RTI = \frac{(Q/MPC)\ \text{waste}}{(Q/MPC)\ U_{ore}}$	Ratio of HI of the waste to HI of the uranium ore mined to generate the waste. This has been generalized to compare with substances other than uranium.

(a) A compilation from published studies.
(b) As defined by originator.

number of MPI in the environment versus time. The potential hazard measure (PHM) (Gera and Jacobs 1972) is an index that is proportional to the quantity of radionuclides buried as a function of time and modified by the probability that this material will reach man. The hazard index (HI) (Claiborne 1975) is a quantity that is proportional to the specific toxicity of a radionuclide. It was formulated to assess the benefits of actinide removal from high-level waste. The hazards available index (HA) (Bruns 1976) is a modification of the hazards index that includes a pathways transport efficiency. It has been used to compare the hazard from Purex waste to the hazard from fallout. The isolation time (T) (Voss and Post 1976) is the time radionuclides must be held to limit their concentration in ground water to one MPC. It was introduced to characterize the effectiveness of geologic isolation in restraining the transport of radionuclides via the groundwater transport path. The relative toxicity index, RTI (Haug 1977, Hamstra 1975, Haug 1976, Cohen and Tonnessen 1977, Rochlin 1977), is the ratio of the hazard indices of nuclear waste to uranium ore. This index has been generalized to compare to toxicity of nuclear waste to the toxicity of other naturally occurring toxic elements.

Although each hazard index has merit for a particular set of conditions, the provision of simple measures of hazard can confuse rather than clarify. For this reason hazard indices are infrequently used in this Statement and dose and associated health effects are presented instead.

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APPENDIX I

COMPARISON OF DEFENSE PROGRAM WASTE TO COMMERCIAL RADIOACTIVE WASTE

Repositories for commercial high-level and TRU wastes may also be used for disposal of defense program wastes.[a] This appendix provides a comparison of defense program radioactive wastes with commercial radioactive wastes. These comparisons indicate that both the HLW and the TRU defense-program wastes could be accommodated in repositories designed for disposal of commercial wastes with comparable environmental impact.

I.1 HIGH-LEVEL WASTE COMPARISONS

The waste quantities and radionuclide contents of defense program and commercial high-level wastes (HLW) are compared in Table I.1.1. The estimated quantities of defense program high-level waste are based on the assumption that waste forms having a 25% loading of waste oxides are encapsulated in 0.6-m x 3-m (2-ft x 10-ft) canisters that are filled to 80% of capacity. The commercial HLW is assumed to be contained in canisters that are 3 m (10 ft) long with diameters up to 0.3 m (1 ft). The quantity of commercial HLW in individual canisters is adjusted, either by dilution or by varying canister diameter, to meet the allowable heat output imposed by the disposal system. The radionuclide content and heat output of individual defense program HLW canisters is a factor of 5 to 10 or more below that of the commercial HLW canisters. The radionuclide content in the defense program HLW canisters relative to the commercial HLW canisters ranges from about the same magnitude for plutonium to orders of magnitude less for some of the other nuclides.

(a) President Carter, Feb. 12, 1980.

TABLE I.1.1. Comparison of Defense and Commercial High-Level Waste

	Canisters Required	Heat Output kW/Canister(a)	Radionuclide Content, Ci/Canister(a)					
			^{90}SR	^{137}CS	^{238}Pu	^{239}PU	^{241}Am	^{244}Cm
Defense HLW(b)								
• Savannah River	8.0×10^{3}	0.2	1.5×10^{4}	1.5×10^{4}	1.4×10^{2}	2.9	8.2	8.2
• Idaho Falls	1.2×10^{4}	0.09	7.3×10^{3}	7.4×10^{3}	4×10^{1}	4×10^{-1}	6.0×10^{-1}	3.1×10^{-1}
• Hanford	2.6×10^{4}	0.06	5.2×10^{3}	4.8×10^{3}	2×10^{-2}	9.2×10^{-1}	6.5	5.4×10^{-1}
Total	4.6×10^{4}							
Commercial HLW(c)	1.0×10^{5} to 2.8×10^{5}	3.2 to 1.2	1.4×10^{5} to 5.0×10^{4}	2.0×10^{5} to 7.1×10^{4}	1.8×10^{2} to 6.5×10^{1}	4.3 to 1.5	1.7×10^{3} to 6.1×10^{2}	1.4×10^{4} to 5.1×10^{3}

(a) Nominal values, assuming uniform distribution of waste radionuclides among the canisters.

(b) Estimated data for the year 1990. Treated waste volumes (assuming a waste form having a 25% loading of waste oxides) and radionuclide contents supplied by J. L. Crandall and W. R. Cornman of the High-Level Waste Lead Office at Savannah River. Canister requirements based on 0.6-m-diameter x 3-m-long canisters, 80% full of treated waste. Heat outputs based on the contained radionuclides.

(c) Data from this Statement for the reprocessing of spent fuel containing 2.4×10^{5} MTHM (Case 3) and radioactivity at 6.5 years after reactor discharge. Canister requirement dictated by the heat output allowed by the disposal system.

I.2 TRU WASTE COMPARISONS

The defense program TRU wastes will require a variety of treatment procedures. Because potential treatment procedures for these wastes are not yet sufficiently well defined to develop good estimates of treated waste forms and quantities, they are compared to commercial TRU wastes on the basis of untreated quantities and radionuclide compositions in Table I.2.1. The quantity of defense program TRU wastes is about the same magnitude as the estimated commercial wastes for the Case 3 growth assumptions (see Chapter 7). The plutonium content is similar to the commercial waste. In both cases, the americium and curium content varies over a wide range.

TABLE I.2.1. Comparison of Defense and Commercial TRU Wastes

	Volume, m^3				TRU Content, Ci/m^3(a)					
	Retrievably Stored	Buried	Soil Contaminated by Burial	Total	kg	kg/m^3	^{238}Pu	^{239}Pu	^{241}Am	^{244}Cm
Defense TRU Waste On hand as of September 30, 1979										
● Hanford	8.0×10^4	1.6×10^5	1.4×10^5	3.8×10^5						
● INEL	3.7×10^4	5.6×10^4	0	9.3×10^4		8×10^{-3}	5×10^{-1}	3.5×10^{-1}	1.4	3.4×10^{-2}
● LASL	1.5×10^4	1.1×10^4	1.7×10^4	4.3×10^4						
● ORNL	1.2×10^3	6.1×10^4	1.6×10^5	1.7×10^5						
● SRP	2.4×10^3	2.7×10^4	3.4×10^4	6.3×10^4		2.8×10^{-2}	1.5×10^2	1.2		1.6×10^1
● Other	2.4×10^3	5.7×10^3	5.0×10^3	1.3×10^4						
Total	6.5×10^4	2.6×10^5	3.6×10^5	7.6×10^5	$>1.1 \times 10^3$	$>1.4 \times 10^{-3}$				
Estimated Annual Generation, 1980 to 2000	6.8×10^3	0	0	6.8×10^3						
Commercial TRU Waste Estimated to Result from Reprocessing 2.4×10^5 MTHM (Case 3 growth projection)										
● Untreated from FRPs	7.0×10^5	0	0	7.0×10^5	1.1×10^4	1.5×10^{-2}	7.9	5.5×10^{-1}	4.8×10^{-1}	9.0×10^{-1}
● Untreated from MOX-FFPs	6.6×10^4	0	0	6.6×10^4	4.5×10^3	6.8×10^{-2}	1.6×10^1	1.2	1.2×10^2	0
Total	7.7×10^5			7.7×10^5	1.6×10^4					

(a) Composition of defense TRU waste is based on estimate for retrievably stored waste only as of late 1977.

Sources of Data for Table I.1.1:

- U.S. Department of Energy. 1980. Strategy Document Long-Term High-Level Waste Technology Program. DOE/SR-WM-79-3 (Rev. 4/80). Savannah River Operations Office, Aiken, South Carolina.
- U.S. Department of Energy. 1979. Technology for Commercial Radioactive Waste Management. DOE/ET-0028. Washington, D.C.

Sources of Data for Table I.2.1:

- W.L. Carter et al., Spent Fuel and Waste Inventories and Projections. ORNL/TM-7320 (3-31-80 Draft). Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- H.C. Shefelbine. 1978. Preliminary Evaluation of the Characteristics of Defense Transuranic Wastes. SAND 78-1850. Sandia Laboratories. Albuquerque, New Mexico.
- Interagency Review Group, 1979. Report to the President by the Interagency Review Group on Nuclear Waste Management. TID-29442, U.S. Department of Energy, Washington, D.C.
- U.S. Department of Energy. 1979. Technology for Commercial Radioactive Waste Management. DOE/ET-0028. Washington, D.C.
- U.S Department of Energy. 1980. Transuranic (TRU) Waste Management Program National Strategy Document. DOE/AL-TRU-8002 (Final Draft, March 1980).

APPENDIX K

GEOLOGIC REPOSITORY DESIGN CONSIDERATIONS

K.1 THERMAL CRITERIA

A major factor in geologic isolation of radioactive waste is the heat generated by high-level waste (HLW) or spent fuel assemblies. This heat flows from the waste, through the emplaced canister and other protective material, into the host rock formation, through the rock surrounding or overlying this formation, and eventually out into the atmosphere. The heat can have definite impacts on:

- the integrity and recoverability of the waste canisters
- room and pillar stability
- integrity of the waste form over long periods of time
- the integrity of the host rock and the surrounding rock units
- any overlying aquifers and buoyancy effects on ground-water flow
- long-term uplift and subsidence of overlying rock.

To assure that the impact of the heat on these factors will not be detrimental to waste isolation objectives, a systematic determination of the repository design thermal loads is required that includes:

- establishment of limits for conditions affected by heat
- determination of acceptable thermal loads that will not bring about conditions beyond the assigned limits
- development of repository design thermal loads, taking into account safety, engineering and operational requirements.

Design limits for the repository can be specified in terms of temperature and thermomechanical criteria. Preliminary estimates of acceptable thermal conditions are summarized in Table K.1.1 and discussed below.

- Maximum Uplift Over Repository

Uplift over the repository centerline was chosen as a measure of the far-field structural consequences of repository thermal loading. The 1.2 to 1.5 m of maximum uplift, neglecting subsidence, is based on the assumption that rock-mass movements caused by uplift may be no worse than movements caused by subsidence over mines in sedimentary rocks, which are sometimes more than twice the stated limit. Far-field effects are currently being studied to determine whether 1.2 to 1.5 m of uplift is reasonable. This tentative limit may change as more information is developed. In any case, this limit must be reevaluated for each site so that the effects of rock-mass movement on the hydrological regime and long-term safety may be assessed.

TABLE K.1.1. Thermal and Thermomechanical Limits for Conceptual Design Studies

Event	Limits
Far-Field Considerations	
Maximum uplift over repository	1.2 to 1.5 m (Russell 1977)
Temperature rise at surface	0.5°C (Science Applications, Inc. 1976)
Temperature rise in aquifers	6°C (Science Applications, Inc. 1976)
Near-Field Considerations	
Room closure during ready retrievability period--salt	10 to 15% of original room opening (Russell 1977)
Room stability--granite, basalt rock strength-to-stress ratio	2 within 1.5 m of openings (Dames and Moore 1978)
Room stability--shale with continuous support rock strength-to-stress ratio	1 within 1.5 m of openings (Dames and Moore 1978)
Pillar stability--non-salt strength-to-stress ratio	2 across mid-height of pillar (Dames and Moore 1978)
Very-Near-Field Considerations	
Maximum HLW temperature as vitrified waste	500°C (Jenks 1977)
Maximum spent fuel pin temperature	300°C (Blackburn 1978)
Maximum canister temperature	375°C (Jenks 1977)
Maximum rock temperature	250°C to 350°C
Maximum fracture of non-salt rock	15 cm annulus around canister (Russell 1977)

- Temperature Rise at the Surface

Temperature rise at the surface has been limited to $< 0.5°C$ to avoid undesirable effects on the biota. This limit must also be reevaluated for each site (Science Applications, Inc. 1976).

- Temperature Rise in Aquifers

Temperature rise in aquifers has been limited to $< 6°C$ because the flow velocity could conceivably carry the higher-temperature water outside the repository area. In addition, temperature rise and temperature gradients can influence ground-water flow patterns and, in the worst case, may provide a transport mechanism to return nuclides to the biosphere. This limit is currently under study and must be reevaluated for each site, with consideration given to flow rate, salinity, and geochemistry, including dissolution, transport, and subsequent precipitation of minerals. Permissible temperature rises of 8° and 28°C for stagnant aquifers 30 and 90 m deep, respectively, have also been proposed (Science Applications, Inc. 1976).

- Near-Field Considerations

Rooms must be accessible at the end of the retrievability period to allow safe entry for the removal of canisters with the same equipment used to emplace them. Calculated room closures of less than the limit imply that the repository will generally remain structurally stable throughout the retrieval period, although some local failure controlled by local rock conditions not accounted for in the analysis may occur.

In addition to thermal loading, the closure of rooms in a salt repository will depend on the depth of the repository; this relates directly to stress and mine-geometry parameters such as the percent extraction of salt and pillar width-to-height ratios. Room closure calculations appear to be relatively insensitive to stratigraphy provided that the salt near the burial horizon is at least hundreds of feet thick.

- HWL Temperature for Glass, 500°C

Typical borosilicate waste glasses have a transition temperature of about 500°C, with a slightly higher softening temperature. Migration of heavy, separate phases in the glass might occur above the softening temperature. Significant increases in cracking and in leach rates have been observed in test glasses heated for a few months in the range 500° to 800°C. Additional information is available for solid waste temperatures of glass, calcine, and sintered glass ceramic (Jenks 1977, Mendel et al. 1977).

- Spent Fuel Pin Temperature, 300°C

A study of possible failure mechanisms during dry storage of spent fuel assemblies sealed in carbon steel canisters recommended a maximum allowable cladding temperature of 380°C based on stress rupture considerations. Some uncertainty regarding possible stress corrosin cracking was noted. To be safe, a 300°C maximum fuel pin temperature is specified here.

- Canister Temperature, 375°C

Austenitic stainless steel, probably 304L, proposed to be used in HLW canisters undergoes changes in structure during long-term exposure in air at temperatures in the range 400 to 900°C. The observed effect is an increased susceptibility to stress cracking when the steel is subsequently exposed to aqueous solutions (Jenks 1977).

- Rock Temperature, 250°C to 350°C

Behavior of salt deposits at temperatures up to 250°C are believed to be predictable. Laboratory tests (Jacobsson 1977) indicate that unconfined rock-salt samples from several locations begin to decrepitate (disaggregate) in the 260° to 320°C range, but samples from other locations show no decrepitation when heated to 400°C. Decrepitation is undesirable because it reduces thermal conductivity of the salt in the vicinity of a waste package and could lead to undesirable higher temperatures in the container and waste. In the case of bedded salt, decrepitation may release brine, which is also undesirable.

For the other rock media, i.e., granite, shale, and basalt, a good basis for specifying maximum rock temperatures had not been established at the time of this analysis. It (the criteria) will probably be quite site-specific. For shale a 250°C maximum may be reasonable and for the hard rocks temperatures higher than 350°C may be acceptable.

It must be emphasized that the limits shown in Table K.1.1 are based on the best available data at this time. As such, they should be reevaluated as more data become available. In addition, these limits require evaluation on a site-specific basis.

K.1.1 Calculation of Acceptable Thermal Loads

For convenience, the thermal criteria, subsequent analyses, and results are classified into three categories: far-field, near-field, and very-near-field. The far-field refers to the formation at distances far removed from the repository. The near-field represents the region within the repository horizon in the vicinity of the emplacement rooms and associated pillars. The very-near-field refers to the waste package and the rock within a few feet of the canister.

The heat induced into the repository and surrounding formation depends upon repository design and the thermal loadings of the repository. These loadings include: 1) the average waste loading of the repository (averaged over full waste emplacement area) that determines the temperature rise of the formation in the far-field; 2) the local thermal loading (average amount of waste emplaced per unit storage area of the repository) that most directly determines the near-field rock thermal and thermomechanical environments; and 3) individual canister loadings that most directly influence the temperatures in the waste, the canister, and the rock in the immediate vicinity of the waste canister, i.e., in the very-near-field. For a given repository design, acceptable loadings can be determined once appropriate temperature and thermomechanical limits have been established.

Thermal and thermomechanical analyses have been performed to determine acceptable thermal loading values for spent fuel repositories and HLW repositories in salt, granite, shale, and basalt. Thse studies use an iterative technique that integrates the waste and canister temperature criteria, room and pillar stability analyses, and far-field thermal and rock mass response analyses.

For isolation of HLW, the following steps were followed in the iterative analysis:

Step 1: Select thermal and thermomechanical criteria.

Step 2: Propose a conservative room and pillar design without consideration of an imposed thermal loading.

Step 3: Make near-field heat-transfer calculations to determine the areal thermal loading range of interest.

Step 4: Make very-near-field heat-transfer calculations to generate very-near-field temperature profiles as a funcion of areal thermal loading and canister loading.

Step 5: Make near-field rock mechanics calculations to determine the areal thermal loading that assures room and pillar stability.

Step 6: Determine maximum canister load from Step 4 data for the areal thermal load from Step 5.

Step 7: Make far-field thermal and rock mechanics calculations to assure that far-field design limits are not exceeded.

If any of the tentative limits in Table K.1.1 are exceeded in any of the above steps, the previous steps are revised and repeated until the calculational results indicate that the limits are not exceeded.

For spent fuel repository analyses, the above procedure was modified slightly. Because it was decided to place PWR or BWR spent fuel assemblies in individual canisters, the thermal load for a given canister was determined, and Step 6 above was not required. Steps 1 through 3 were followed by Steps 5 and 7. Very-near-field heat transfer calculations were then performed to determine if canister or spent fuel temperature limits were exceeded.

This iterative procedure results in baseline thermal load design values for the canisters in terms of kW per canister at waste emplacement and for the loading of a repository room (local areal thermal load) in kW/acre. The canister load must be sufficiently low so that the waste and canister temperatures do not exceed the values in Table K.1.1. The local areal thermal load must be sufficiently low so that rock mechanics analyses predict room and pillar stability throughout the readily retrievable period, and so that near-field hydraulic conductivities are not significantly increased and long-term as well as far-field restrictions are not exceeded.

The design thermal limits generated by these analyses depend strongly upon characteristics of the repository site and formation. These characteristics include media strength, stress-to-strain ratio, heat capacity, thermal conductivity, overlying strata and their characteristics, etc. The following simplifying assumptions were made for these analyses:

- Only high-level waste and spent-fuel canisters are considered.
- The entire repository is assumed to be loaded simultaneously and instantaneously.
- Thermal properties of geologic media and other materials are based on reasonable estimates.
- The effects of stress upon thermal properties are not included.
- The presence of water is neglected in the thermal analysis.
- Only simplified horizontal stratigraphies are assumed.
- No compaction or subsidence of the formation is considered.

The analyses utilize cylindrical symmetry to describe the temperatures within the waste package. Details of the waste package including overpack and other contents of the emplacement hole are taken into account. In the case of spent-fuel canisters, details of the assemblies, radiation and convection are explicity included in the calculation. The boundary conditions at the emplacement hole surface are provided in a three-dimensional Cartesian near-field model with asymmetric spacings between canisters. The heat-generating waste and waste canister are explicitly described as well as the properties of the rock in the pillars and above and below the waste storage room. The storage room was not modeled since it has little impact on canister temperatures. The storage room including radiative and convective heat transfer effects has been included in other calculations, however. The boundary conditions above and below the storage room and canister are provided in a far-field model. Temperatures in this model are calculated in cylindrical symmetry and stratigraphy of the host formation can be explicitly modeled.

The thermal load limits and the controlling factors associated with each limit generated by these analyses for 10-year-old spent fuel and HLW are presented in Table K.1.2. The far-field average repository loading limits are based on the far-field studies and the estimated maximum uplift of the formation caused by heat from the stored waste. Far-field average repository thermal loading limits apply to the thermal density of wastes averaged over each waste type's overall emplacement area, including corridors and ventilation drifts and excluding the areas for shafts or emplacement areas for other waste types. In linear thermomechanical expansion studies for salt, a surface uplift of 1.2 to 1.5 m was obtained for average far-field loadings shown in Table K.1.2. This maximum uplift is felt to be acceptable for a repository at 600 m over the time frame involved (Russell 1977). Similar calculations for granite and basalt for loadings of 190 kW/acre, and shale for 120 kW/acre, give less than 0.4 m of surface uplift. Although Table K.1.2 indicates that thermal loading limits for both the far-field and near-field for spent fuel and HLW in granite, shale, and basalt, and for HLW in salt are equivalent, the far-field average repository loading will always be less because of the passive regions of the repository such as corridors and waste handling areas.

The near-field local areal loading limits are based on room and pillar stability considerations. Near-field local thermal loading limits are applied to the thermal density of wastes in an individual waste type's emplacement room area including the area of one-half the rock pillar on each side. Areas for corridors, shafts, and other waste type emplacement areas, are excluded. Linear thermomechanical analyses based upon the predicted near-field temperature distributions indicate that readily retrievable operations could continue in the storage rooms for at least 5 years with the loadings in Table K.1.2 (Dames and Moore 1978).

Although salt can accept 150 kW/acre based on room and pillar stability considerations, this density cannot be achieved in the case of spent fuel because of the more limiting far-field criteria. Reduced loadings are necessary here because of the long-term heat contributions from the plutonium as shown in Table K.1.3. The additional long-term heat contribution of the plutonium does not affect room stability but does increase surface uplift. In order to meet the far-field limit of 60 kW/acre, the maximum near-field density that can be achieved is 75 kW/acre for spent fuel. All other wastes may be emplaced at the 150 kW/acre near-field and far-field criteria for nonplutonium wastes in salt.

TABLE K.1.2. Thermal Load Limits for Conceptual Repository Designs

	Thermal Load Limit (controlling factor)[a]			
	Salt	Granite	Shale	Basalt
Canister Limits During Retrieval Period (kW)[b]				
Vitrified glass HLW	3.2(A)	1.7(A)	1.2(A)	1.3(A)
Calcined HLW	2.6(A)	1.6(A)	1.1(A)	1.1(A)
Near Field Local Areal Thermal Loading Limits[c] (kW/acre)				
5-yr retrieval--HLW	150(B)	190(B)	120(B)	190(B)
5-yr retrieval--spent fuel	(e)	190(B)[f]	190(B)[f]	190(B)
Far-Field Average Repository Thermal Loading[d] Limits (kW/acre)				
HLW	150(C)	190(B)	120(B)	190(B)
Spent fuel	60(C)	190(B)	120(B)	190(B)

(a) Controlling factors: A = Canister temperature limit
B = Room closure
C = Earth surface uplift.

(b) Analysis assumes 15-cm annulus of crushed rock around waste package.

(c) Acreage includes rooms and adjacent pillars, but not corridors, buttress pillars, and receiving areas.

(d) Acreage includes storage area for waste including corridors and ventilation drifts, but does not include area for shafts, or storage areas for other waste types if separate.

(e) In salt, the emplacement of spent fuel and HLW with plutonium is controlled by the more restrictive 60 kW/acre far-field thermal limit. Otherwise the near-field limit would be 150 kW/acre.

(f) In order to maintain spent fuel cladding temperatures within the 300°C limit with these areal thermal loadings, the annulus around the canister is left open (no backfill). Heat is transferred across this air space more readily than through crushed backfill material and results in cooler canister and cladding temperatures.

TABLE K.1.3. Cummulative Heat Generated by 10-Yr-Old Spent Fuel and High-Level Waste

	kW-yr/MTHM	
Years	Spent Fuel Once-Through Cycle	HLW U & Pu Recycle
0	0	0
10	9	9
50	40	30
100	58	36
200	78	43
300	92	46
400	102	49
500	116	50
1000	143	55

In the very-near-field analyses, the baseline canister-emplacement design was a single overpacked canister placed in a hole. In general, the void space between the sleeve and the hole was assumed to be backfilled with crushed rock. In each of the HLW calculations, a 15-cm annulus of crushed or fractured rock was assumed.

K.1.2 Thermal Loadings Achieved in Conceptual Repository Designs

Engineering or operational constraints may restrict any of the thermal loadings discussed in the above section to values lower than the limits presented in Table K.1.2. These constraints include such factors as reasonable HLW concentration in canisters, available canister sizes, permissible hole spacing, and room stability limitations on hole arrangements. Spent-fuel canister loading is limited in this Statement to a single PWR or BWR spent fuel assembly so that canister heat loads are below limiting values. The HLW canister diameters are reduced as necessary in each case so that the canister loadings are below the limits of Table K.1.2. Alternatively the waste could be diluted with inert material without reducing canister sizes to achieve the same result.

As a hedge against uncertainties in the criteria and other factors and to ensure a conservative estimate of repository capacities, the design areal thermal lodaings for both spent fuel and HLW were established at 2/3 of this limiting areal loading parameter in Table K.1.2. The age of both the spent fuel and HLW were assumed to be 6.5 years. Using the criteria in Table K.1.2 for 6.5-year-old waste provided a further degree of conservatism since the criteria were developed for 10-year-old waste (the thermal limits could be increased for younger wastes). The resulting thermal densities actually achieved in the first conceptual repositories are listed in Table K.1.4. The limiting thermal parameter, i.e., near-field or far-field, is denoted by an asterisk. In the case of BWR fuel in shale and the RH-TRU waste in all media except salt, structural limitations on canister placements limit thermal loading.

Temperature profiles calculated for the conceptual repositories using the achieved loadings are shown in Figures K.1.1 through K.1.8. The profiles show temperature increases above ambient temperature as a function of depth at several times after the repository is loaded, for both spent fuel and HLW and for the four geologic media. For example, the profiles for a spent fuel repository at a depth of 600 m in salt with the average loadings of Table K.1.4, are shown in Figure K.1.1. The figure shows that the temperature at the repository depth reaches a maximum value about 70 years after emplacement. The calculation is made assuming that the heat source is uniformly dispersed at the repository level. The temperature is calculated along a line perpendicular to the plane of the repository and passing through the center of the emplacement area. Actual temperatures in the vicinity of the repository level will vary with the discontinuities of the temperature profile around each canister.

Figure K.1.2 gives the profiles for the repository in salt for the high-level waste from the reprocessing cycle. Corresponding profiles for each cycle are shown in Figures K.1.3 and K.1.4 for granite, K.1.5 and K.1.6 for shale, and K.1.7 and K.1.8 for basalt repositories.

TABLE K.1.4 Thermal Loadings Achieved at Conceptual Repositories

Cycle	Thermal Loading at Emplacement	Salt	Granite	Shale	Basalt
Once-Through					
	PWR				
	kW/can	0.72	0.72	0.72	0.72
	Near-field local kW/acre	50	130*	80*	130*
	Far-field average kW/acre	40*	100	65	100
	BWR				
	kW/can	0.22	0.22	0.22	0.22
	Near-field local kW/acre	50	130*	55	130*
	Far-field average kW/acre	40*	100	44	100
U & Pu Recycle					
	HLW				
	kW/can	3.2	1.7	1.2	1.3
	Near-field local kW/acre	100*	130*	80*	130*
	Far-field average kW/acre	76	95	60	95
	RH-TRU (hulls)				
	kW/can	0.32	0.32	0.32	0.32
	Near-field local kW/acre	100*	93	42	77
	Far-field average kW/acre	76	70	32	60

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* Denotes limiting thermal parameter.

Predicted temperature histories over the first 100 years for the waste (center line) or spent fuel (center pin), the canister wall, and for the rock near the surface of the emplacement hole are shown for the design canister loadings in Figures K.1.9 through K.1.16. These temperatures correspond to the highest values obtained anywhere in the formation rock. The temperatures have been calculated in models with detailed treatment of the very-near-field, including 15 cm of crushed formation material between the rock and the canister in the emplacement hole. Additional details of the models and analyses are contained in DOE/ET-0028. The results for PWR spent fuel canisters and the HLW canisters, respectively, in a salt formation are shown in Figures K.1.9 and K.1.10. The corresponding temperature histories for granite, shale and basalt are shown in Figures K.1.11 and K.1.12, K.1.13 and K.1.14, and K.1.15 and K.1.16 respectively.

The temperature histories are all well within the temperature criteria in Table K.1.1 except for the center pin temperature for spent fuel in basalt, which just reaches the 300°C criteria. One method of reducing these temperatures is elimination of the crushed backfill surrounding the emplaced canisters. Heat is transferred across the resulting air space more readily than through the crushed backfill material and results in cooler canister and cladding temperatures. A higher conductivity backfill material could also be used.

A tabulation of the material properties used in making these thermal calculations is shown in Tables K.1.5 and K.1.6.

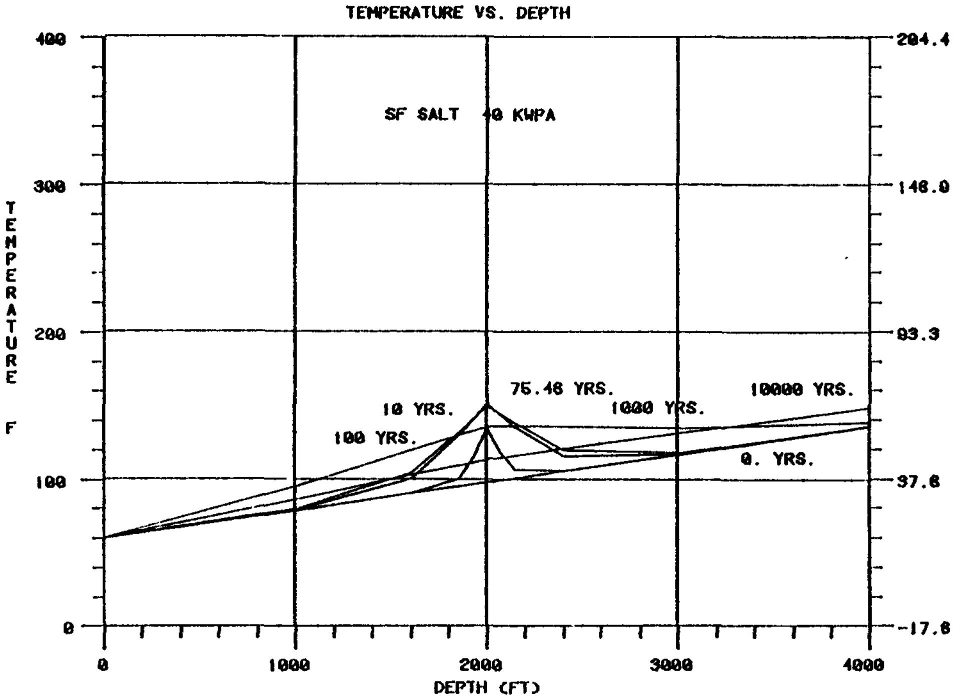

FIGURE K.1.1. Formation Temperature versus Depth and Time for Repository in Salt--Once-Through Fuel Cycle

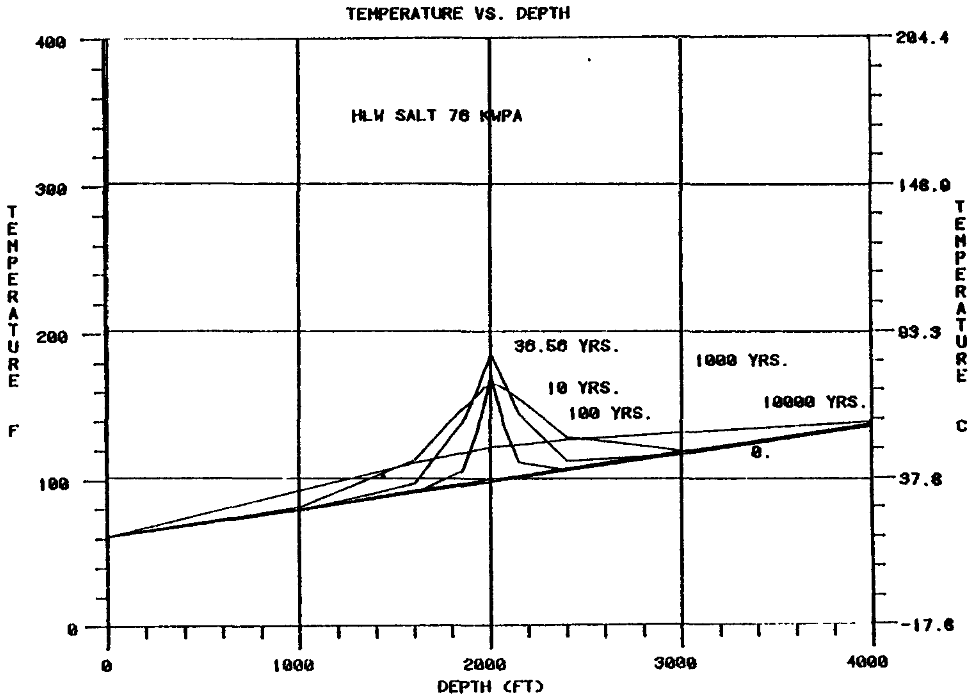

FIGURE K.1.2. Formation Temperature versus Depth and Time for Repository in Salt--Reprocessing Fuel Cycle

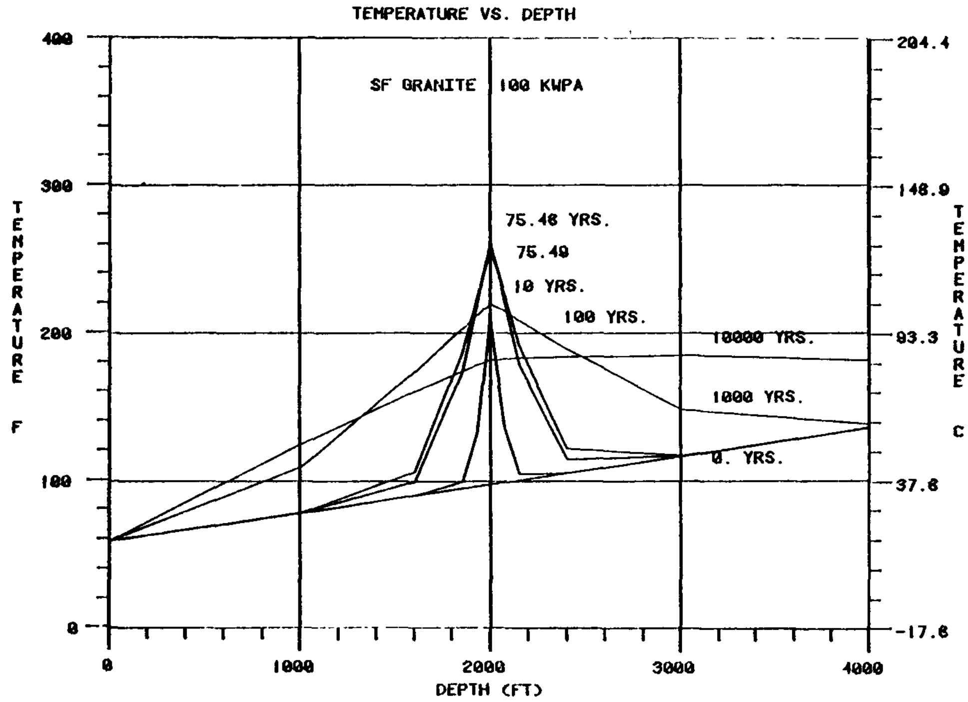

FIGURE K.1.3. Formation Temperature versus Depth and Time for Repository in Granite--Once-Through Fuel Cycle

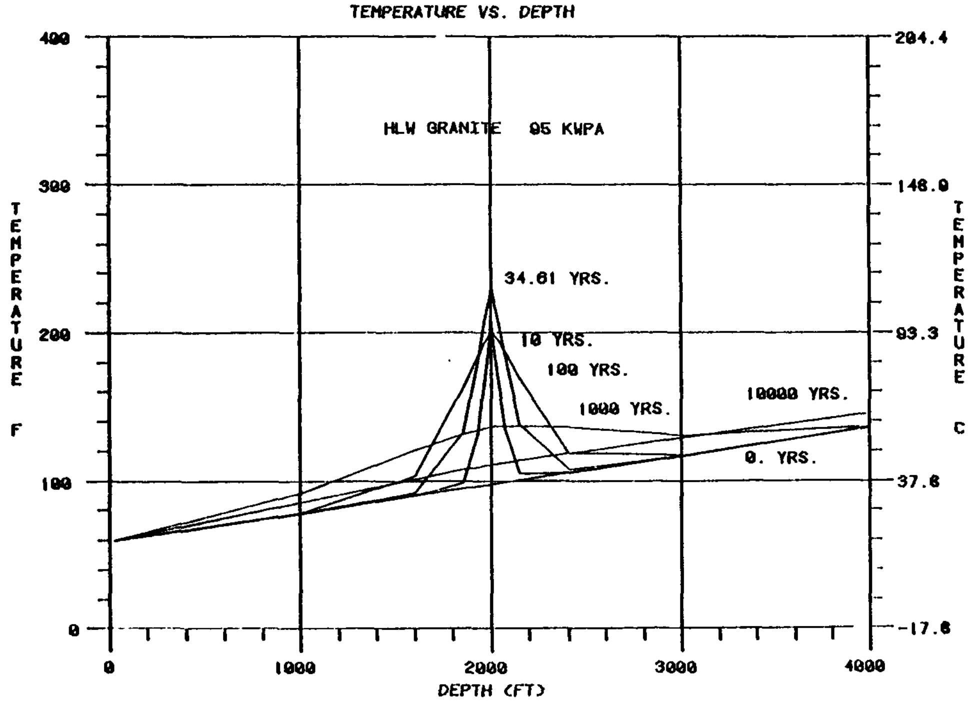

TABLE K.1.4 Formation Temperature versus Depth and Time for Repository in Granite--Reprocessing Fuel Cycle

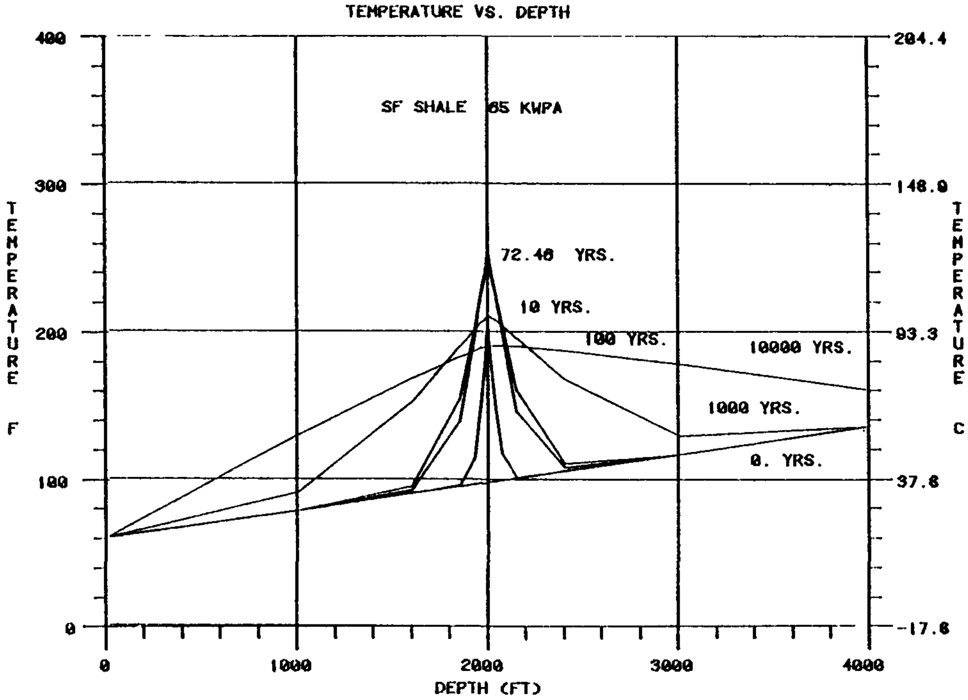

FIGURE K.1.5. Formation Temperature versus Depth and Time for Repository in Shale--Once-Through Fuel Cycle

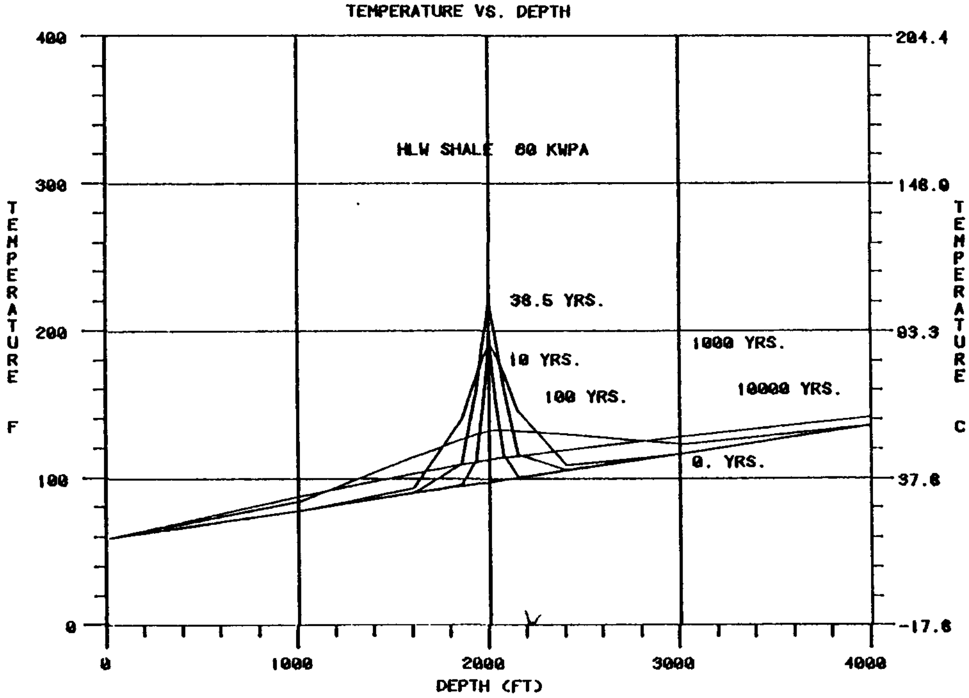

FIGURE K.1.6. Formation Temperature versus Depth and Time for Repository in Shale--Reprocessing Fuel Cycle

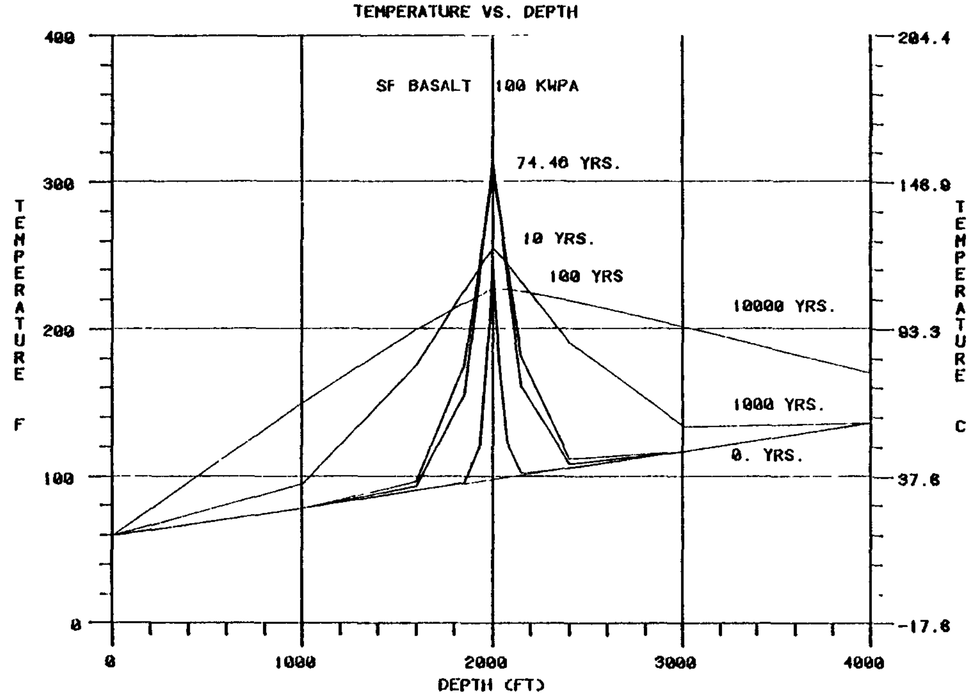

FIGURE K.1.7. Formation Temperature versus Depth and Time for Repository in Basalt--Once-Through Fuel Cycle

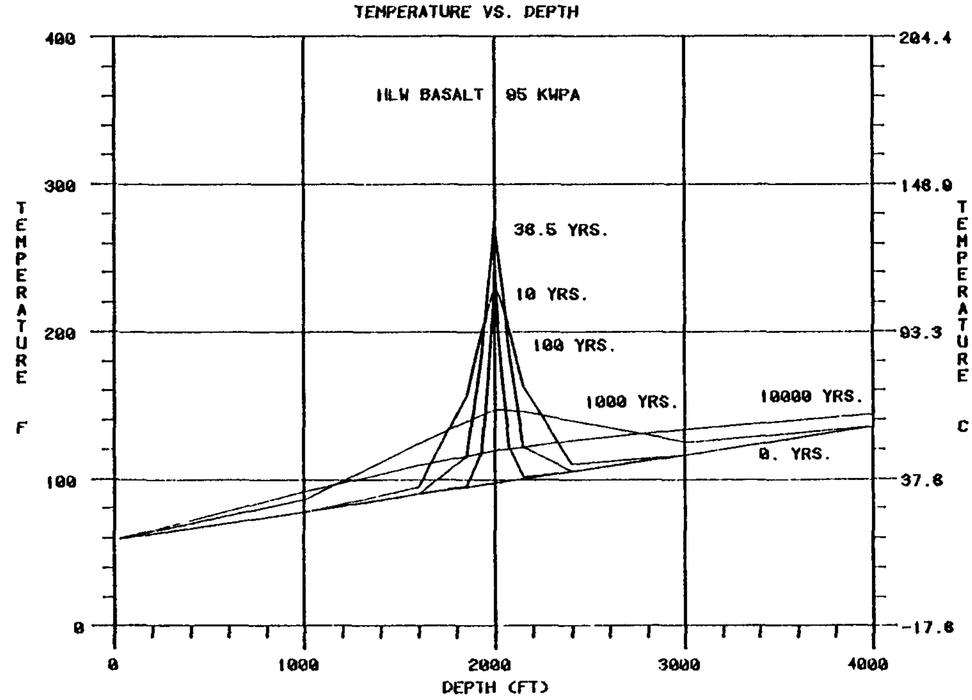

FIGURE K.1.8. Formation Temperature versus Depth and Time for Repository in Basalt--Reprocessing Fuel Cycle

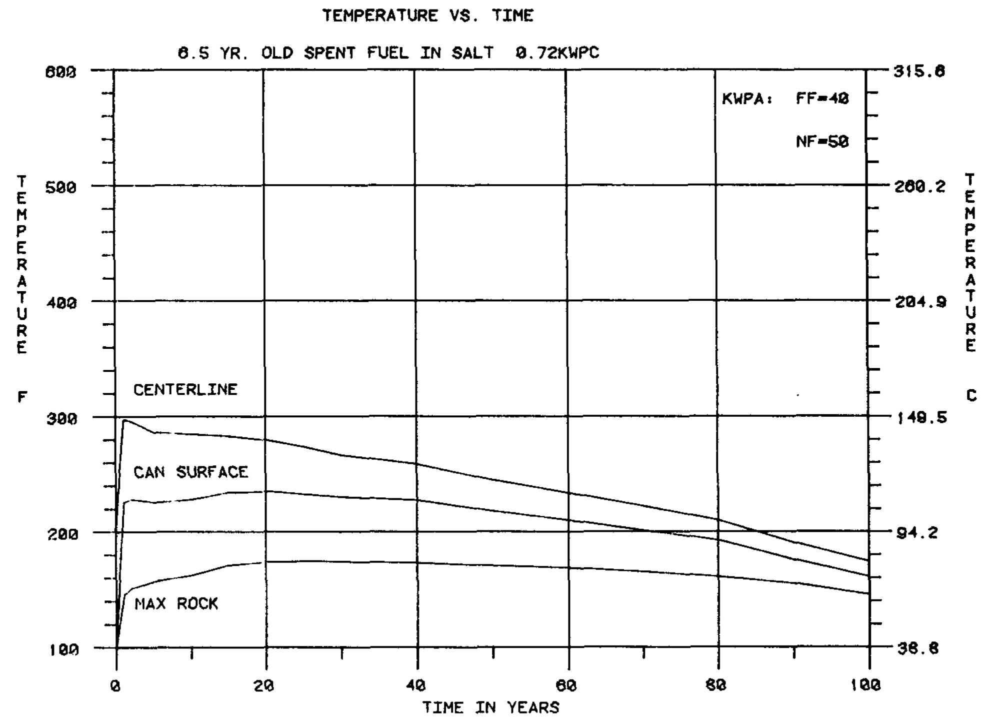

FIGURE K.1.9. Very-Near-Field Temperatures versus Time for Repository in Salt--Once-Through Fuel Cycle

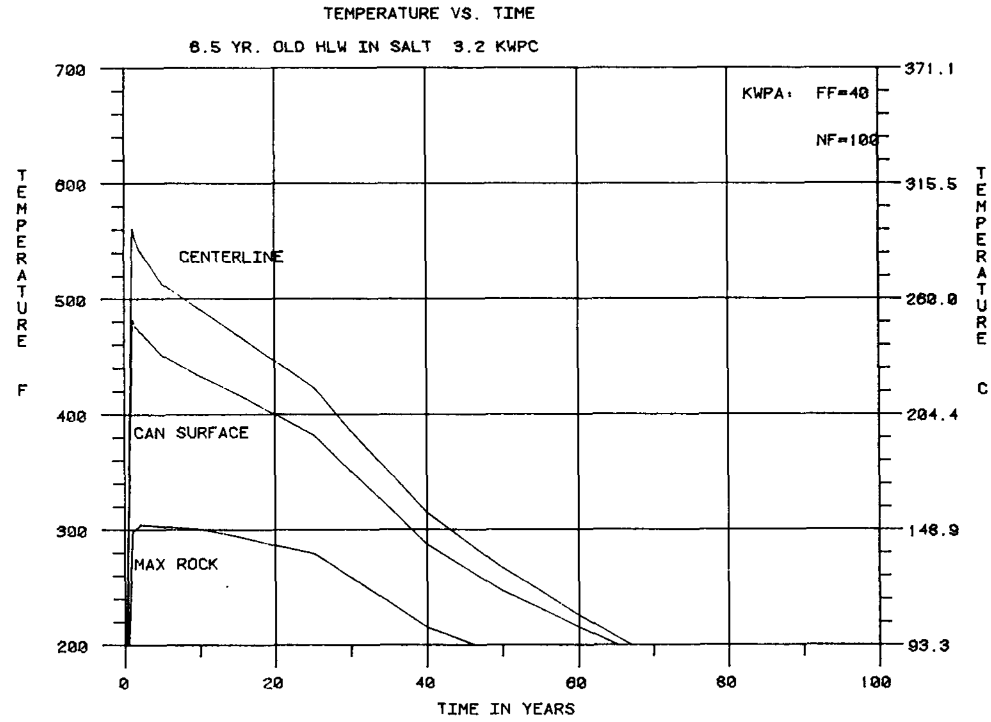

FIGURE K.1.10. Very-Near-Field Temperatures versus Time for Respository in Salt--Reprocessing Fuel Cycle

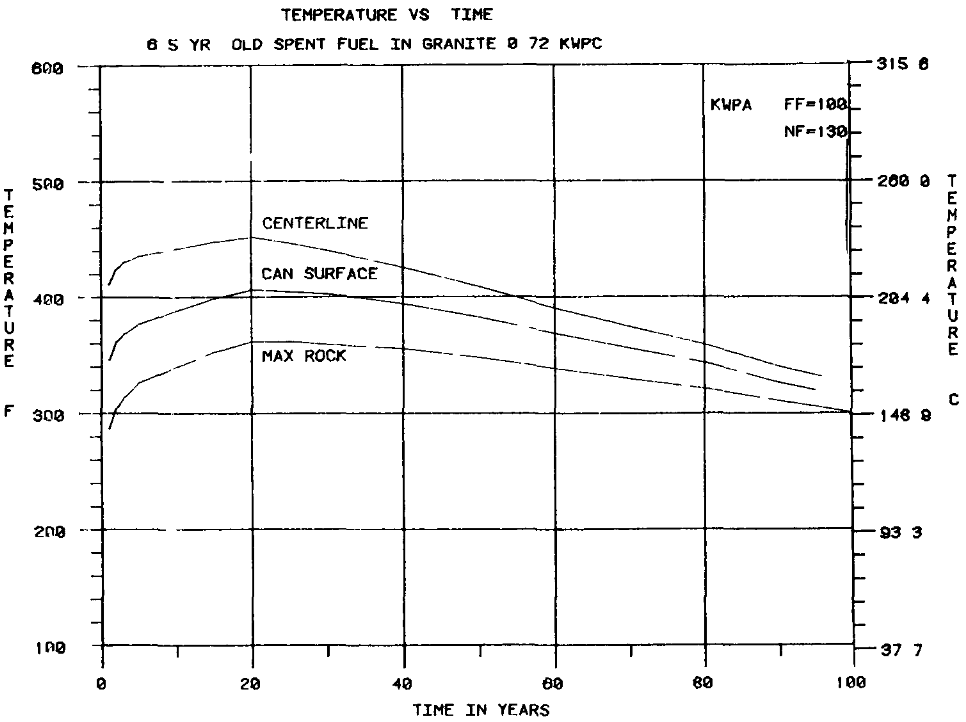

FIGURE K.1.11. Very-Near-Field Temperatures versus Time for Repository in Granite--Once-Through Fuel Cycle

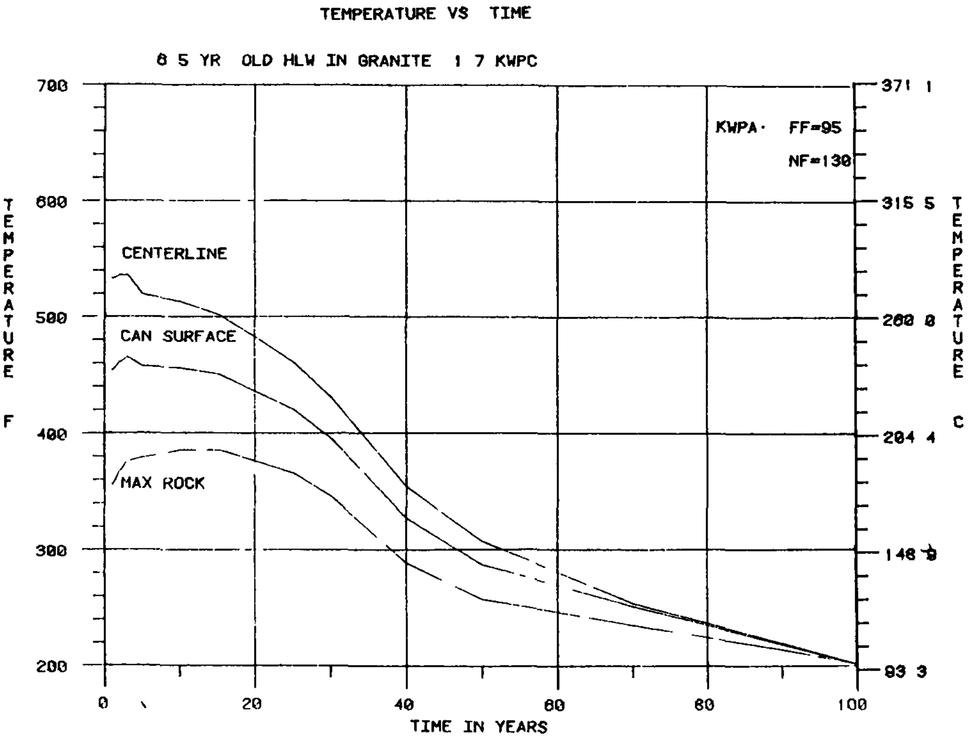

FIGURE K.1.12. Very-Near-Field Temperatures versus Time for Repository in Granite--Reprocessing Fuel Cycle

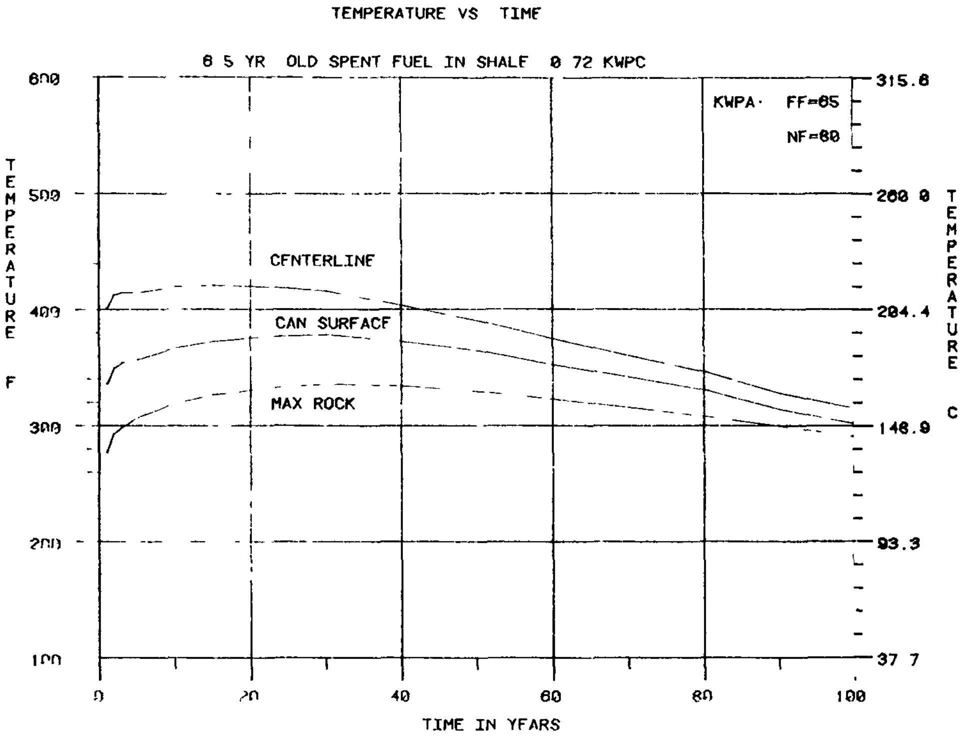

FIGURE K.1.13. Very-Near-Field Temperatures versus Time for Repository in Shale--Once-Through Fuel Cycle

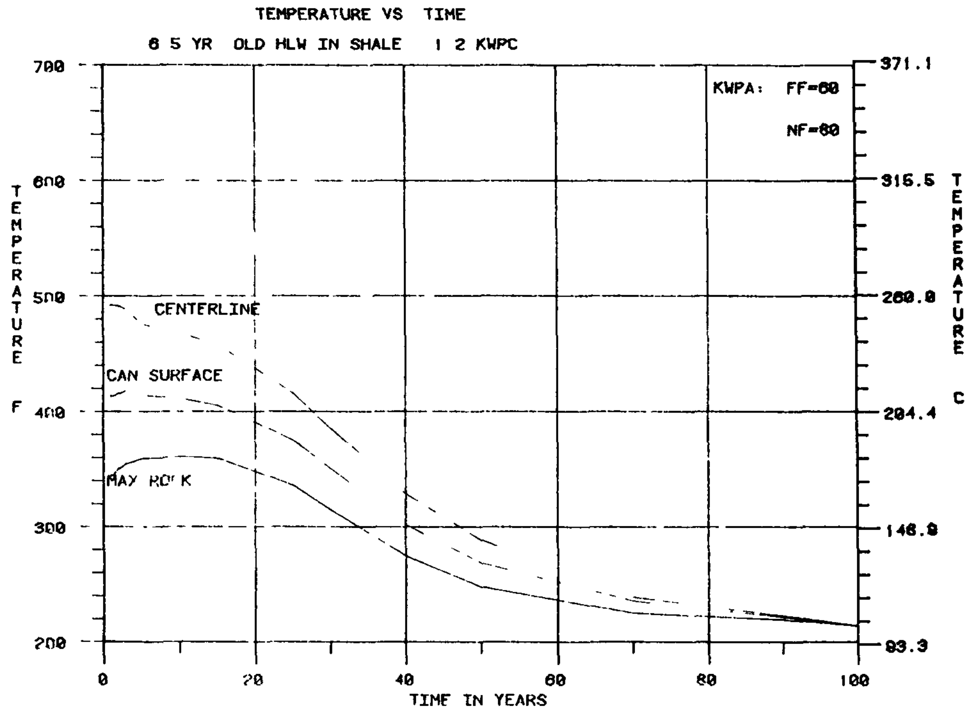

FIGURE K.1.14. Very-Near-Field Temperatures versus Time for Repository in Shale--Reprocessing Fuel Cycle

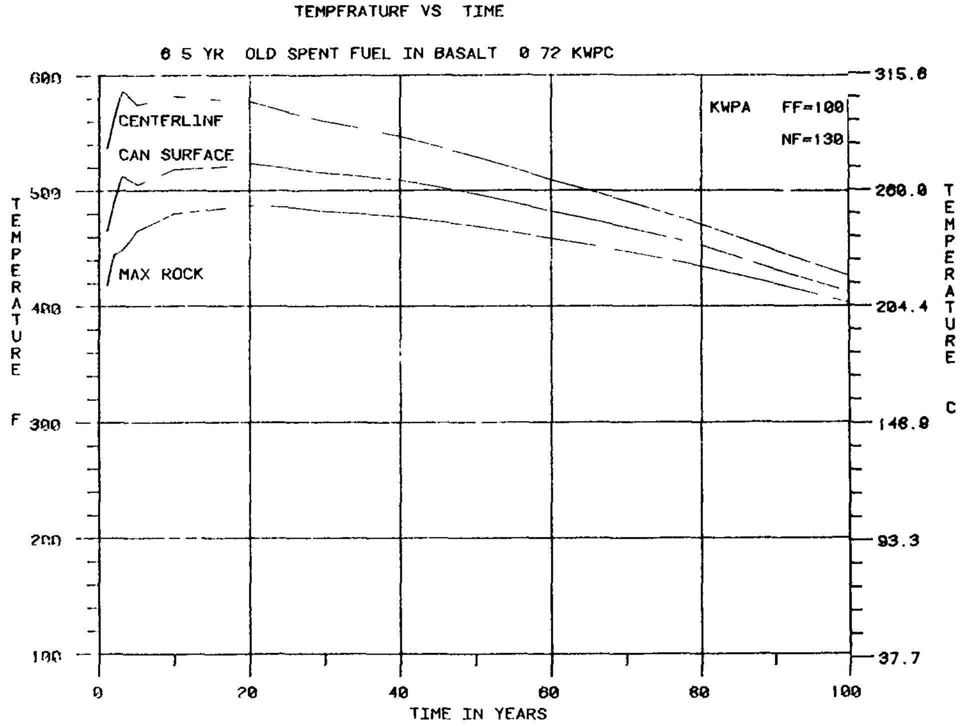

FIGURE K.1.15. Very-Near-Field Temperatures versus Time for Repository in Basalt--Once-Through Fuel Cycle

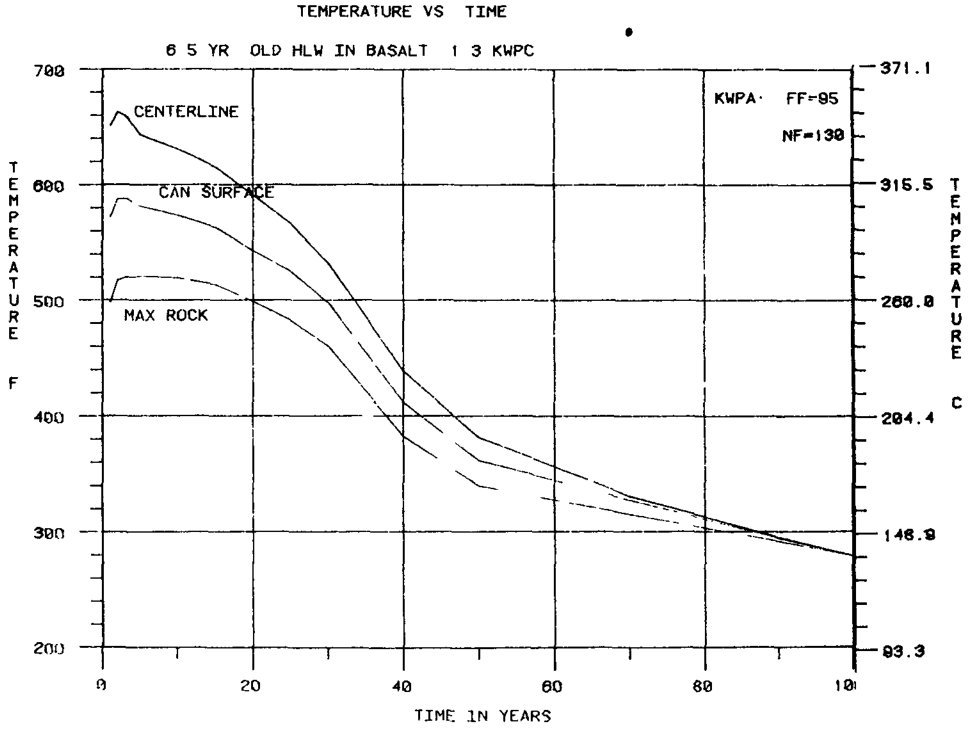

FIGURE K.1.16. Very-Near-Field Temperatures versus Time for Repository in Basalt--Reprocessing Fuel Cycle

TABLE K.1.5. Material Properties

	Density kg/m³	Specific Heat W yr/kg °C	Thermal Conductivity W/m °C
Salt	2162.0	2.65×10^{-5}	(see Table K.1.6)
Shale	2563.2	2.65×10^{-5}	(see Table K.1.6)
Granite	2675.0	2.65×10^{-5}	(see Table K.1.6)
Basalt	2883.0	2.65×10^{-5}	(see Table K.1.6)
Waste	2995.7	2.65×10^{-5}	1.21
Concrete	2306.9	2.65×10^{-5}	0.935
Backfill	2563.2	2.65×10^{-5}	0.346

TABLE K.1.6. Thermal Conductivities W/m°C

Temperature (°C)	Basalt	Granite	Salt	Shale(a) (horizontal)
0	1.16	2.86	6.11	1.94
50	1.19	2.70	5.00	1.78
100	1.26	2.56	4.21	1.77
150	1.32	2.44	3.60	1.75
200	1.37	2.34	3.12	1.73
300	1.49	2.15	2.49	1.71
400	1.56	1.99	2.08	1.70

(a) Shale vertical conductivity = 0.739 x shale horizontal conductivity.

K.1.3 Impacts of Waste Age

The thermal criteria discussed in Section K.1.1 are calculated on the basis of 10-year-old waste. Criteria estimates for waste ages of 5 to 50 years were also developed. As spent fuel or HLW ages, the intensity of emitted radiation and heat declines and the quantity of these materials that can be emplaced in a given repository area increases somewhat. The thermal loading criteria required to meet the same temperature limits tend to decline for older wastes but heat emissions decline at a faster rate resulting overall in an increase in capacity.

Table K.1.7 lists maximum thermal loading criteria developed for both spent fuel and HLW at 5, 10, and 50 years of age. These loadings take into account the temperature and thermo-mechanical limitations listed in Table K.1.1.

The thermal loadings used to calculate repository capacities are shown in Table K.1.8. These loadings take into account: 1) loading at 2/3 of calculated maximum, 2) the relationship between the near-field and far-field areas (i.e., the unused passive areas for corridors, etc.), and 3) the limiting parameter, which is denoted by an asterisk.

TABLE K.1.7. Thermal Loading Limits for Waste Repositories (kW/Acre)

		Spent Fuel		HLW	
Formation	Age of Waste at Emplacement (yr)	Near-Field Local Areal Loading Limit	Far-Field Average Repository Loading Limit	Near-Field Local Areal Loading Limit	Far-Field Average Repository Loading Limit
Salt	5	240	100(a)	190	190
	10	150	60(a)	150	150
	50	100	31(a)	130	80(a)
Shale	5	180	180	140	140
	10	120	120	120	120
	50	70	63(a)	120	120
Granite	5	300	300	210	210
	10	190	190	190	190
	50	140	140	180	180
Basalt	5	300	300	210	210
	10	190	190	190	190
	50	140	140	180	180

(a) Long-term far-field considerations limit average repository loading in these cases.

TABLE K.1.8. Thermal Loadings Used, kW/Acre

		Spent Fuel		HLW	
Formation	Age of Waste at Emplacement (yr)	Near-Field Local Loading	Far-Field Average Loading	Near-Field Local Loading	Far-Field Average Loading
Salt	5	84	67*	130*	97
	10	50	40*	100*	76
	50	25	20*	70	54*
Shale	5	120*	96	94*	70
	10	80*	65	80*	60
	50	52	42*	80*	60
Granite	5	200*	162	140*	108
	10	130*	105	130*	100
	50	94*	76	120*	93
Basalt	5	200*	162	140*	108
	10	130*	105	130*	100
	50	94*	76	120*	93

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* Denotes limiting parameters.

The calculated repository capacities at these loadings are shown in Table K.1.9 assuming 2000-acre repositories. These results are plotted and discussed in Section 5.3. Maximum temperatures calculated for these loadings in both the near-field and far-field are shown in Tables K.1.10 through K.1.12. The thermal criteria are met in all cases except for spent fuel in basalt where spent fuel center pin temperature exceeds the 300°C criteria at both 5- and 10-year loadings, indicating that basalt capacities may be overstated. The variation in the maximum temperature in all media indicates that further optimization of the loading criteria is desirable.

TABLE K.1.9. Repository Capacities as a Function of Waste Age, MTHM

Waste Type and Median	5-Year Age	10-Year Age	50-Year Age
Spent Fuel			
Salt	57,600	61,100	64,700
Granite	141,000	150,000	193,000
Shale	70,700	76,300	90,600
Basalt	141,000	150,000	193,000
Reprocessing HLW			
Salt	66,300	83,200	124,000
Granite	66,200	89,700	137,000
Shale	36,900	46,300	68,000
Basalt	63,000	83,300	122,000

TABLE K.1.10. Maximum Near-Field Temperatures with Spent Fuel

Formation	Age of Waste	Maximum temperature, °C and Year		
		Formation	Canister	Waste Centerline
Salt	5	92 @ 30 yr	127 @ <1 yr	143 @ <1 yr
	10	88 @ 40 yr	106 @ 20 yr	116 @ 10 yr
	50	107 @ 80 yr	110 @ 80 yr	116 @ 80 yr
Granite	5	218 @ 30 yr	232 @ 20 yr	243 @ 1 yr
	10	227 @ 30 yr	238 @ 25 yr	243 @ 25 yr
	50	204 @ 70 yr	210 @ 70 yr	213 @ 70 yr
Shale	5	193 @ 30 yr	227 @ 1 yr	252 @ 1 yr
	10	204 @ 30 yr	221 @ 25 yr	227 @ 20 yr
	50	171 @ 60 yr	182 @ 40 yr	187 @ 40 yr
Basalt	5	288 @ 20 yr	312 @ 2 yr	332 @ 1 yr
	10	299 @ 30 yr	312 @ 30 yr	318 @ 25 yr
	50	254 @ 60 yr	260 @ 60 yr	262 @ 60 yr

TABLE K.1.11. Maximum Near-Field Temperatures with HLW

Formation	Age of Waste	Maximum temperature, °C and Year		
		Formation	Canister	Waste Centerline
Salt	5	160 @ 1 yr	334 @ <1 yr	416 @ <1 yr
	10	191 @ 10 yr	343 @ 3 yr	422 @ 2 yr
	50	160 @ 5 yr	332 @ <1 yr	415 @ <1 yr
Granite	5	180 @ 1 yr	279 @ <1 yr	321 @ <1 yr
	10	235 @ 15 yr	312 @ 10 yr	349 @ 3 yr
	50	242 @ 25 yr	306 @ 15 yr	344 @ 5 yr
Shale	5	179 @ 1 yr	243 @ 1 yr	266 @ 1 yr
	10	218 @ 10 yr	268 @ 10 yr	296 @ 10 yr
	50	232 @ 25 yr	277 @ 25 yr	302 @ 5 yr
Basalt	5	262 @ 1 yr	331 @ 1 yr	360 @ 1 yr
	10	318 @ 10 yr	374 @ 10 yr	402 @ 5 yr
	50	319 @ 25 yr	364 @ 25 yr	394 @ 5 yr

TABLE K.1.12. Maximum Far-Field Temperature Increases

Formation	Age of Waste	Spent Fuel		HLW	
		Max°C	Year	Max°C	Year
Salt	5	40	54	34	52
	10	38	54	58	34
	50	27	500	48	54
Granite	5	115	54	64	34
	10	120	86	87	54
	50	160	500	97	54
Shale	5	92	86	57	22
	10	102	100	73	34
	50	103	500	84	54
Basalt	5	144	86	87	22
	10	155	100	130	34
	50	175	500	125	34

The heat generation rates used in these calculations are shown for both spent fuel (PWR) and reprocessing HLW in Table K.1.13.

TABLE K.1.13. Heat Generation Rates for Spent Fuel and High-Level Wastes

Waste Age	Watts/MTHM	
	PWR Spent Fuel	HLW
5	2.18×10^3	1.90×10^3
10	1.18×10^3	1.08×10^3
20	9.45×10^2	8.0×10^2
30	7.7×10^3	6.0×10^2
40	6.5×10^2	4.5×10^2
50	5.6×10^2	3.6×10^2
100	3.0×10^2	1.2×10^2
200	1.6×10^2	2.5×10^1
300	1.3×10^2	1.8×10^1
400	1.1×10^2	1.6×10^1
500	9.5×10^1	1.4×10^1
1000	5.5×10^1	7.5×10^0

K.2 REMOVAL OF EMPLACED WASTE

Once wastes are emplaced at a geologic repository it is considered unlikely that they will require removal. Confidence in the suitability of the repository to isolate wastes will be high at the time waste emplacement operations commence because of extensive preemplacement testing and exploration, thorough DOE and peer review, and NRC licensing. In spite of this, repository design takes into account the possible need to remove emplaced wastes. Conditions that may be postulated to require waste removal include:

- detection of defective canisters that require removal, repackaging, and reemplacement
- disqualification of a portion of the repository that neccessitates removal and reemplacement of the affected canisters
- failure of in-situ tests and data acquired during monitoring of repository operations to provide sufficient confidence in long-term repository performance, which requires removal of wastes and abandonment of the repository site.

As discussd in Section 5.3.1.5, wastes are emplaced in a readily retrievable manner during initial operations and are emplaced recoverably during the remainder of repository operations. Removal of emplaced wastes will require different levels of effort depending upon the phase of repository operations during which removal takes place.

K.2.1 Readily Retrievable Emplacement

During the initial phase of repository operation wastes are emplaced so that they can be readily retrieved. During this period emplacement holes are lined with steel sleeves and sealed with removable concrete plugs. The sleeves and plugs ensure that the canisters are accessible and minimize corrosion or other damage. Verification of repository functions continues throughout the period of ready retrievability; extensive in-situ testing rock core analysis, and other confirmatory programs are performed. In-situ testing and monitoring include sensors for temperature, strain and pressure, and sampling systems for air and ground water installed with a statistically significant number of canisters. From these activities, additional data will become available for use in the various mechanistic, computational models that form the basis for long-term projections of performance.

Should a decision be made to extend the period of readily retreivable emplacement beyond the initial 5 years, the use of sleeve-lined holes and concrete plugs would continue and rooms would be left open. For extension beyond a few years, the areal thermal density of emplaced wastes may need to be decreased. By decreasing the amount of thermal energy stored in the rooms, thermal stresses in the ceiling and supporting pillars are reduced to the point where room opening stability can be reasonably assured for the longer period.

Table K.2.1 lists calculated near-field local thermal densities for 25-yr readily retrievable emplacement of 10-year-old spent fuel at the conceptual repositories located in salt, granite, shale, and basalt formations. Consistent with the conservative approach

TABLE K.2.1. Near Field Local Thermal Densities[a] for 25-Year Ready Retrievability of 10-year-old Spent Fuel

Near-Field Allowable Thermal Loading, kW/acre			
Salt	Granite	Shale	Basalt
24	53	36	53

(a) These densities are conservative values that are 2/3 of the calculated densities.

taken in the 5-yr readily retrievable case, the values in Table K.3.1 are two-thirds of the calculated maximum acceptable thermal densities for 25-yr ready retrievability.

As discussed previously in Section K.1, Thermal Criteria, the criteria controlling placement of spent fuel in salt with 5-yr ready retrievability is the far-field average thermal density. However, in the case of 25-yr ready retrievability, near-field local thermal density becomes the controlling criterion because maintaining room and pillar stability for 25 years requires a more restrictive thermal density than is needed to limit long-term uplift.

An additional concern for the repository in salt is the creep closure of rooms over the 25-yr period of ready retrievability. To compensate for this, room ceiling heights are increased 7.6 m for 25-yr ready retrievability (6.7 m for 5-yr ready retrievability).

An alternative approach for achieving 25-yr ready retrievability is to provide heat removal from the mine by continuously ventilating emplacement rooms. This technique could allow higher thermal densities by removing heat from the rock formation to keep room and pillar stresses within acceptable limits. Additional details of this approach are provided in Y/OWI/TM-44 (Union Carbide Corp. 1978).

The unit cost for providing 25-yr ready retrievability for emplaced spent fuel elements at a repository located in salt is $90/kg HM (mid-1978 dollars) compared to $54/kg HM for 5-yr ready retrievability. The primary reason for this difference in cost is the reduction of repository waste capacity by about a factor of two for the 25-yr ready retrievability option. Another contribution to the higher cost is $70 million for additional mining and backfilling that is necessary as a result of increased ceiling height for the repository in salt. Use of sleeves for all emplaced wastes also costs an extra $4 million annually. Unit costs for 25-yr readily retrievable emplacement of spent fuel in the other rock media would also increase although additional mining to increase ceiling height would not be required.

During the initial phase of readily retrievable emplacement, removal operations are relatively straight-forward. Because rooms are left open and the lined emplacement holes are sealed with removable concrete plugs, removal of emplaced wastes simply involves reversing the emplacement procedures. A transporter reenters the emplacement room and positions itself over the sealed hole. The concrete plug would be removed and the waste canister raised into the transporter. The transporter then delivers the canister to a waste receiving station where it is loaded into a shaft and lifted to the surface. On the surface the canisters are placed into temporary dry well storage until a new repository is ready.

K.2.2 Recoverable Emplacement

At the end of the period of readily retrievable emplacement (assumed to last 5 years for this conceptual repository), holes are no longer lined with sleeves or sealed with concrete plugs, and rooms are backfilled after being filled with waste. For the remainder of repository emplacement operations the wastes are considered to be recoverable with considerably greater effort than required for removal of readily retrievable wastes. Although sufficient confidence in repository performance existed to justify termination of ready retrievable emplacement, observations and measurements will likely continue.

Recovery operations are more complex after the phase of readily retrievable emplacement ends. Before removal operations could begin, backfilled rooms first have to be reexcavated. This is done using standard earth-moving equipment with care taken to avoid excessive damage to emplacement holes. Backfill is removed from emplacement holes using shielded boring equipment; again, care is taken to avoid damage to the hole or canister. At this point the waste canister is removed to the surface as described for the readily retrievable case.

In the event that a canister has become damaged and is not able to be extracted directly from the hole special steps need to be taken. This may include core drilling around the damaged canister through the surrounding rock. The rock and waste are then transported to the surface and repackaged for temporary storge and disposal elsewhere.

K.3 ENGINEERED SORPTION BARRIERS

In addition to retardation of radionuclide migration with an appropriate canister design or inert coating of the waste form, certain materials can be used to absorb or otherwise slow radionuclide migration from the package and the repository.

Possible retardation mechanisms include surface adsorption, ion exchange, coprecipitation, and redox effects. The use of coprecipitation appears impractical as a retardation mechanism because of its rather selective nature and because a wide range of radionuclide chemical species must be retarded.

K.3.1 Performance Requirements

Solids selected for radionuclide adsorption, ion exchange, and redox effects in several combinations can be used for repository backfilling, for an overpack in the immediate vicinity of the canister exterior, and/or for a protective packing between the waste form and the interior surface of the canister (Karn-Bransle-Sakerhet 1978). The sorption material must be mechanically, thermally, and chemically stable in the repository environment. Also, it must be dry when in contact with the canister interior and in the waste form radiation field to prevent accelerated canister corrosion or pressurization. Good heat conducting properties and relatively low permeability to ground water also are desirable sorption material characteristics. If the material is used for repository backfilling, it should have sufficient loadbearing capacity to prevent cavern roof collapse onto stored wastes and to prevent major movement of the waste canisters. The organic contents of the filling material should be very low, probably less than 1%, to avoid radionuclide complexing and enhanced migration rates. Materials may be added to affect oxidation-reduction changes that retard radionuclide migration. Radionuclide migration rates of the elements antimony, iodine, neptunium, plutonium, ruthenium, technetium, and uranium may be affected by changes in the redox potential.

K.3.2 Sorption Materials Performance

Research sponsored by the Office of Nuclear Waste Isolation (ONWI) is determining sorption coefficients of many minerals and rocks that may be of interest for sorption barrier use. Swedish (Allard et al. 1977, Haggblom 1977) and Canadian (Acres Consulting Services, Ltd. 1977) workers also have ongoing programs to investigate sorption of radionuclides in clays and rocks. Sorption investigations involving 19 radionuclides that are of interest in waste disposal operations were summarized in a 1976 EPA literature search (Ames and Rai 1978).

The solution species formed from the radionuclides of the various elements are a primary control on their adsorption by a potential retardant. Possible solution species, based on existing thermodynamic data, are shown in Table K.3.1. Rocks, soils, and sediments are predominately cation exchange materials. The inorganic anion exchangers include the amorphous hydrated oxides from iron, aluminum, and manganese, which are found naturally, and other synthetic anion exchange materials such as zirconia or titania. The environmental factors reported to effect radionuclide adsorption are summarized in Table K.3.2.

TABLE K.3.1. Predominant Solution Species of Elements Without Organic Ligands (Karn-Bransle-Sakerhet 1978)

Elements	Little Affected by Oxidation-Reduction	In an Oxidizing Environment	In a Reducing Environment
Am	Am^{3+}, $AmSo_4{}^+$, $Am(OH)^{2+}$		
Sb		$HSbO_2{}^\circ$, $Sb(OH)_3{}^\circ$, $SbOF^\circ$, $Sb(OH)_4{}^-$	SbO^+
Ce	Ce^{3+}, $CeSO_4{}^+$		
Cs	Cs^+		
Co	Co^{2+}, $Co(OH)_2{}^+$		
Cm	Cm^{3+}, $CmOH^{2+}$, $Cm(OH)_2{}^+$		
Eu	Eu^{3+}, $EuSO_4{}^+$, $Eu_2P_2O_7{}^{2+}$		
I		I^-, $IO_3{}^-$	I^-
Np		$NpO_2{}^+$, $NpO_2HPO_4{}^-$, NpO_2HCO_3	$NpOH^{3+}$, Np^{4+}
Pu		$PuO_2{}^{2+}$, $PuO_2(CO_3)(OH)_2^{2-}$, $PuO_2{}^+$	$PuOH^{2+}$, Pu^{3+}
Pm	Pm^{3+}		
Ra	Ra^{2+}		
Ru		$Ru(OH)_2^{2+}$, $RuO_4{}^-$, $RuO_4{}^{2-}$	$RuO_4{}^-$
Sr	Sr^{2+}		
Tc		$TcO_4{}^-$	TcO_2
Th	ThF^{3+}, $Th(OH)_3{}^+$		
^3H	H^+, ^3H-O-H		
U		UO_2^{2+}, UO_2F+, $UO_2(OH_2)^\circ$, $UO_2(CO_3)_3^{4-}$	UO_2^{2+}, UOH^{3+}, $UO_2{}^+$ $UO_2(CO_3)_3^{4-}$
Zr	$Zr(OH)_4{}^\circ$, $Zr(OH)_5^-$, ZrF^{3+}		

Examples of inorganic sorption materials are given in Table K.3.3. Chabazite, erionite and clinoptilolite are zeolites that occur in large deposits of sedimentary origin (Hay 1966) and montmorillonite is the main clay mineral in bentonites. Thermal and hydrothermal stabilities generally are acceptable for the intended use. The thermal conductivities of both clay minerals and zeolites are comparatively low. The zeolites are quite permeable to ground-water while sodium-based montmorillonites show low permeabilities (Jacobsson 1977).

Pusch (1978) has suggested that varying amounts of quartz sand be added to bentonite and that it be compacted to improve its load-bearing and thermal conductive characteristics while retaining some of its cation exchange properties. Through the use of simple relationships between diffusion or solution flow-controlled migration and equilibrium distribution coefficients, Neretnieks (1977) determined the retention time in years in 1-m-10% bentonite/90% quartz and clinoptilolite sorption barriers as shown in Table K.3.4.

The barrier depths (in meters) required to retard various radionuclides for 30 half-lives are shown in Table K.3.5. Clinoptilolite is a better sorption barrier, but it is more permeable and has less bearing strength than the bentonite-quartz mixture. For use within the canister, the clay minerals and zeolites can be dehydrated at just below their stability temperatures.

TABLE K.3.2 Factors Reported to Effect Adsorption of Radioelements Over the pH Range of 4 to 9 (Karn-Bransle-Sakerhet 1978)

	Factors								
						Complex Ions			
Element	pH	Eh	Soil CEC	Competing Ions	Selectively Adsorbed on	Inorganic Ligands	Organic Constutuents	Colloid Formation	Probable Adsorption Mechanisms
Am			X	X		X			IE
Sb		X			Iron Oxides	X	X	X	PPT
Ce	X					X	X	X	TE, PPT
Cs			X		Zeolites, Micas				IE
Co	X				Illite, Iron Oxide	X	X	X	IE, PPT
Cm						X		X	PPT
Eu	X			X		X			IE, PPT
I					OM		X		OM
Np						X		X	UNK
Pu	X	X	X			X	X	X	IE, PPT
Pm	X			X			X		IE, PPT
Ra			X	X	Zeolites, Barite				IE
Ru	X				OM	X	X		PPT
Sr	X		X	X	Calcite, Zeolites	X	X		IE
Tc							X		UNK
Th	X		X		OM	X	X	X	IE, PPT
^3H					H_2O				NONE
U	X	X	X		OM	X	X		PPT,IE
Zr	X					X	X	X	PPT

(a) CEC = Cation Exchange Capacity.
(b) IE = Ion exchange, OM = Organic Matter Adsorption, PPT = Precipitation, UNK = Unknown.

TABLE K.3.3. Thermal Stabilities and Cation Exchange Capacities of Several Clay Minerals and Zeolites (Breck 1974, Eberl et al. 1978, Ames and Sand 1958, Grim 1968)

Material	Composition	Hydrated Cation Exchange Capacity, meq/100 g	Thermally Unstable in Air at, °C
Chabazite	$Ca_2\left[(AlO_2)_4(SiO_2)_8\right]\cdot 3H_2O$	390	600
Erionite	$Ca_{4.5}\left[(AlO_2)_9(SiO_2)_{27}\right]\cdot 27H_2O$	310	750
Clinoptilolite	$Ca_3\left[(AlO_2)_6(SiO_2)_{30}\right]\cdot 24H_2O$	220	750
Mordenite	$Ca_4\left[(AlO_2)_8(SiO_2)_{40}\right]\cdot 24H_2O$	230	800
Montmorillonite	$(Al_{3.34}Mg_{0.66})Si_8O_{20}(OH)_4\cdot H_2O$	150	390

Hydrothermal Stabilities at 100 Bars Pressure for 10 Days

	°C	Products	Composition
Chabazite	230	Wairakite	$Ca_8\ (AlO_2)_{16}(SiO_2)_{32}\cdot 16H_2O$
Clinoptilolite	360	Mordenite	
Montmorillonite	400	Quartz, Feldspar	SiO_2, $NaAl_3Si_3O_8$
Montmorillonite	300	Quartz, Montmorillonite	

TABLE K.3.4 Retention Time Ranges on 1-m Barriers for Several Radionuclides (Neretnieks 1977)

Radionuclide	Retention Time, Years 10% Bentonite/ 90% Quartz	Clinoptilolite
^{90}Sr	30	600 to 1,400
^{137}Cs	20 to 30	2,200 to 5,200
^{226}Ra	40 to 50	600 to 1,400
^{229}Th	50 to 300	unknown
^{237}Np	2.1×10^6	unknown
^{239}Pu	2.4×10^4	unknown
^{241}Am	458	1,000 to 30,000
^{99}Tc	1	1
^{129}I	1	1

TABLE K.3.5 Barrier Depth (m) Required to Retard Various Radionuclides 30 Half-Lives (Neretnieks 1977)

Radionuclide	30 Half-Lives Barrier Depth, m 10% Bentonite/ 90% Quartz	Clinoptilolite
^{90}Sr	1	0.2
^{137}Cs	1	0.1
^{226}Ra	40	1.5
^{241}Am	1	0.1 to 0.7

If the reduced or oxidized species is less soluble than the original radionuclide solution species, an oxidation-reduction (redox) reaction may be used to retard the mobilities of certain radionuclides. Very little work has been done using redox controlling materials as migration retardants. An example of redox control is the use of wustite (FeO) to surround the waste form. The oxidation of ferrous to ferric ion would reduce technetium in the highly mobile pertechnetate ion (TcO_4) from Tc(VII) to Tc(IV). (Latimer 1952 and Pourbaix 1966). Tc(IV) is a much less mobile form of technetium than Tc(VII).

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APPENDIX L

WASTE ISOLATION RESEARCH AND DEVELOPMENT PROGRAM

A program of waste isolation research and development is underway to obtain the data identified as needed in this report, as well as those identified in other review activities. The Department of Energy (DOE), conducting research and development toward waste isolation, has placed emphasis on the development of plans and strategies which incorporate an iterative approach which includes substantial scientific peer review. An important activity of this type was the preparation of the Earth Science Technical Plan (ESTP) for Disposal of Radioactive Waste in a Mined Repository (DOE/USGS 1980). The ESTP describes the research and development programs sponsored by the Departments of Energy and Interior. Additional work is in progress in the U.S. sponsored by the Nuclear Regulatory Commission (NRC), Environmental Protection Agency (EPA), and the utility industry. Additional work is also in progress in Sweden, Germany, France, England, Japan and Russia. A list of ongoing research projects organized by the technology categorization of Section 5.2 (Geologic Disposal--States of Technology and Research and Development) is presented below. This list is not complete, but rather is intended to suggest the scope and depth of current research.

L.1 GEOLOGIC SITE SELECTION

Research and development projects supporting site selection technology are listed below by several subcategories.

L.1.1 Long Term Geologic Stability

ONWI[a]	Regional studies to exclude tectonically active areas from further siting considerations
LASL/SLA	Prediction of volcanic activity
LLL/SLA	Flow charts for investigation and evaluation of candidate sites
LLL	Derivation of parameters for evaluating sites
ONWI	Criteria for geologic disposal of radioactive waste and site qualification criteria
DOE/Woodward-Clyde	Evaluation of the Paradox Basin
DOE/TBEG	Evaluation of the West Texas Bedded Salt
DOE/Law Eng.	Evaluation of Gulf Coast Salt Domes
DOE/Stone & Webster	Evaluation of the Salina Salt Basin

(a) The research and development organizations indicated by abreviation are identified on page L.1.7.

USGS/LASL-SLA	Evaluation of the Nevada Test Site and Southern Nevada
DOE/RHO et al.	Evaluation of the Columbia Plateau
DOE/PNL	Release scenario modeling
DOE/LLL	Derivation of parameters for evaluating sites
ONWI	Criteria for geologic disposal of radioactive waste and site qualification criteria
USGS	Long term prediction of natural events and changes
DOE/SLA	Climatic/tectonic stability of the West Texas Salt Flats Basin
USGS	Climatic stability, Pecos River history
DOE/SLA	Climatic stability, San Simon Sink.

L.1.2 Characterization of Current Geology and Hydrology

USGS	Radar techniques, high-frequency electromagnetic borehole techniques, geophysics for site characterization
LLL/Texas A&M	Radar exploration techniques
Texas Bur. Mines/CONOCO	Improving resolution of existing geophysical techniques
DOE/LBL	Evaluation of geophysical techniques in fractured crystalline rock
Georgia Tech.	Geothermometry
DOE/ORO	The utility of petroleum exploration data in delineating structural features within salt anticlines
USGS	Water flux in the unsaturated zone of deserts, field test of flow in unsaturated alluvium, nonisothermal water fluxes in the unsaturated zone, characterization of local ground water systems, short-term hydraulic effects, fluid flow in fractured rocks, solute transport model in the unsaturated zone
USGS/SLA	Characterization of regional ground water systems
DOE/LLL	Fracture permeability of rocks under pressure, permeability measurements
DOE/LBL	Crystalline rock hydrology.

L.1.3 Seismicity

DOE/SRL	Subsurface earthquake damage
DOE/SLA	Effect of depth on ground motion

NRC/NUREG	Workshop/review of site suitability criteria
ONWI	Geological criteria for suitable sites of high-level radioactive waste; criteria for the geologic disposal of radioactive waste and site qualification criteria, preliminary site selection for SPR facilities in Louisiana and Mississippi
OWI/Woodward-Clyde	Preliminary geologic site-selection criteria for NWTS.

L.1.4 Land Use and Transportation Considerations

TRW	Socioeconomic studies
HARC	Socioeconomic studies
Stearns-Roger	Conceptual Design No. 1
Kaiser	Conceptual Design No. 2; SAI
NUS	Environmental Criteria.

L.2 HOST ROCK PROPERTIES

Research and development projects to better define host rock properties are listed below by several subcategories.

L.2.1 Discontinuities

USGS	Development of geophysical techniques, high frequency electromagnetic borehole techniques
LLL	Development of single hole electromagnetic probe
RHO	Verification studies of specific geologic structures of the Columbia Plateau.

L.2.2 Rock Strength and Excavation Stability

USGS/LASL-SLA	Evaluation of granite, argillite, and tuff at the Nevada Test Site and in southern Nevada
USGS	Surveys of granite and other crystalline rocks, argillaceous rocks, western Cretaceous shales tuff and zeolitised tuff
DOE/LBL	Directional permeability of Stripa granite
DOE/BNL	Geothermometry of shale
DOE/SLA	In-situ test of Conasauga Shale
DOE/LLL	Granite heater and rock mechanics test Climax Stock.

L.2.3 Hardness and Mineability

ORNL/SAI	Expected repository environments
RE/SPEC	Repository concepts analysis
Univ. of Minn.	Development of displacement-discontinuity models
ORNL	Salt model piller studies
USGS	Geomechanics
RHO/CSM	Advanced rock testing of basalt
LLL	Mechanical behavior of rocks under pressure
LBL	Material behavior of strips granite
LBL	Ultra-large rock core tests
RHO/PNL/and Others	Field investigation to determine in-situ geologic, hydrologic, and engineering parameters.

L.2.4 Rock Permeability and Ground Water Flow

LBL	Development of fractured flow and thermal-hydraulic flow models
USGS	Solution of solute transport equations
LBL	Development of analytical transport models
UCB	Brine migration modeling
SLA	Tracer tests of overlying strata
SRL	Osmotic effects of clay minerals
USGS	Solute transport in the unsaturated zone
USGS	Water flux in the unsaturated zones of deserts
USGS	Field test of flow in unsaturated alluvium.

L.2.5 Rock Pressure

DOE/LBL	In-situ stress measurements techniques (Stripa 7). In-situ thermomechanical test in Stripa granite
DOE/RE/SPEC	In-situ test--Avery Island Salt Dome
DOE/SLA	Instrumentation development for in-situ tests. Thermal-structural interaction--bench and in-situ tests. In-situ test of Conasauga Shale
DOE/LLL	Granite heater and rock mechanics tests
DOE/RHO	Near-surface Test Facility programs for in-situ testing of basalt at the Hanford Reservation, rock mechanics methods and in-situ heater tests in basalt.

L.3 THERMAL AND RADIATION EFFECTS

DOE/LLL	Mechanical behavior of rocks under pressure
DOE/SDSM	Bench-scale creep tests on rock salt
DOE/Texas A&M	Transient creep in rock salt
DOE/SLA	Thermal-structural interactions
DOE/SAI-LBL	Analysis of thermomechanical response of salt
USGS	Geomechanics of thermally induced stress on in-situ stress and fracturing
DOE/LBL	In-situ stress measurement techniques (Stripa 7)
DOE/RHO-Univ. of Minn. & Dames & Moore	Numerical modeling of rock stresses within a basaltic nuclear repository
NRC/TASC	Information base for waste repository design, Volume 3; Waste Rock Interactions
DOE/ORNL	Radiolysis of brine
DOE/SLA	Thermal-structural interactions in salt, pressure effects on thermal conductivity and expansion of geologic materials
DOE/LBL	In-situ thermomechanical tests of Stripa granite, large scale permeability tests of granite in the Stripa Mine and thermal conductivity tests
DOE/LLL	Granite heater and rock mechanics tests Climax Stock
DOE/RE/SPEC	Parametric thermoelastic analysis of high-level waste and spent fuel repositories in granite and other non-salt rock types.

L.4 REPOSITORY PERFORMANCE

DOE/ORNL	Borehole plugging--cement technology studies
DOE/SLA	Materials development, instrumentation, and field testing for borehole plugging
NRC/TASC	Information base for waste repository design, Volume 1, Borehole and Shaft Sealing
DOE/RHO	Borehole plugging programs at Hanford
ONWI/PNL	Borehole plugging and shaft sealing for geologic isolation of radioactive waste.
ONWI/PNL	Assessment of the effectiveness of geologic isolation systems
ONWI/PNL	Waste/rock interaction technology
NRC/SLA	Risk methodology for radioactive waste disposal in geologic media
NRC/LLL	Standards for the management and disposal of high-level and transuranic waste
EPA/Univ. of N.M.	Assessment method for geologic isolation of nuclear waste
EPA/ADL	Technical base for establishing regulations for disposal of HLW
USGS	Long term prediction of natural events and change
RHO/Furgo, Inc.	Assessment of geothermal and volcanic activity
SLA/LASL	Evaluation of tectonic, seismic, and volcanic hazards, Nevada Test Site and vicinity
BDM/INTERA/SAI/SLA	Nuclear waste repository safety assessment

Glossary of Acronyms Used in Appendix L

ADL	Arthur D. Little, Inc.
BDM	BDM Corporation
BNL	Brookhaven National Laboratory
BWIP	Basalt Waste Isolation Program
CONOCO	Continental Oil Co.
CSM	Colorado School of Mines
DEIS	Draft Environmental Impact Statement
DOE	U.S. Department of Energy
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
GCR	Geologic Characterization Report (WIPPO)
HARC	Human Affairs Research Center (Battelle)
HLW	High-Level Waste
INTERA	INTERA Environmental Consultants
LASL	Los Alamos Scientific Laboratory
LBL	Lawrence Berkely Laboratory
LLL	Lawrence Livermore Laboratory
N	Subcontractor not determined
NRC	U.S. Nuclear Regulatory Commission
NWTS	National Waste Terminal Storage
NUS	NUS Corp
ONWI	Office of Nuclear Waste Isolation (Battelle)
ORNL	Oak Ridge National Laboratory
ORO	Oak Ridge Operations (DOE)
OWI	Office of Waste Isolation
PBQ&D	Parsons, Brinkerhoff, Quade & Douglas
PIR	Preliminary Information Report
PNL	Pacific Northwest Laboratory
RE/SPEC	Re/Spec, Inc.
RHO	Rockwell Hanford Operation
SAI	Science Applications, Inc.
SDSM	South Dakota School of Mines
SLA	Sandia Laboratories-Albuquerque
SRL	Savannah River Laboratory
SSA	Southern Science Applications, Inc.
TASC	The Analytic Sciences Corporation
TBEG	Texas Bureau of Economic Geology
TRW	TRW Inc.
USGS	U.S. Geologic Survey
WIPP	Waste Isolation Pilot Plant
WISAP	Waste Isolation Safety Assessment Program

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APPENDIX N

WASTES FROM THORIUM-BASED FUEL CYCLE ALTERNATIVES

A number of thorium-based fuel cycle alternatives to the light water uranium-plutonium cycle have been proposed. The alternatives include: the uniform enrichment of thorium in LWR and heavy water; spike blanket systems in LWRs; crossed progeny in LWR's heavy water and fast converters; light water breeder (LWBR); and high-temperature gas-cooled reactor (HTGR) fuel cycles. For this Statement the LWBR and HTGR cycles have been chosen for discussion because their demonstration is nearer completion. Thus, they may be the first systems able to employ a thorium load. Moreover, a standard LWR using a thorium fuel cycle will have fission-product yields very similar to those of the LWBR. Analyses for managing wastes from these thorium fuel cycles have not been made in as great detail as for the LWR uranium cycles presented elsewhere in this Statement. The basis for this discussion is DOE/ET-0028, and that document should be referred to for a more-complete presentation.

As in the slightly enriched light water reactor cycle, power reactors could use thorium in either recycle or nonrecycle modes. In the recycle mode, spent fuel is reprocessed to remove fissionable ^{233}U that has been generated and to remove the initial fissionable species that remains unburned from the irradiation.(a) This material (mostly bred ^{233}U) can then be refabricated into fuel elements for reinsertion into a nuclear power reactor. This can be accomplished whether or not the amount of fissile material generated is large enough for the reactor to constitute a true breeder, which, once started, provides its own fissionable fuel. The system may not be operated as a breeder, but even so, the fissionable material required for makeup (^{235}U, plutonium, ^{233}U from other sources) may not be large.

In the nonrecycle mode, the fissionable material generated is not returned to the core, either because the fuel is not reprocessed or because the product from the reprocessing plant is treated as waste or is stored for future use. In this case, new fissionable material would be supplied for each core loading.

In the discussion that follows, wastes from the reprocessing of thorium fuels from LWBR and HTGR are compared with those from commercial light waste reactors (LWRs). It is assumed that 99.5% of the plutonium is separated from the LWR waste in reprocessing, but is not recycled. All comparisons are based on production of equal quantities of electrical energy.

(a) Under DOE management directives it is mandatory that ^{233}U and ^{239}Pu be disposed of in a similar manner. The reasoning for this is not because of any near-term risk from the ^{233}U but because of the higher specific toxicity of the daughter products in the long term.

Fission product activity in thorium wastes is about the same as that in LWR wastes, with only slight aggregate differences because of the mass distribution of ^{233}U fission fragments and the greater thermal efficiency of HTGRs. Some of the specific isotope yields are different by a factor of about two, but these differences are not among controlling long-lived isotopes and thus neither simplify nor complicate long-term waste storage as visualized and being developed for the slightly enriched uranium (SEU) cycle in LWRs.

Radiogenic heating is of importance when considering storage and isolation of certain radioactive wastes. Heat generation rates in the thorium wastes are essentially the same as in LWR wastes for the first several thousand years. They reach a maximum at less than twice the LWR rate in about 100 years, then decrease and finally peak again at 50 to 100 thousand years. Although the latter peak can exceed the LWR rate by a factor of 15, the actual value of the heat generation rate is quite small by that time.

For the first few thousand years, actinide and heavy element radioactivity in LWBR wastes is somewhat less than that in the LWR wastes. The radioactivity in HTGR wastes at these times exceeds that in LWR wastes by up to a factor of 7 because of the plutonium (primarily ^{238}Pu) which is present. After hundreds of thousands of years, the radioactivity in both HTGR and LWBR wastes exceeds that of LWR wastes by factors of 10 to 20. As in the case of heat generation, however, the absolute activity at these long times is relatively small.

In the instance of thermal neutron reactors, the more ^{233}U recycled, the lower will be the releases of transuranium isotopes formed by successive neutron captures in the fuel. This is due mainly to the fact that the capture-to-fission ratio is less for ^{233}U than for ^{235}U, ^{239}Pu, or ^{241}Pu. On the other hand, more (5 to 10%) ^{233}U in thorium fuel cycles must be fissioned than ^{235}U or plutonium in the SEU because the energy yield per fission for ^{233}U is less, and because thorium has about one-fifth the fast-fission effect of ^{238}U.

The actinide radioactivity and the heat generation rate differences are also influenced by the way the transuranic isotopes are managed, in particular regarding the yields on processing and the goal exposure of the fuels. However, when the gross characteristics of the LWBR-generated waste (total activity, heat output, chemical and physical form) are compared to LWR-generated waste, these characteristics are very similar (DOE 1979). As a result, no special waste management requirements are posed by the LWBR concepts which do not already exist for the LWR and no changes are anticipated to be necessary in the waste isolation program for LWR systems to accommodate a thorium-based system. ERDA (1976) performs an environmental assessment of a thorium-uranium fuel cycle and should be referred to for detailed information.

Gaseous releases from a facility reprocessing thorium-^{233}U fuel would be somewhat greater than those from a reprocessing facility. This is particularly true for ^{85}Kr, although the xenon yields are more nearly equal. Because of the greater ^{85}Kr release, an analysis is required to determine the significance of the release.

The ^{14}C release from an HTGR reprocessing facility could be up to 15 times larger than that of SEU in LWRs because of the large amount of graphite in the fuel and the burning operation used to separate the fuel from the structural material. In this amount a system might be required to remove ^{14}C from the reprocessing facility off-gas stream.

Because of high radioactivities, the isotopes ^{232}U and ^{228}Th incidentally generated in the ^{232}U-thorium cycle pose some short-term handling problems not significantly present with the SEU system. Uranium-232 has a 70-year half-life followed by much shorter half-lived daughters leading to ^{208}Tl, which has a 2.6 MeV gamma. In the recycle case, this complicates the handling of ^{233}U fuels even though it is present in only a few parts per million. However, as a diluent in uranium, it does not appreciably complicate waste storage. A long-term concern may be the precursor of ^{232}U, namely ^{231}Pa. The concentration in the wastes of ^{231}Pa with its 32,500-year half-life will depend on how it is managed in the successive recycle. There is, of course, an incentive to hold the protactinium in a processing vessel to assure that the ^{233}Pa fully decays to ^{233}U, which is then bled off and recycled. Under these circumstances there is no reason to recycle protactinium and thus ^{231}Pa is not "burned out." Its concentration in the wastes is correspondingly increased to levels that may approach the ^{239}Pu concentration in wastes from plutonium recycle. This could be alleviated by purposefully irradiating ^{231}Pa as an isolated target and by adding the ^{232}U generated into the high-level wastes in dilutions so localized heating will not be produced.

Currently it is believed necessary to add fluorine to dissolve spent thorium oxide fuel. The effects of fluorine, if any, upon the waste processing are unknown. However, steps could be taken to obviate the fluorine in the processing. This may involve addition of magnesium, calcium, or other elements to thorium oxide which will add to waste volume, but not appreciably to radioactivity. This may, however, increase the solubility of thorium dioxide in water coolant streams, increasing contamination of water coolant streams if fuel jackets develop leaks.

It is not believed that fluorine will detract from the qualities of the waste glass as fluoride is a constituent of many commercial glasses and enamels. The fluorine content of commercial glasses rarely exceeds 6%. Fluoride at those high concentrations acts as an opacifier in the glass owing to dispersed fluoride crystals. considerable laboratory experimentation has already been done on the incorporation of fluoride in nuclear waste glass.

REFERENCES FOR APPENDIX N

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APPENDIX P

MINERALS THAT COULD BE USED TO CONTAIN RADIONUCLIDES

This appendix presents a review of minerals that are candidates for the isolation of radionuclides in synthetic minerals, as discussed in Section 4.3.2.3. Analyses of the potential hazard from certain HLLW radionuclides suggest the greatest effort in solidification into synthetic minerals would be placed on the following groups of elements:

- Actinides and Lanthanides. The actinides Np, Pu, Am, Cm and their daughters constitute the major hazard in nuclear wastes from about 1000 to 5000 years of storage, with the exception of ^{226}Ra, which does not become significant until about 10^5 years (Cohen 1977). The majority of the lanthanide elements (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho) are present as stable isotopes after a few years, and only trace amounts of a few Sm and Eu radionuclides have long half-lives. However, the lanthanides could be included with the actinides for several reasons: they occur together at one stage of partitioning; lanthanides and actinides are crystallographically and chemically very similar and usually occur together in the same minerals; the lanthanides can act as diluents in synthetic minerals for α-emitting actinides in order to minimize radiation effects.
- Strontium and cesium. These elements constitute both the major heat producers and biohazards in nuclear wastes for the first 600 years or so (Cohen 1977).
- Techetium and iodine. These two fission products have long-lived isotopes (^{99}Tc, $t_{1/2} = 2.1 \times 10^5$ y; ^{129}I, $t_{1/2} = 1.7 \times 10^7$ y) and are biohazards. They have the additional characteristics of forming anions that can migrate in soils and rocks as fast as the solutions in which they are dissolved (Rai and Seine 1978), i.e., without any substantial hold-up due to ion exchange or adsorption.

The minerals reviewed here are either known to contain substantial amounts of these elements or are likely to accept these elements based on compatible crystal chemistry. The physico-chemical and crystal chemical criteria for selecting host minerals, along with the common mineral synthesis methods, are discussed and tables of candidates are presented. A thorough treatment of what is known about the process of metamictization and metamict minerals is also included.

P.1 PHYSICO-CHEMICAL PRINCIPLES

P.1.1 Stability Criteria

The physical and chemical foundations used to define whether a known mineral is classified as very stable, relatively unstable, or very unstable with respect to alteration, weathering and diagenesis include solubility and geologic data.

P.1.1.1 Use of Solubility Data

Chemical weathering and alteration are most often the result of the interaction between an electrolyte aqueous solution and the various minerals being weathered. Several factors are important in determining the mobility of elements via weathering ionic solutions. One group of factors is related to the overall physical properties of the "weathering system," i.e., of the hydrologic system and the host mineral assemblage. For example, the flow rate of solution through a permeable system is determined by Darcy's Law:

$$\vec{u} = -\frac{k}{\mu}(\rho\vec{g} + \nabla P) \qquad v = \frac{\vec{u}}{\rho\emptyset}$$

where $\vec{u}$ = fluid flux vector (g/cm^2/sec)
$\vec{v}$ = true fluid velocity (cm/sec)
$\vec{g}$ = gravity force vector (cm/sec^2)
k = permeability of the rock assemblage (cm^2)
μ = viscosity of the fluid (cm^2/sec)
ρ = density of the fluid (g/cm^3)
P = pressure (bars)
$\emptyset$ = porosity of rock.

Clearly, then, the water flow depends on gravity and the pressure gradient at the given locality (a property of the hydrologic system as a whole) as well as on the porosity and permeability of the rock assemblage in the locality, and the density and viscosity of the fluid.

The hydrodynamic equations, which incorporate Darcy's Law, allow us to calculate the hydrodynamic mobility of a given cation or anion in solution from its original location within a given mineral of the weathered rock to its place of deposition such as a sedimentary deposit, rivers, oceans or the biosphere. We can obtain absolute flux rates for a given ion (i.e., moles/cm^2/sec), however, only if we know its concentration in the percolating solution.

The magnitude of the concentration of a given element in a solution that is in contact with a weathering mineral assemblage is the central element used in establishing the intrinsic stability of a particular nuclear waste element-containing mineral to alteration and weathering. This concentration is generally a function of time, since it is kinetically controlled. Nevertheless, almost all geochemical work on the mobility of elements via solutions has applied a thermodynamic and not a true kinetic approach. Whether true thermodynamic equilibrium is reached between solution and a particular mineral depends, among other things, on how long they are in contact (i.e., the flow rate); this concept often appears as the ambiguous "water-rock ratio" in the literature. It seems likely that under most circumstances the concentration of an element in a weathering solution will be kinetically controlled. Unfortunately, there is a dire need for suitable kinetic data. The kinetic factors involved in the time dependence of the concentration, which may keep the concentration well below the thermodynamic limit, will be discussed below.

One can usually establish only an upper limit to the concentration of a given element by the use of thermodynamics. Assuming equilibrium between minerals and solution, the concentration of any particular nuclear waste element will then be governed by the solubility of the minerals containing it.

Before discussing the thermodynamic approach to stability, a brief review of the general qualitative work on weathering stability in the literature is presented. Soil geochemists have set up a qualitative scale of the different inherent tendencies of minerals to alter by weathering processes. The weathering rate depends on the structure and composition of the minerals, as well as the weathering environment. Goldich (1938) formulated such a weathering stability series for the major elements. He found that the major elements are removed from rocks and minerals in the order:

$$Ca^{+2} > Na^{+} > Mg^{++} > K^{+} > SiO_2 > Fe_2O_3 > Al_2O_3.$$

Loughnan (1969) gives a similar result (see Table P.1.1).

Much less is known about the relative mobilities of the trace elements (lanthanides, actinides, and others). Jackson and his colleagues (Jackson et al. 1948, 1952, Jackson and Sherman 1953) set up a weathering sequence of clay-size minerals in soils and sedimentary deposits (see Table P.1.2). Pettijohn (1941) compared the frequency of occurrence of each species in recent and older sediments and established an order of persistence, which is in agreement with the Goldich series (see Table P.1.3).

TABLE P.1.1 Mobilities of the Common Cations

→increasing rate of loss from the environment→

1. Ca^{++}, Mg^{++}, Na^{+}--readily lost under leaching conditions.
2. K^{+}--readily lost under leaching conditions but rate may be retarded through fixation in the illite structure.
3. Fe^{++}--rate of loss dependent on the redox potential and degree of leaching.
4. Si^{4+}--slowly lost under leaching conditions.
5. Ti^{4+}--may show limited mobility if released from the parent mineral as $Ti(OH)_4$; if TiO_2 forms, immobile.
6. Fe^{3+}--immobile under oxidizing conditions.
7. Al^{3+}--immobile in the pH range of 4.9 to 9.5.

Although still poorly understood, structure must play an important part in the accessibility of waters to the soluble cations. Thus, orthosilicates, e.g., olivine, weather much faster than framework silicates, e.g., feldspars and quartz. However, zircon, also an orthosilicate, is highly resistant to weathering, which indicates that resistance to weathering cannot be based solely on such a simple structural division of the silicates.

The qualitative lists of minerals in Tables P.1.2 and P.1.3 should be quantitatively understood in terms of both thermodynamics (i.e., solubility data) and kinetics (i.e., leaching rates). The solubility and hence the thermodynamic stability of a particular

TABLE P.1.2. Weathering Sequence of Clay-Size Minerals in Soils and Sedimentary Deposits(a)

Weathering Stage and Symbol	Clay-Size Mineral Occurring at Various Stages of the Weathering Sequence
1, Gp	Gypsum (also halite, etc.)
2, Ct	Calcite (also dolomite, aragonite, etc.)
3, Hr	Olivine-hornblende (also diopside, etc.)
4, Bt	Biotite (also glauconite, chlorite, antigorite, etc.)
5, Ab	Albite (also anorthite, microcline, stilbite, etc.)
6, Qtz	Quartz (also cristobalite, etc.)
7, Il	Illite (also muscovite, sericite, etc.)
8, X	Hydrous Mica - Intermediates
9, Mt	Montmorillonite (also beidellite, etc.)
10, Kl	Kaolinite (also halloysite, etc.)
11, Gb	Gibbsite (also boehmite, etc.)
12, Hm	Hematite (also goethite, limonite, etc.)
13, An	Anatase (also rutile, ilmenite, corundum, etc.)

(a) After Jackson et al. (1948).

TABLE P.1.3. Persistence Order of Minerals(a,b)

-3. Anatase
-2. MUSCOVITE
-1. Rutile
1. Zircon
2. Tourmaline
3. Monazite
4. Garnet
5. BIOTITE
6. Apatite
7. Ilmenite
8. Magnetite
9. Staurolite
10. Kyanite
11. Epidote
12. HORNBLENDE
13. Andalusite
14. Topaz
15. Sphene
16. Zoisite
17. AUGITE
18. Sillimanite
19. Hypersthene
20. Diopside
21. Actinolite
22. OLIVINE

(a) After Pettijohn (1941).
(b) Capitals signify common minerals listed in the Goldrich sequence.

mineral in a weathering solution depend on many environmental factors such as pH, Eh, complexing agents, temperature, fixation/adsorption, ion exchange and ionic strength. These factors are explained briefly below.

- pH. Most minerals are leached faster and have higher solubilities in acid environments. The natural range of possible weathering solutions is pH = 4 to 10. One of the earliest steps in the chemical weathering of a mineral is the exchange of the small and mobile H^+ ion for a cation on the mineral surface, with subsequent disruptions of the structure (Loughnan 1969). Obviously, low pH solutions can accomplish this more effectively.
- Eh. For ions that can exist in several valence states (e.g., U^{+4} and U^{+6}) Eh is very important in determining their solubility. The Eh of natural solutions in contact with the atmosphere is $\sim$600 mv. Subsurface solutions can have an Eh range of -400 mv to +400 mv, with the more reducing (low Eh) conditions found in alkaline environments (Garrels and Christ 1965). For example, a mineral with very low solubility, such as uraninite (UO_2), requires a low Eh for stability to weathering (i.e., Eh < +200 mv if pH = 6, Eh < 0 mv if pH = 8) (Langmuir 1978).
- Complexing. The formation of complexes has long been recognized as essential in explaining the transport of metals required to form ore deposits. The same must be investigated for the cations of the nuclear waste elements, since complexing can increase the solubility of an element by several orders of magnitude. At lower temperatures (<200°C), we expect carbonates, phosphate, sulfate/sulfide and organic complexes to be important.
- Temperature: The solubility of various minerals can change significantly with temperature. Temperatures in the vicinity of synthetic minerals containing heat producers (^{90}Sr, ^{137}Cs, Actinides) could rise up to several hundred degrees above ambient.
- Adsorption. The ability of ions, such as K^+, to adsorb strongly to clays and other minerals, retards their mobility and limits their concentration in solution, following leaching of the ions. This may be important, for example, in the case of uranium, which adsorbs strongly to Mn-oxides, Fe-oxides and hydroxides.
- Cation Exchange. An important consideration in establishing the stability of a given nuclear waste element-containing mineral to the leaching of such elements, is the ability of that mineral to exchange the troublesome nuclear waste element for another ion in solution. Thus, K^+ may be exchanged for Cs^+, or Cl^- may be exchanged for I^-. On the other hand, ion exchange of the radionuclide with clays and other minerals can also retard the mobility of the radionuclide in solution.

Rai and Lindsey (1975) applied simple solubility calculations to deduce the relation between log a_{Al} and log $a_{H_4SiO_4}$ at given values of pH, T, and solution compositions (e.g., a_{Ca}, a_{Mg}, etc.) for several aluminosilicates. At a given value of $a_{H_4SiO_4}$ the minerals with the lowest $a_{Al^{3+}}$ were most stable. Using values of $a_{H_4SiO_4}$ typical of soil waters ($a_{H_4SiO_4} \sim 10^{-3.2}$ m) they obtain the stability sequence muscovite > microcline > low albite > anorthite > analcine > pyroxene > K-glass (K-feldspar composition) > Na-glass (albite composition); that is in agreement with Goldich's sequence. Likewise one can plot regions of stability for various minerals on an Eh-pH diagram, as outlined by Garrels and Christ (1965).

P.1.1.2 Use of Geologic Data

Because geologic time spans the lifetimes of the radionuclides of the critical elements, it is very logical to use nature as a laboratory and examine conditions of stability of minerals that may contain the critical elements. In general one recognizes three main geologic environments (igneous, sedimentary, and metamorphic) and asks which mineral phases may exist in each environment and what happens to a mineral grain as it sees a change in its environment. Minerals of the igneous environment see extreme temperatures (and pressures) such that they have crystallized from a melt or a fluid derived from a melt (pegmatites and hydrothermal deposits). The sedimentary environment includes the effect of exposure to the atmosphere and running water and the physical effects of separation and movement of mineral grains. The metamorphic environment involves changing pressure, temperature and pore fluid conditions inducing mineral changes in situ.

As one identifies mineral species that may be potential repository compounds, a test of their stability is to determine the geologic environments under which they can endure. If any modifications in the mineral phase do occur, then the time frame of the modifications can also be deduced. The best test of a mineral's stability is to determine the range of changes through which it can exist.

Many of the minerals that are potentially interesting host phases form initially in the igneous environment. Feldspars, feldspathoids and micas crystallize directly from the melt. Many others are pegmatitic in origin, especially those containing rare earth elements (REE). This information implies conditions that may be necessary to form the phase desired. It may not be the only condition under which the compound will form.

After the compound has formed, the question of what happens to it as the conditions change may be answered. Because stability is the main question, one asks what phase may endure weathering and erosion unchanged, and what new phases are formed if changes do occur. Many minerals survive the rigors of weathering and erosion and these are ultimately collected in detrital deposits. When the detrital deposit has an economic value it is called a placer. These minerals are usually of high density and chemical resistance. Other minerals, called detrital-heavy minerals, may not survive the entire erosion cycle but persist for quite some time. Detrital-heavy minerals may last sufficiently long to allow included radionuclides sufficient time to decay. Therefore, it is useful to identify the placer minerals and other detrital-heavy minerals.

The Placer Minerals

Table P.1.4 identifies the minerals that have been recognized in placer deposits. These minerals are characterized by high densities and chemical and physical resistance. All the noble metals--platinum, iridium, palladium, gold--are known to occur as placer minerals. Many oxides containing lanthanides as well as carbonates, phosphates, tungstates

TABLE P.1.4 Placer Minerals[a]

Element minerals

Platnium, Osmium, Palladium, Iridium, Platiniridium Iridosmine, Osmiridium, Ferroplatinum, Gold, Electrum, Silver, Diamond

Oxide minerals

Tantalite, $FeTa_2O_6$; Thoreaulite, $ThTi_2O_6$; Cassiterite, SnO_2; Samarskite, YNb_2O_6; Baddeleyite, ZrO_2; Euxenite, YNb_2O_6; Chromite, $FeCr_2O_4$; Magnetite, Fe_3O_4; Columbite, $FeNb_2O_6$; Polycrase, YTi_2O_6; Aeschynite, YTi_2O_6; Loparite, $CeTi_2O_6$; Ilmenorutile $(Ti,Nb)_3O_6$; Ilmenite, $FeTiO_3$; Zirkelite, $CaZti_2O_7$; Pyrochlore, $Ca_2Nb_2O_6OH$; Rutile, TiO_2; Brookite, TiO_2; Anatase, TiO_2; Corundum, Al_2O_3; Spinel, $MgAl_2O_4$; Quartz, SiO_2

Tungstate minerals

Ferberite, $FeWO_4$; Wolframite, $(Fe,Mn)WO_4$; Hubnerite, $MnWO_4$; Scheelite, $CaWO_4$

Phosphates

Monazite, $CePO_4$; Xenotime, YPO_4

Carbonates

Bastnaesite, $CeCO_3F$; Parisite, $Ce_2Ca(CO_3)_3F_2$

Silicates

Thorite, $ThSiO_4$; Zircon, $ZrSiO_4$; Garnet, $(Fe,Mg)_3Al_2Si_3O_{12}$; Topaz, $Al_2SiO_4F_2$; Phenakite, Be_2SiO_4

and silicates are known placer minerals and therefore are potential lanthanide and actinide phases. Some low density minerals, such as quartz, spinel, garnet, corundum and diamond also occur in placers.

Other minerals might be on this list of placer minerals under special conditions. If the sedimentary conditions are more reducing than usually occurs in nature, uraninite and many sulfide minerals may survive. This possiblity is evidenced by the placers of Witwatersrand District of Africa, which formed in the reducing environments of the Pre-Cambrian.

Detrital Minerals

A great many minerals survive long distances of transport in stream beds, although the final fraction of that mineral is often much lower than in the source area. These minerals are listed in Table P.1.5. The rate of degradation of some of these minerals may be sufficiently slow to allow that phase to be a host for radionuclides. Minerals such as apatite, barite, allanite and titanite are particularly interesting. Apatite and allanite contain significant amounts of lanthanides and actinides. Strontium varieties of apatite also occur.

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[a] Simplified formulae are given. Actual minerals usually contain many additional solid solution substitutions.

TABLE P.1.5. Detrital Minerals(a)

Elements

Lead

Oxide minerals

Hematite, Fe_2O_3; Uraninite, UO_2; Uranothorite, $(U,Th))_2$; Leucoxene, Ti oxide-hydroxide

Sulfide minerals

Cinnabar, HgS; Pyrite, FeS_2; Marcasite, FeS_2; Chalcopyrite, $CuFeS_2$; Arsenopyrite, $FeAsS_2$; Pyrrhotite, $Fe_{1-x}S$; Molybdenite, MoS_2; Cobaltite, $CoAsS_2$; Dyscrasite, Ag_3Sb; Michenerite

PdBiTe; Geversite, $PtSb_2$; Glaucodot, CoAsS; Moncheite, PtTe

Sulfate minerals

Barite, $BaSO_4$

Phosphate minerals

Apatite, $Ca_5(PO_4)_3F$

Silicate minerals

Actinolite, $Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$; Andalusite, Al_2SiO_5; Biotite, $K(Fe,Mg)_3AlSi_3O_{10}(OH)_2$; Chlorite, $(Mg,Fe)_6(Al,Si)_4O_{10}(OH)_8$; Chloritoid, $(Fe,Mg)\ Al_4Si_2O_{10}$; Hornblende, $Ca_2(Fe,Mg,Al)_5Al_2Si_6O_{22}(OH)_2$; Hypersthene, $(Mg,Fe)Sio_3$: Kyanite, Al_2SiO_5; Olivine, $(Mg,Fe)_2SiO_4$; Allanite, $Ce_2Al_2FeSi_3O_{11}(OH)$; Sillimanite, Al_2SiO_5; Staurolite, $Fe_2Al_9Si_4O_{23}OH$; Titanite, $CaTiSiO_5$; Tourmaline, $Na(Mg,Fe)_3\ Al_6(BO_3)_3Si_6O_{18}(OH)_4$; Zoisite, $Ca_3Al_2Si_3O_{11}O(OH)$; Gadolinite, $Be_2Y_2FeSi_2FeSi_2O_{10}$

(a) Simplified formulae are given. Actual minerals usually contain many additional solid solution substitutions.

Mineral Associations

In addition to defining regions of stability for specific mineral phases, geologic evidence indicates which phases may occur together in an equilibrium assemblage. These mineral associations are good indicators of compatible phases. The pegmatite environment contains many of the minerals of interest. Rare earth phosphates, rare earth oxides and rare earth carbonates which are good hosts for the lanthanides and actinides, coexist with a variety of complex silicates, which may host other critical elements. These in turn coexist with some of the common silicates, which may be more appropriate hosts for ^{90}Sr and ^{137}Cs.

P.1.2 Kinetic Factors

Often the concentration of an element in solution is not determined by thermodynamic solubility data but by the kinetics of water-rock interactions. Data on this part of the stability criteria are most urgently needed. We outline here the principal factors that indicate the kinetic stability of various minerals.

P.1.2.1 Leaching rate

If the leaching is surface-controlled, the rate at which a cation is leached from a mineral depends on: 1) the reactive specific surface area of the mineral and the solution; 2) the concentrations of the species or ions involved in the transition state of the rate-determing step for surface reaction; 3) the free energy of activation of the activated complex; and 4) the temperature of the solution-rock system. The effects of pH, Eh and complexes enter via their effect on the numbers in 2). The role of temperature in kinetic processes is much more prominent than its role in solubility calculations, due to the high activation energies (10 to 100 Kcal/mole) often encountered. Thus it is crucial to measure accurately the activation energies for the important leaching rates.

Leaching rates can also be controlled by the rate of transport (i.e., diffusion) of leached cations from the weathering mineral-solution interface to the bulk of the solution. In this case, temperature will play a much more minor role, since diffusion activation energies are $\sim$4 to 5 Kcal/mole in electrolyte solutions. Experiments should decide which mechanism is operative for each mineral (e.g., feldspars and calcite seem to weather according to the surface-controlled mechanism, while olivine dissolves by a diffusion-controlled mechanism). The leaching rate may sometimes be severely limited by inhibitors. These inhibitors could be organic substances or ions such as $[PO_4]^{3-}$, which deactivate the active sites on a surface (e.g., such as the effect of $[PO_4]^{3-}$ on calcite dissolution). A protective coating may sometimes also form on the surface of the weathering mineral. All these factors add to the kinetic stability of a mineral.

Neither data on leaching rates of relevant minerals nor an understanding on their mechanisms are now available. This gap certainly needs to be filled. The theoretical framework to understand the kinetics of leaching or dissolution is developed to a reasonable degree (Nielsen 1964, Hofmann et al. 1974); however, application to relevant geologic materials is needed.

P.1.3 Crystal Chemical Criteria

P.1.3.1 Element Substitution

In establishing which minerals are appropriate to contain the relevant nuclear waste elements, one may use minerals that are known to contain the element or elements of interest and satisfy the stability criteria. Many such examples will be identified, particularly for Sr, lanthanides, and U. However, elements such Cs, I, actinides, and Tc are so rare in nature that few known minerals contain them as essential elements. One can then use the principles of crystal chemistry to predict the formation of mineral-like phases that will contain the elements in question or mineral phases into which significant quantities may be incorporated in solid solution.

The critical elements all behave essentially like ions in their compounds, so one can use the principles of element substitution in ionic compounds as criteria for predicting appropriate host phases. The main criteria are similarity of chemical parameters, particularly the ionic radius and the charge. Other parameters such as polarizability and d-orbital interactions will have a lesser effect in determining the amount of substitution. Thus one can use a table of ionic radii to predict possible substitutions, remembering that charge balance must be maintained by a coupled substitution of another element whenever necessary.

P.1.3.2 Ionic Radii

Table P.1.6 lists the ionic radii of the important nuclear waste elements and of the elements present in minerals which are most likely to be substituted. Usually, complete substitution may occur if the ionic radii differ by no more than 15%. Limited substitution may occur if the radii difference is larger, or a new compound may be induced to form. This compound may be isostructural with the host phase or may have a distinctly different structure. If the phase is isostructural, then stability properties of the new phase may be similar to that of the host, or certainly be close enough to warrant further investigation.

TABLE P.1.6 Selected Ionic Radii[a]

Ion	CN[b]	Ionic Radius (A)	Ion	CN	Ionic Radius (A)
Cs^+	X	1.81	Na^{1+}	VI	1.02
Sr^{2+}	VIII	1.25		IX	1.32
I^{1-}	VI	2.20	K^{1+}	VI	1.38
I^{5+}	VI	0.95		IX	1.55
Tc^{4+}	VI	0.65	Ca^{2+}	VI	1.00
Tc^{7+}	VI	0.56		VIII	1.12
La^{3+}	VIII	1.16	Ba^{2+}	VI	1.36
				VIII	1.42
Dy^{3+}	VIII	1.03	Cl^{1-}	VI	1.81
Ce^{4+}	VIII	0.97	Br^{1-}	VI	1.96
U^{4+}	VIII	1.00	Y^{3+}	VIII	1.02
U^{6+}	II	0.45	Zr^{4+}	VIII	0.84
Np^{4+}	VIII	0.98	Ti^{4+}	VI	0.61
Pu^{3+}	VI	1.00	Th^{4+}	VIII	1.04
Pu^{4+}	VIII	0.96	Mn^{3+}(HS)[c]	VI	0.65
Am^{3+}	VI	1.00	Fe^{3+}(HS)	VI	0.65
Am^{4+}	VIII	0.95	Cr^{3+}	VI	0.62
Cm^{3+}	VI	0.98	Ce^{3+}	VIII	1.11

(a) After Shannon and Prewitt (1969).
(b) CN = coordination number.
(c) HS = high spin.

Using Table P.1.6 as a guide, one can see that Cs^{+1} is large and most like K^{+1} and possibly Ba^{+2}. There is only one mineral in which Cs is essential, and that is pollucite ($Cs_2Al_2Si_4O_{12} \cdot nH_2O$), a member of the analcime ($Na_2Al_2Si_4O_{12} \cdot nH_2O$) family of minerals. The fact that it is acting in the role of Na^{+1} suggests that other Na^{+1} and K^{+1} phases may act as hosts for Cs^{+1}. Other possible examples include the feldspars (K,Na,Ca) $(Al, Si)_4O_8$, feldspathoids, (K,Na,Ca) $(Al,Si_2O_3O_{4-6}$, zeolite, (K, Na, Ca) Al, $Si)_mO_{2m} \cdot nH_2O$ and micas, $(K,Na,Ca)_2(Al,Mg,Fe)_{4-6}(Al,Si)_8O_{20}(OH)_4$. Traces of cesium are known to occur in each of these minerals.

The next element, Sr^{+2}, is found in many compounds in nature. Often it shows substitutional relations with Ba^{+2} and sometimes with Ca^{+2}. It may also occur in many of the same phases as indicated for Cs^{+1} above.

Iodine exists in nature both as I^- in two compounds and as IO_3^- in several other phases. Its crystal chemistry is similar to the halogens; it behaves most similarly to Br^- and possibly Cl^-, although the radii are markedly different. Very few synthetic iodine compounds have bromine of chlorine isostructural counterparts. Ways to tie iodine up in the crystalline state are discussed later.

Technetium is chemically most similar to manganese and rhenium. There are no known technetium compounds in nature, and there is little knowledge of its crystal chemistry. It is discussed separately below.

The rare earth elements are all very similar in ionic size, although the heavier ones are small enough to cause them to form different series of compounds in some instances from the larger ones. For example, the large lanthanides behave similarly to Ce^{+3} and commonly substitute for it. The smaller lanthanides tend to substitute for Y^{+3}. Rare earths are also known to substitute for Th^{+4} and Zr^{+4} in many of their minerals.

The actinides show some similarities in size and commonly follow Y^{+3}, Th^{+4}, Zr^{+4}, U^{+4} and Ce^{+4}. There are enough differences between uranium chemistry and actinide chemistry to make casual geochemical reasoning suspect and specific research is needed. Uranium readily oxidizes in nature and is commonly found as U^{+6} uranates and as uranyl, UO^{+2}. Plutonyl and Neptonyl can be made and may substitute for uranyl.

Crystalline Sollutions

Because of the ease of substitution of ions for other similar ions, it is common for solid solutions to occur. A solid solution is a compound in the crystalline state in which one or more ions have replaced other similar ions in the crystal structure without disrupting the atomic arrangement. Substitutions may be complete (e.g., Fe-Mg in olivine $(Mg, Fe)_2SiO_4$), or limited, (e.g., K-Na in nepheline (Na,K) $AlSiO_4$) between two end member compositions.

Natural compounds are rarely pure end members, as solid solution is very common in minerals. Some minerals may have several substitutions and thus extreme variability in chemical compositions occurs. The amphibole family, which has four different sites that allow substitution, is an extreme example. Partial solid solution may actually be desirable as a waste element fixation mechanism, because the mineral's stability may be better controlled by the host composition. In other words, the waste ion would be sufficiently dilute in the host structure that it does not substantially modify the stability of that host.

Isostructural Compounds

Crystals that allow solid solution necessarily have the same crystal structure for the end members. Compounds with the same structure may show no or very limited solid solubility, usually because of marked size differences of the ions involved. Such isostructural groups may have similar stability properties. Thus it may be useful to identify families of compounds with certain structural properties that may predict the existence of a stable compound of a particular waste element. Calcium compounds, for example, may indicate possible strontium compounds. Bromides and chloride compounds may indicate possible iodide compounds. Several isostructural possiblities are identified below.

P.1.4 Synthesis

Preparation of synthetic minerals requires that the desired elements from the waste streams be mixed with other materials. The mixture is then reacted to form the synthetic mineral. Considered here are the problems that may arise in the processing of nuclear wastes into synthetic minerals.

The purity of the partitioned waste stream will determine whether side reactions will lead to additional phases in the synthetic mineral assemblage. The controlling factors will be the ionic size and the ionic charge of the additional cations present. Ions whose size and charge are similar to those of the element being packaged will dissolve into the synthetic mineral as a minor solid solution. Many of the mineral phases are very "forgiving"; that is, they will accept many elements into solid solution at least in small amounts. If there is a large size or charge mismatch, the impurity elements in the waste stream will react to form secondary minerals of their own. Whether this is detrimental to the processing will have to be evaluated in individual cases.

Three general methods of reaction are in common use among geochemists for the synthesis of minerals: calcination, solid state reaction, and hydrothermal reaction. In each method, it is necessary to mix the waste elements with the other components in the right proportions to form the minerals. Many minerals are nearly stoichiometric, that is the components must be mixed in exactly the proportions called for in the mineral formula. If this is not done, some components will be left over to form additional phases. The stoichiometry of minerals that form solid solutions is not quite so critical.

Mineral synthesis by calcination involves these steps:

- taking each component into solution (for example, as the nitrates)
- mixing the solutions in correct proportions using volumetric methods
- precipitating the solution as a gel, spray drying, or by another method forming a calcine (a highly reactive fine-grained, often poorly-crystallized powder)

- firing the calcine, at temperatures of typically 900° to 1400°C (temperatures depend on the mineral being synthesized) to form the final well-crystallized mineral phase.

The first step is not discussed here since the partitioned wastes are in nitrate solution. Calcination can be carried out using the types of spray calciners that have already undergone considerable development and testing for the solidification of radioactive wastes. No new technology is involved to adapt these devices to synthetic minerals and the expected difficulties are those of remote handling and metering of the solutions and of calciner operation. Firing the calcine to form the final crystalline product in general will require temperatures that can be reached in base metal furnaces or gas-fired kilns.

Mineral synthesis by direct solid-state reaction is done as the name implies. The radioactive waste and the other components needed to construct the mineral phase are mixed as solids. The solid must be intimately mixed, ground, and compacted before reaction. Reaction temperatures are higher and reaction times are longer because the components are crystalline solids and transport can only take place by diffusion. The main difficulty expected here is the maintenance of equipment at the high firing temperatures. There may be more problems with furnace burn-out and breakage or fluxing of refractories. Rare earth and actinide oxides, for example, tend to be very refractory and will require high reaction temperatures if this method is employed.

Hydrothermal synthesis is the technique of reacting materials using high pressure, high temperature water as both a solvent and as a catalyst. It has the tremendous advantage of causing reaction between poorly reactive substances at modest temperatures (200° to 800°C is the experimental range) but it has the important difficulty of requiring reaction at high pressure (hundreds of thousands of atmospheres). To this must be added the difficulties associated with assembling and disassembling the pressure vessel by remote handling. Hydrothermal synthesis is not suited to large scale processing. About the only commercial process that uses hydrothermal synthesis on a large scale is the growth of quartz crystals for the electronics industry. This is a batch process and inherent limitations of pressure vessels require that the batches be fairly small. Commercial quartz-growth vessels are 2 to 3 m high and 0.3 to 0.5 m in diameter.

P.2 DISCUSSION OF MINERAL GROUPS

P.2.1 Silicate Minerals

Silica, SiO_2, makes up over 60% of the earth's crust, and alumina, Al_2O_3, makes up another 15%. It is not surprising that these elements dominate the rock-forming minerals. About half of the known mineral species are alumino-silicates, most of which are composed of one or more of the other eleven most abundant elements in the earth's crust. Feldspar alone makes up 58% of the earth's crust. Because of the abundance of these silicate minerals and their occurrence in a wide variety of rocks, one naturally asks if any of them might be potential radionuclide hosts. Detailed chemical and crystallographic data on most of the silicate minerals have been compiled by Deer, Howie, and Zussman (1962).

The suitability of silicates as hosts depends specifically on the ability of the radionuclide to substitute in solid solution for one of the essential ions of the compound. This is especially true for the common rock-forming silicates. We examine each of the major groups of silicate minerals and consider the general principles of crystal chemistry that might elucidate any ionic substitutions of interest. We also consider some common families of silicate minerals that may to have potential as repository minerals.

We can dismiss some groups quite easily. The silica (SiO_2) family of minerals is usually rigidly stoichiometric, although substitutions of Al for Si create a charge imbalance; this is usually compensated for by "stuffing" the framework with Na^+, K^+ or Ca^+. Cs^+ and Sr^{+2} are too large to enter into these compounds. The olivine-related minerals, including the humite series, are structurally based on close packaging of oxygen ions, and the largest ion that finds its way into these compounds is $(Ca^{+2})VI$ at 1.00 Å. Only Tc^{+4} is small enough to fit comfortably, but it is too highly charged. The lanthanide and actinide elements likewise are too highly charged.

P.2.1.1 Pyroxene Minerals

The pyroxene group of minerals are a series of compounds with a general formula $XY(Si,Al)_2O_6$, where X represents usually a mono- or di-valent ion with ionic radius in the range 0.6 to 1.0 A. Examples are Na^+, Ca^{+2}, Mn^{+2}, Fe^{+2}, Mg^{+2} and Li^+. The Y cations are di- or tri-valent ions with radii in the range of 0.5 to 0.8 Å. Examples include Mn^{+2}, Fe^{+2}, Mg^{+2}, Fe^{+3}, Al^{+3}, Cr^{+3}, and Ti^{+4}. These small ranges in ionic size result from a structure that is quite closely packed in terms of the oxygen ions. Too much distortion from substitution of larger ions usually breaks down the structure.

About the only critical element which might substitute in pyroxene would be Tc^{+4} with an ionic radius of 0.6 Å. The only other 4-valent ion that occurs in pyroxenes is Ti^{+4} (radius--0.605 Å). Titanium rarely substitues in quantites greater than one percent by weight, although in some of the titanaugites it may reach 3 to 5%.

The suitability of pyroxene as a technetium host require considerable research and, as a host, pyroxenes are marginal. It is probable that ferrite-like phases will prove more suitable hosts for technetium than any silicate.

The reported rare earth content of any pyroxene is never greater than trace quantities, and these are probably due to minute inclusions of other rare earth minerals.

Pyroxenes form easily in both dry and hydrothermal systems, and they are common reaction products in many silicate experiments. In studies on the decomposition of nuclear waste products in glass under mild hydrothermal conditions, pyroxene was a common end product. Even with the presence of all radionuclides at moderate concentration levels, none of them was detected in the pyroxene phase.

P.2.1.2 Amphibole Minerals

The general formula of the amphibole minerals is $W_{0-1}X_2Y_5(Si_2Al)_8O_{22}(OH)_2$. The X and Y sites are essentially identical with those so labeled in the pyroxene minerals. The limits on ionic substitutions are the same also. The W site, which is not always occupied in amphiboles, accepts low-charge cations in the ionic radius range 0.95_x to 1.35_x Å. These are usually only Na^+ and K^+, and no other ions are known as substitutes. Amphiboles have sometimes been called "nature's waste-baskets" because the W, X and Y sites can accept so many elements, but the structures are not suitable for any of the critical radionuclides except possibly Tc^{+4}. The remarks concerning Tc^{+4} are the same as for the pyroxenes discussed above.

The synthesis of amphiboles is not favorable for them to be considered as potential repository phases. Because the minerals are hydrous, water pressures must be maintained during the synthesis. This, in turn, requires that hydrothermal methods be used. Volcanic rocks rarely contain amphiboles because the water leaves the lava when it reaches the surface. Amphiboles that survive are usually formed in the magma chamber before eruption.

P.2.1.3 Epidote Minerals

The compositional formula for the epidote minerals is $X_2Y_3Z_3(O,OH,F)_{13}$ in which

$X = Ca, Ce^{3+}, La^{3+}, Y^{3+}, Th, Fe^{2+}, Mn^{2+}, Mn^{3+}$
$Y = Al, Fe^{3+}, Mn^{3+}, Fe^{2+}, Ti$
$Z = Si, Be.$

The compositions of epidote minerals that occur commonly are:

zoisite/clinozoisite	$Ca_2Al_3Si_3O_{12}(OH)$;
epidote	$Ca_2FeAl_2Si_3O_{12}(OH)$
piemonite	$Ca_2(Mn,Fem,Al)_3Si_3O_{12}(OH)$
allanite	$(Ca,Ce,La,Y)_2(Mn,Fe^{+2},Fe^{+3},Al)_3Si_3O_{12}(OH)$

Allanite is resistant to weathering and appears as a detrital mineral.

The large X-cation site in epidote is suitable for incorporating ^{90}Sr, rare earths, and possibly actinides in synthetic analogs of allanite. However, epidote is not suitable as a nuclear waste host because of the difficulty in synthesizing the mineral. All of the epidote minerals are stable at low temperatures and modest to high pressure. At high temperature (greater than 600 to 700°C) the epidotes dissociate according to the reaction

$$\underset{\text{zoisite}}{4Ca_2Al_3Si_3O_{12}(OH)} \quad \underset{\text{anorthite}}{5CaAl_2Si_2O_8} + \underset{\text{wollastonite}}{CaSiO_3} + \underset{\text{gehlenite}}{Ca_2Al_2SiO_7} + 2H_2O.$$

Epidote appears readily on a laboratory time scale only at pressures in excess of 3 kilobars and temperatures in the range of 600°C (Deer, Howie, and Zussman 1962). Successful synthesis at atmospheric pressure by calcination or related techniques does not appear likely.

P.2.1.4 Garnet Minerals

The garnets are orthosilicates with the general formula

$$X_3Y_2Si_3O_{12}$$

where X = Mg, Fe^{2+} or Ca; Y = Al, Fe^{3+} or Cr^{3+}.

Although the garnets are dense and close-packed structures, the 8-coordinated X-cation site will accept large ions; Sr-substituted grossular ($Ca_3Al_2Si_3O_{12}$) may fit there. However, grossular is best synthesized at temperatures in the range of 800°C under hydrothermal conditions with a water pressure of 2 kilobars. Attempts at lower pressure synthesis lead to a hydro-garnet, in which OH is substituted for the oxygen, or to mixtures of calcium silicates. In general, garnets are high-pressure phases in nature where they occur in metamorphic rocks. Once formed, the garnets are resistant to weathering and appear as detrital minerals.

P.2.1.5 Calcium Silicate Minerals

Possible candidates among the calicum silicate minerals are limited, partly because of the hydraulic nature of the anhydrous di- and tri-calcium silicates and partly because of the poor resistance of the hydrated phases to mechanical degradation and their high reactivity under quite mild hydrothermal conditions. As with the pyroxenes to which they are related, the structures of possibly useful calcium silicate phases tend to be close-packed with limited possibilities for isomorphous replacement or crystalline solution (at least in the pure phases). Wollastonite ($CaSiO_3$) and rankinite ($Ca_3Si_3O_7$) appear the only serious contenders in the group. Both form from oxides at 1200 C and represent the end members of dehydration for hydrated calcium silicate phases. They show little reactivity at lower temperatures; in particular, neither is hydraulic. Strontium can replace calcium in both, making them possible hosts for that cation.

Possibly of more potential use are compounds closely related to the calcium silicates but with off-stochiometric composition. Bustamite $\left[(Ca,Mn,Fe)SiO_3\right]$ and rhodonite $\left[(Mn,Cu)SiO_3\right]$, formally allied to wollastonite, have more "open" structures than wollastonite and may be able to accommodate a larger range of foreign ions in substitution. Synthesis and stability of these phases are similar to wollastonite.

Although the pure di-calcium silicates must be ruled out, appreciable amounts of lanthanide solution occurs and stabilizes the non-hydraulic, γ-Ca_2SioO_4 form. This phase may act as strontium and a lanthanide host, but studies are needed to define solubility limits and the stability of material.

Recently, Scott (1976) described the crystal structure of a hydrated potassium-calcium silicate, miserite $[KCa_5(Si_8O_{22})(OH)F]$, which appears capable of incorporating a wide variety of cations into a vacant site and "locking" them there. The mineral occurs with aegirine and orthoclase, sometimes with wollastonite; it appears to be geologically stable and a potentially useful host for a wide range of cations if some way to incorporate them into structure can be found. Studies of the synthesis and stability of miserite could prove fruitful.

P.2.1.6 Layer Silicate Minerals

The layer silicate minerals include the micas, the clays and the chlorite families. The mica family has the general formula $W_{0-1}Y_{2-3}(Si_2Al)_4O_{10}(OH)_2$ where W and Y have the same meaning as in the pyroxene and amphibole discussion. The same range of ionic substitutions occurs as in the amphiboles and pyroxenes. Fluorine and less commonly Cl^- and S^{2-} may substitute for the (OH). Biotite is commonly reported from granites and pegmatites, which contain traces of rare earth elements, but these traces can usually be attributed to xenotime $(Y...)PO_4$ inclusions rather than to being incorporated into the mica structure directly.

The remarks also pertain to the other groups of layer silicates as far as ionic substitutions are concerned. Because chlorites and clays may have layer units with residual electronic charges, some ions may be adsorbed on the surfaces. Interlayer ions may be easily exchanged. The permanence of these attachments, however, is poor and the materials cannot be considered potential repository phases.

P.2.1.7 The Melilite Minerals

The common melilites are a solid solution

$$\underset{\text{åkermanite}}{Ca_2MgSi_2O_7} - \underset{\text{gehlenite}}{Ca_2Al_2SiO_7}$$

in which magnesium is gradually replaced by aluminum. The entire series can be prepared synthetically by dry-firing--that is, calcination techniques at temperatures in the range of 1000 to 1200°C. The minerals as found in nature in high temperature, low pressure environments and synthetically in slags are related materials. They appear to be stable under ambient conditons. Strontium analogs can be made and this mineral series is a potential host for ^{90}Sr.

P.2.1.8 Feldspar Minerals

The feldspar minerals are the most abundant mineral group on the earth and a major constituent of granite rocks, but they are remarkably simple in chemistry. They have the formula $(K,Na,Ca,Ba)_1Al_{1-2}Si_{2-3}O_8$ with almost no other chemical substitutions allowed. Boron and Fe^{+3} are known to substitue for Al, and Cs and Sr may substitute for the cation. A $SrAl_2Si_2O_8$ phase can be synthesized, which is analogous to $BaAl_2Si_2O_8$, but the level of Sr in natural feldspars is rarely 0.5 wt%. The level of Cs is never greater than 0.005 wt%. Feldspars weather slowly to clay minerals under surface ambients but are very stable in rocks.

P.2.1.9 Feldspathoid Minerals

The feldspathoid minerals form when alkali-rich aluminosilicate compositions have insufficient SiO_2 to form free quartz. The minerals usually coexist with feldspar, particularly the one with the corresponding alkali ion. The important feldspathoids are nepheline, $(Na,K)_4Al_4Si_4O_{16}$; leucite, $KAlSi_2O_6$; analcime, $NaAlSi_2O_6\ H_2O$; soldalite, $Na_8Al_6Si_6O_{24}Cl_2$, and cancrinite $(Na,K,Ca)_{6-8}\ (Al,Si)_{12}O_{24}(Cl,So_4,CO_3)_{1.5-2.0}\ nH_2O$. Scapolite, $(Na,Ca,K)_4Al_3Ial,Si)_3Si_6O_{24}(Cl,SO_4,CO_3)$, may also be considered here because it resembles sodalite and cancrinite in behavior although it is not formally considered a feldspathoid.

Nepheline is a stuffed derivative of tridymite (SiO_2) and can accept alkali ions in the framework to charge compensate the Al that substitutes for Si. The cages are just large enough to accept K (ionic radius = 1.38 Å) and actually prefer some Na (ionic radius = 1.02 Å) to relieve some of the strains on the framework linkages. To accept larger cations such as Cs and Sr would be too much strain on the structure. Cs and Sr are generally not reported in any nepheline analyses.

Leucite and analcime have similar crystal structures with identical frameworks. The cages are larger than in nepheline and Cs will substitute freely in the analcime to form the only Cs mineral in nature. Pollucite, $CsAlSi_2O_6\ 0.5H_2O$, forms readily from its components, and is the leading candidate as a repository phase for Cs (Komarnini et al. 1978). Considerable study has already been made on pollucite for this purpose. The possiblity of a Sr analog also exists, but it does not occur in nature.

Sodalite, cancrinite and scapolite may have two uses as potential waste minerals although considerable research is needed to verify their potential. All three minerals may have Cs and Sr analogs, where these elements substitute for Na, Ca, or K, as in leucite-analcime. The framework cages are larger than in leucite and analcime, but because of this increased size the alkali cations are easily exchanged and hence easily leachable. Another interesting aspect of these structures is the trapping of large anions in the cages. All three minerals are known to have significant quantities of Cl^-, $SO^=$ and $CO^=$ in the structural cages, and sodalite often has $S^=$. This behavior immediately suggests the possibility of trapping I^- inside the cages. If the structure can be grown around the I^- before the iodine volatilizes, it may be effectively caged because its radius (2.20 Å) is considerably larger than the cage opening (1.40 Å). Much research is needed on this potential.

P.2.1.10 Zeolite Minerals

The zeolites are a large group of industrially important compounds, many of which exist as minerals. Their properties have been surveyed by Breck (1959). They have aluminosilicate framework structures with larger cages and cage openings than do the feldspathoids, and all zeolites show exchange properties of the nonframework cations. This property is undesirable in a repository compound unless the radionuclide can be stabilized in the structure.

Both Cs and Sr zeolites have been synthesized, and one Sr zeolite occurs in nature, the mineral brewsterite, $SrAl_2Si_6O_{16}\cdot 5H_2O$. It is found in volcanic basalts in gas cavities as a very late-formed mineral.

Zeolites can be synthesized by gel and by hydrothermal methods. They contain considerable water, which helps keep the framework open and which can be driven off by heat. Some structures collapse at relatively low temperatures, even as low as 100°C; but may retain their structural integrity as high as 800°C. The exchangeability of the cation, however, suggests that the zeolites in general will not desired cations for sufficient times under various conditions to be effective repository compounds.

Rare earths have been exchanged in some of the zeolite phases. In particular the faujasite series may be synthesized with a Ce:Ca ratio of 6:4 (Olsen et al. 1967). The faujasites have one of the more open zeolite framework structures. Considerable research is needed to determine the suitability of zeolite structures as waste repositories; they cannot be dismissed summarily.

P.2.11 Borosilicate Minerals

Because boron forms a very stable oxyanion, both as BO_3 and BO_4 coordination polyhedra, many borosilicates are quite stable mineral structures. Beryllium as BeO_4 coordination polyhedra also forms quite stable minerals with silicates. Many minerals of this type are known to contain rare earth elements (REE) either as essential elements or in solid solution to significant levels. Table P.2.1 lists the most important of these minerals. These minerals are considered possible repository phases.

The borosilicates and berylosilicates are primarily found in rare-earth bearing pegmatites, both granite and nepheline syenite types. The affinity for rare-earth elements is indicated by their formation. The stability of these phases under repository conditions is unknown. Considerable experinentation is needed to determine their suitability.

P.2.1.12 Zirconosilicate and Titanosilicate Minerals

Interest in the zirconosilicate and titanosilicate minerals arises from the known substitution of rare-earth elements and actinides for both Ti and Zr. Usually, the quantities are small. The known minerals are listed in Table P.2.2. Both the zirconosilicates and titanosilicates are formed in pegmatite deposits. They are commonly associated with other rare-earth bearing minerals. Evidence suggests that many of them may be quite resistant to weathering and zircon and titanite are known to survive as heavy minerals in placer deposits.

TABLE P.2.1 Borosilicate and Berylosilicate Minerals

Borosilicates	Formula
Cappelenite	$(Ba,Ca,Na)(Y,La)_6B_6Si_{13}(O,OH)_{27}$
Danburite	$CaB_2Si_2O_8$
Hellandite	$(Ca,Y)_2(Si,B,Al)_3O_8 \cdot H_2O$
Melanocerite	$(Ce,Ca)_5(Si,B)_3O_{12}(OH,F) \cdot nH_2O$
Stillwellite	$(Ce,La,Ca)BSiO_5$
Tadzhikite	$Ca_3(Ce,Y)_2(Ti,Al,Fe)B_4Si_4O_{22}$
Tourmaline	$(Na,Ca)(Mg,Fe...)_3Al_6(BO_3)_3(Si_6O_{18})(OH,F)_4$
Tritomite	$(Ce,La,Y,Th)_5(Si,B)_3(O,OH,F)_{13}$
Tinzenite	$(Ca,Mn,Fe)_3Al_2BSi_4O_{15}(OH)$

Berylosilicates	Formula
Aminoffite	$Ca_2(Be,Al)Si_2O_7(OH) \cdot H_2O$
Gadolinite	$Be_2Y_2FeSi_2O_{10}$
Semenovite	$(Ca,Ce,La)_{12}(Be,Si)_8Si_{12}O_{40}(O,OH,F)_8 \cdot H_2O$
Tugtupite	$Na_4AlBeSi_4O_{12}Cl$

TABLE P.2.2. Zirconosilicate and Titanosilicate Minerals

Zirconosilicates	Formula
Armstrongite	$CaZrSi_6O_{15}$ $2.5H_2O$
Bazirite	$BaZrSi_3O_9$
Catapleiite	$Na_2ZrSi_3O_9 \cdot 2H_2O$
Elpidite	$Na_2ZrSi_6O_{15} \cdot 3H_2O$
Eudialyte	$Na_4(Ca,Ce,Fe)_2ZrSi_6O_{17}(OH,Cl)_2$
Hilairite	$Na_2ZrSi_3O_9 \cdot 3H_2O$
Lavenite	$(Na,Ca)_3ZrSi_2O_7(O,OH,F)_2$
Lemoynite	$(Na,Ca)_3Zr_2Si_{10}O_{26} \cdot 8H_2O$
Vlasovite	$Na_2ZrSi_4O_{11}$
Wadeite	$K_2ZrSi_3O_9$
Zircon	$ZrSiO_4$

Titanosilicates	Formula
Batisite	$Na_2BaTi_2Si_4O_{14}$
Chevkinite	$(Ca,Ce,Th)_4(Fe,Mg)_2(Ti,Fe)_3Si_4O_{22}$
Ilmajokite	$(Na,Ba,Ce)_{10}Ti_5Si_{14}O_{22}(OH)_{44} \cdot nH_2O$
Joaquinite	$Ba_2NaCe_2Fe(Ti,Nb)_2Si_8O_{26}(OH,F)$
Karnasurtite	$(Ce,La,Th)(Ti,Nb)(Al,Fe)(Si,P)_2O_7(OH)_4 \cdot 3H_2O$
Lamprophyllite	$Na_2(Sr,Ba)_2Ti_3(SiO_4)_4(OH,F)_2$
Mosandrite	$(Na,Ca,Ce)_3TiSi_2O_8F$
Perrierite	$(Ca,Ce,Th)_4(Mg,Fe)_2(Ti,Fe)_3Si_4O_{22}$
Titanite	$CaTiSiO_5$
Tranguillityite	$Fe_8(Zr,Y)_2Ti_3Si_3O_{24}$
Tundrite	$Na_3(Ce,La)_4(Ti,Nb)_2(SiO_4)_2(CO_3)_3O_4(OH) \cdot 2H_2O$

The stability of this group of minerals under repository conditions deserves more study. They may actually prove to accept Cs^{+1} and Sr^{+2} in some of their structures for Ca, Na, or Ba. One Sr phase, lamprophyllite, is known.

P.2.1.13 Rare-Earth Silicate Minerals

A large number of minerals are essentially rare-earth silicates with or without other essential elements. These compounds must all be considered potential repository phases for both the lanthanides and actinides. Some of the phases have demonstrated stabilities, having formed in granites or pegmatites and then survived the sedimentary cycle to be deposited in Placers. Alanite is one exmple; it was discussed with the epidote minerals. Thorite, huttonite, and cheralite are other examples.

Most of the minerals in Table P.2.3 are formed in pegmatites. The lanthanide (Ln) families of $Ln_2Si_2O_7$ and Ln_2SiO_5 phases are easy to prepare synthetically. Many of them show severalstructural modifications, but they have high melting or decomposition temperatures. Some of the minerals such as coffinite, $USiO_4$, may be synthesized at 100°C. These minerals form in sedimentary rocks from circulating ground waters.

TABLE P.2.3. Rare-Earth Silicate Minerals

Rare-Earth Silicates	Formula
Allanite	$(Ce,Ca,Y)_2(Fe,Al_3)(SiO_4)_3(OH)$
Ashcroftine	$KNaCaY_2Si_6O_{12}(OH)_{10}\cdot 4H_2O$
Britholite	$(Ca,Ce)_5(SiO_4,PO_4)_3(OH,F)$
Cheralite	$(Ca,Ce,Th)(P,Si)O_4$
Coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
Ekanite	$(Th,U)(Ca,Fe,Pb)_2Si_8O_{20}$
Huttonite	$ThSiO_4$
Iimorite	$Y_5(SiO_4)_3(OH)_3$
Kainosite	$Ca_2(Ce,Y)_2Si_4O_{12}(CO_3)\cdot H_2O$
Miserite	$K(Ca,Ce)_4Si_5O_{13}(OH)_3$
Nordite	$(La,Ce)(Sr,Ca)Na_2(Na,Mn)(Zn,Mg)Si_6O_{17}$
Phosinaite	$H_2Na_3(Ca,Ce)SiO_4PO_4$
Sazhinite	$Na_3CeSi_6O_{15}\cdot 6H_2O$
Soddyite	$(UO_2)_5Si_2O_9\cdot 6H_2O$
Thalenite	$Y_2Si_2O_7$
Thorite	$ThSiO_4$
Thorosteenstrupine	$(Ca,Th,Mn)_3Si_4O_{11}F\cdot 6H_2O$
Thörtveitite	$(Sc,Y)_2Si_2O_7$
Tombarthite	$Y_4(Si,H_4)_4O_{12-x}(OH)_{4+2x}$
Tornebohmite	$(Ce,La)_3Si_2O_8(OH)$
Umbozerite	$Na_3Sr_4ThSi_8(O,OH)_{24}$
Uranophane	$Ca(UO_2)_2(SiO_3OH)_2$
Weeksite	$K_2(UO_2)_2Si_6O_{15}\cdot 4H_2O$
Yttrialite	$(Y,Th)_2Si_2O_7$

Again, these minerals require considerable research to define their suitability as repository phases. Their long-time stability must be defined particularly under hydrothermal conditions.

P.2.2 Oxide Minerals

P.2.2.1 Perovskite Structure--ABO_3 ($CaTiO_3$)

A = Ca, REE, Na, Th, U radius ∿1.0 Å
B = Ti, Nb, Ta, Fe^{3+}, Mg, Zr radius ∿0.7 Å
Knopite $(Ca,Ce)(Fe,Ti)O_3$
Dysanalyte $(Ca,Ce,Na)(Ti,Nb,Fe)O_3$
Loparite $(Na,Ce,Ca)(Ti,Nb)O_3$
Irinite $(Na,Ce,Th)_{1-x}(Ti,Nb)O_{3-x}(OH)_x$
Metaloparite $(Ce,Ca)_{1-x}(Ti,Nb)_{3-x}(OH)_2$

Loparite, irinite and knopite are found as metamict minerals. Perovskite occurs as an accessory mineral in basic igneous rocks, often in association with melilite, nepheline or rare earth apatite, as well as in metamorphosed calcareous rocks in contact with basic igneous rocks. The B ion is mostly Ti with a little Nb and Fe^{3+} in all the various minerals above. The variety rich in rare earths, chiefly cerium, is knopite and is also high in alkalis (Na), loparite, or its hydrate, metaloparite. Dysanalyte is high in Nb and irinite is distinguished by its high thorium content.

Since Ca^{2+} is in 12-fold coordination in perovskite, it is replaced preferentially by the large light lanthanides, i.e. La and Ce ($r_{La^{3+}}$ = 1.15 Å, $r_{Ce^{3+}}$ = 1.11 Å), rather than the yttrium earths. Hydrothermal alteration of loparite leads to metaloparite with loss of alkalis, assimilation of water and enrichment in the rare-earth elements (Vlasov 1966). Thus it seems that loparite retains the REE in alteration. Loparite is also known to occur as a placer deposit-forming mineral. Therefore, perovskite minerals are a possible host for lanthanide and actinide elements.

We can calculate the conversion of perovskite to rutile by a weathering solution, i.e.

$$CaTiO_3 + 2H^{2+} \rightarrow Ca^{2+} + H_2O + TiO_2$$

$$K_{298} = 10^{18.14}$$

Hence for pH = 6 $a_{Ca^{2+}} = 10^{6.14}m$;
pH = 8 $a_{Ca^{2+}} = 10^{2.14}m$.

Evidently the reaction, at equilibrium proceeds overwhelmingly to the right, which suggests that loss of Ca (and maybe REE) would follow if equilibrium were maintained. However, the kinetics of the above reaction may be slow, and more work is needed to determine the leaching rate.

P.2.2.2 Pyrochlore--$A_2B_2O_6(O,F,OH)$ or $(Ca,Na,Ce)_{2-x}(Nb,Ti)_2O_6(OH,F)$

The pyrochlores are also characteristic of basic rocks and alkali rock massifs (nepheline-syenites, alkali syenites, albitized granites and carbonatites) and occur in close association with albite, zircon, apatite, sphene, biotite. Pyrochlore occurs in both the metamict and crystalline state. It has quite a variety of names:

Pyrochlore $(Na,Ca,U,Ce,Y)_{2-x}(Nb,Ta,Ti)_2O_6(OH,F)$;
Betafite $(U,Ca)_{2-x}(Nb,Ti,Ta)_2O_{6-x}(OH)_{1+x}$, high Ti and U;
Zirconolite $(CaZrTi_2O_7)$;
Microlite $(Ca,Na)_2Ta_2O_6(O,OH,F)$, high Ta;
Djalmaite $(Ca,Na,U)_2Ta_2O_6(O,OH,F)$, high U relative to microlite;
Obruchenite $(Y,U,Ca)_{2-x}Nb_2O_6(OH)$, low Ti, high Y and U.

The differences among minerals reflect only the amounts of U, Ti, Ta, Y relative to pyrochlore. Pyrochlore from carbonatites can have up to 4% ThO_2. Hydration of pyrochlore leads to loss of mobile REE, Ca, Na and an increase in U (Vlasov 1966). Pyrochlore can have up to 19% U_3O_8 and high Sr. Pyrochlore also occurs as a placer deposit-forming mineral.

P.2.2.3 AB_2O_6--Nb-Ti-Ta Oxides

Columbite Structure

Columbite $(Fe,Mn)(Nb,Ta)_2O_6$ (tantalite). Columbite can have up to 3% REE, little U.

It is very abundant in acid rocks, e.g. (rarer) granite, granitic pegmatites, quartz veins; occurs in association with biotite, albite, zircon. Columbite-tantalite is a placer deposit-mineral and is insoluble in acids (Vlasov 1966). Furthermore, it is very resistant to weathering and accumulates in deluvial, eluvial, and alluvial placers, resulting from the weathering of columbite-bearing granite and pegmatite. In placers, it is associated with cassiterite, zircon, ilmenite and rutile. Columbite may be a good candidate for hosting lanthanide and actinide elements.

Euxenite Structure

Euxenite-polycrase $Y(Nb,Ti)_2(O,OH)_6$--$Y(Ti,Nb)_2(O,OH)_6$
Delorenjite $Y(Ta,Nb)_2(O,OH)_6$
Fersmite $(Ca,Ce)(Nb,Ti,Fe)_2(O,OH,F)_6$

Thorium is in higher coordination in euxenite structures than in columbite structures. Th, U, and Ca can replace Y up to several percent, U up to 16% UO_2, Th up to 8% ThO_2. Euxenites are widespread in granite pegmatites. Euxenite occurs as accessory mineral in granites and is also found in small amounts in placers. It is associated with ilmenite, monazite, xenotime, zircon, and garnet.

Fersmite is found in nepheline-syenite and carbonatite massifs in association with columbite, apatite, calcite, fluorite. It is typical of rocks of intermediate composition (for weathering and alteration see below).

Priorite Structure

Priorite-Aeschynite $(Ce,Nd,Th,Y)(Ti,Nb)_2O_6$
Polymignite $(Ca,Fe,Ce)(Zr,Ti,NbO_2O_6$
Sinicite $(Ce,Nd,Th,U)(Ti,NbO_2O_6$, high U.

Priorite differs from euxenite by having cerium REEs and a high content of thorium and Zr (little U). The REE have the same coordination as in the euxenite structure. Aeschynite occurs as an accessory in some deposits related to nepheline-syenite and alkali-syenite massifs in association with zircon, biotite, corundum, muscovite, sphene, and fluorite.

The weathering and alteration of the AB_2O_6 and $A_2B_2O_6(O,OH,F)$ REE-Nb-Ti-Ta complex oxides can be handled in one group. These oxides have pervasive alteration with a usual weathered crust surrounding fresher oxides (Ewing 1975a). The results of weathering are leaching of the A-site cations (i.e., U, REE) and introduction of H_2O or OH^- or $O^=$ into the oxide. The B cation remain basically unchanged (Ewing 1975a, Wambeke 1970).

In weathering, up to 40% decrease in the REE content is possible, although the REE distributions remain nearly the same (Ewing 1975a). For example, a priorite from the Kibara Mountains, North Katanga, had a fresh inner zone (black) with $\sim$0.075 cerium atoms and 0.95 U atoms per 5.58 O atoms. Wambeke (1970) gives the relative leaching rate of A cations as 110 REE atoms, 120 Na atoms and 40 U atoms per 100 atoms of Ca leached out. There are little hard data on the kinetics or solubility of these complex oxides; these should be obtained. It seems that columbite might be a good candidate among this group for Ce disposal, since it can be very resistant to alteration. Euxenite is the candidate for the U elements.

P.2.2.4 ABO_4 Oxides

Fergusonite Structure

A = Y, REE, U, Ca, Th
B = Nb, Ta, Ti.

Solid solution: $YNbO_4$ - $YTaO_4$
fergusonite formanite

The REE in fergusonite are mostly the yttrium rare earths (Vlasov 1966). Fergusonite occurs as a metamict mineral. Fairly abundant in granite pegmatites, it accumulates in small amounts in placers and is found as an accessory mineral in granites. In pegmatites, it is associated with zircon, monazite, xenotime and euxenite. A study of monazite-bearing alluvial deposits in Malaya (Flinter et al. 1963) showed fergusonite occurring with columbite, Ta/Nb rutile, cassiterite and garnet. The samples were derived from a cassiterite-bearing granite. It thus seems that fergusonite might be relatively stable as a host of REE and actinides.

P.2.3 Carbonate and Sulfate Minerals

P.2.3.1 Rare Earth Fluorocarbonates

Carbonate minerals are compounds of some cations with the carbonate anion, CO_3^{-2}, often with hydroxyls and waters of hydration. Of more than 70 naturally occurring carbonate compounds, most are either water soluble or are easily decomposed. These include the simple and complex carbonates of the alkali metals, the alkaline earth metals, and the transition metals. Most carbonates are sensitive to pH and dissolve easily in low pH solutions.

Exceptions to the general instability of carbonate minerals are the fluorocarbonate compounds of the rare earths. These are:

Bastnaesite	$(Ce,La)CO_3F$
Parisite	$Ca(Ce,La)_2(CO_3)_3F_2$
Cordylite	$Ba(Ce,La)_2(CO_3)_3F_2$
Synchisite	$Ca(Ce,La)(CO_3)_2F$.

Bastnaesite and parisite are relatively insoluble even in low pH solutions at ambient temperatures. None are insoluble in hot, low pH solutions. The rare-earth fluorocarbonates could act as hosts for rare-earth elements in neutral or alkaline repository rocks.

P.2.3.2 Sulfate Minerals

The number of sulfate minerals numbers several hundred but nearly all are soluble in water or are otherwise unstable. Two exceptions of interest are barite, $BaSO_4$, and celestine, $SrSO_4$. The solubility of barite in cold water is only 2.2 ppm while the solubility of celestine is 113 ppm. There is a complete solid solution between barite and celestine although intermediate compositions are not found in nature.

Use of barite and celestine as hosts for ^{90}Sr would be of value in a bedded anhydrite repository (anhydrite = $CaSO_4$) because of the chemical compatiblity.

P.2.4 Phosphate Minerals

Natural phosphate minerals are all orthophosphates, the major one being fluorapatite. The phosphate-containing minerals include a subset, that seems particularly suited to the disposal of nuclear waste elements: the apatite family and the monazite-xenotime family.

Since in nature phosphorus will exist in only one valence state (+5) (for example, $H_2PO_3^- > H_2PO_4^-$ only when $fO_2 < 10^{-101}$ at 250°C), the distribution and stability of its species in solution will be Eh-independent. On the other hand, the dominant phosphorus species in solution will be strongly dependent on pH and on possible complexing cations, since $PO_4^{\equiv}$, $HPO_4^{=}$ and $H_2PO_4^-$ form strong complexes [e.g. with uranium (Langmuir 1978)]. The reaction

$$H_2PO_4^- \rightarrow HPO_4^{=} + H^+ \tag{P.1}$$

has a $\Delta G_r^\circ = 9.83$ kcal/mole and a $\Delta H_r^\circ = +0.99$ kcal/mole at 25°C, which yields a $K_1 = 10^{-7.21}$ at 25°C. Hence, for pH <7.21, $H_2PO_4^-$ will be the dominant PO_4 species in solution and for pH $\angle$7.21, $HPO_4^{=}$ will be dominant. Ignoring complexes, this will also be true at higher temperatures, since ΔH_r° is so small. The total phosphorus content of ground waters, ΣPO_4, is most often greater than 0.1 ppm but rarely greater than 1 ppm.

In the mineral structure, the PO_4 tetrahedra can often be replaced by the CO_3, SO_4, and SiO_4 groups leading to a variety of phosphate minerals.

P.2.4.1 Apatite Family-$Ca_5(PO_4)_3(OH,F)$

Apatite is the most abundant phosphorus-bearing mineral. It is a common accessory mineral in many types of rocks (acid to basic). Apatite can take up significant amounts of Sr (up to 11.6 wt% SrO) and also rare earths (up to 11 wt% REE) and so may be a suitable host for nuclear waste elements. The rare earths, predominantly Ce, may replace Ca in apatites of alkaline igneous rocks. U^{+4} (r = 0.97 Å) can also substitute for Ca^{2+} (r = 0.99 Å). Natural apatites have ∿0.01% U, if primary igneous apatite, or slightly richer; 0.02% U if sedimentary marine apatite. Thorium is more abundant than U by a factor of 3 or 4 (Deer 1962). Apatites can contain CO_3, SO_4 and SiO_4 groups replacing PO_4. In sedimentary phosphorites, the apatite can have up to 7 to 8% CO_3 content, with much lesser SO_4 or SiO_4 substitution. The carbonate content of onshore phosphorites is less (3%) than that of sea floor phosphorites, suggesting that weathering reduces the carbonate content.

In terms of geologic evidence for stability to weathering apatite is not uncommon in sedimentary rocks where it occurs both as a detrital mineral and as a primary deposit. It is not classified as a placer deposit-forming mineral, however. On the weathering stability list of Pettijohn (1941), apatite has an index of 6, putting it beneath biotite and garnet. Smithson (1941) from a study of Jurassic sandstones in Yorkshire, England, lists apatite as stable in unweathered rock but decomposed in weathered rocks. Graham (1950) lists apatite with olivine as least stable and Jackson (1953) puts it low in the second stage of the weathering sequence of clay-size mineral particles. Thus, the stability of apatite has yet to be firmly shown.

Strontium apatite results in the solid solution:
$Ca_5(PO_4)_3F$ -$NaCeSr_3(PO_4)_3(OH)$.
fluor-apatite belovite

However, belovite is unstable under surface conditions and is readily replaced by rhabdophanite, $CePO_4\ H_2O$; Sr and Na are then rapidly lost (Vlasov 1966). There is unlimited substitution in the systems $Ca_5(PO_4)_3F$-$Sr_5(PO_4)_3F$ and $Ca_5(PO_4)_3(OH)$-$Sr_5(PO_4)_3(OH)$. Sr-apatite, found in alkali pegmatites, is readily soluble in acids (Vlasov 1966).

We can use the solubility criteria laid out in the introduction to this appendix to examine the stability of apatite minerals. Although thermodynamic data for Sr-apatite are lacking, there are data for fluorand hydroxy-apatite (Naumov et al. 1974). Using these data, we can compute the following:

$$Ca_5(PO_4)_3F + 3H^+ \rightarrow 5Ca^{2+} + 3HPO_4^{=} + F^- \qquad (P.2)$$
$$K_1 = 10^{-33.33} \times 10^{1997.7[1/T-1/298]}$$

$$Ca_5(PO_4)_3F + 6H^+ \rightarrow 5Ca^{2+} + 3H_2PO_4^- + F^- \qquad (P.3)$$
$$K_2 = 10^{-11.70} \times 10^{2646.8[1/t-1/298]}$$

$$Ca(PO_4)_3(OH) + 4H^+ \rightarrow 5Ca^{2+} + 3HPO_4^{=} + H_2O \qquad (P.4)$$
$$K_3 = 10^{-12.17} \times 10^{7051.0[1/T-1/298]}$$

$$Ca_5(PO_4)_3(OH) + 7H^+ \rightarrow 5Ca^{2+} + 3H_2PO_4^- + H_2O \qquad (P.5)$$
$$K_4 = 10^{+9.46} \times 10^{7698.0[1/T-1/298]}$$

If we use $\Sigma\ PO_4 = 10^{-6}m$ (∿0.1 ppm) and $a_{F^-} = 1.6 \times 10^{-5}m$ (∿0.3 ppm), typical values for ground waters, we obtain the following values for the activity of calcium in equilibrium with the apatites:

Fluor-apatite

	$a_{Ca^{2+}}$	
pH/T	25°C	75°C
6	$1.04 \times 10^{-5}m$	$5.81 \times 10^{-6}m$
8	$1.24 \times 10^{-7}m$	$7.95 \times 10^{-8}m$

Hydroxy-apatite

	$a_{Ca^{2+}}$	
pH/T	25°C	75°C
6	$1.23 \times 10^{-3}m$	$2.24 \times 10^{-4}m$
8	$5.83 \times 10^{-6}m$	$1.22 \times 10^{-6}m$

In ground waters, $a_{Ca^{2+}}$ is typically $\sim 10^{-3}m$ (Rai and Lindsay 1975). Therefore in alkaline environments we expect both apatites to be stable at temperatures from 25°C to 100°C. However, in acid environments hydroxy-apatite will not be stable, while fluor-apatite will be somewhat stable, more so at higher temperatures. Chien (1977) has also shown that the carbonate substitution may increase the equilibrium dissolution of apatite.

P.2.4.2 Monazite-Xenotime Family--(Ce,La)PO_4-YPO_4

This family is one of the most promising for the disposal of nuclear wastes. Both monazite, (Ce,La)PO_4 and xenotime, YPO_4, as well as their hydrates, rhabdophanite, (Ce,Ca)$PO_4 \cdot H_2O$, and churchite, $YPO_4 \cdot H_2O$, are simple orthophosphates. They are always crystalline even though they may contain significant amounts of U and Th. Monazite is isostructural with huttonite, $ThSiO_4$, and xenotime is isostructural with zircon ($ZrSiO_4$) and coffinite ($USiO_4$). Monazite can acquire quite a high content of thorium (28%) by the substitution $Th^{4+} + Si^{4+} \rightarrow Ce^{3+} + p^{5+}$ (i.e., $ThSiO_4$-$CePO_4$ solid solution). Monazite is a selective cerium mineral (i.e., large-radius rare earths). It has lesser amounts of uranium (up to 4%) (Deer et al. 1962, Vlasov 1966). It is sparingly soluble in acids and is very stable under weathering conditions, often collecting in placers formed from the disintegration of monazite-containing granites. It occurs as an accessory in granites and granitic pegmatites and is abundant in metamorphic deposits (Vlasov 1966). It occurs as a detrital mineral in sands from weathering of granites and gneisses.

Dryden and Dryden (1946) compared the changes in relative abundance of various minerals from the fresh rocks to the weathered products in samples from the Wissahickon schist in Pennsylvania and Maryland. They found, by taking the ratios of the number of grains of each mineral in fresh and weathered rock, that the resistance of zircon relative to garnet is 100 (i.e., $\text{garnet/Zr}_{\text{fresh}}/\text{garnet/Zr}_{\text{weathered}} \sim 100$), sillimanite 40, monazite 40, chloritoid 20, kyanite 7 and all other minerals less than 5. This is in agreement with Pettijohn (1941) who ranked monazite in his "weathering sequence" as 3 after zircon (1) and tourmaline (2). The general geologic evidence points to a very resistant mineral.

We can calculate the solubilities for monazite to establish its thermodynamic stability. Taking $\Sigma PO_4 = 10^{-6}$m (0.1 ppm), we can compute the solubility of Ce^{3+} in a natural leaching solution as a function of pH and temperature. The thermodynamic data for $CePO_4$ were obtained from Naumov, et al. (1974). We obtain:

$$CePO_4 + 2H^+ \rightarrow Ce^{3+}(aq) + H_2PO_4^- \tag{P.6}$$

$$\Delta G_r^\circ = 3.27 \text{ kcal/mole} \quad \Delta H_r^\circ = -11.71 \text{ kcal/mole}$$

$$CePO_4 + H^+ \rightarrow Ce^{3+}(aq) + HPO_4^= \tag{P.7}$$

$$\Delta G_r^\circ = 12.10 \text{ kcal/mole} \quad \Delta H_r^\circ = -10.72 \text{ kcal/mole.}$$

Therefore

$$K_6 = 4.00 \times 10^{-3}\, e^{\,5893.3[1/T-1/298]}$$

$$K_7 = 2.46 \times 10^{-10}\, e^{\,5395.1[1/T-1/298]}$$

Assuming no complexing, pure solids, and $\Sigma PO_4 = 10^{-6}$m, then

$a_{Ce^{3+}(aq)}$

pH/T	25°C	50°C
6	4.0×10^{-9}m	8.6×10^{-10}m
8	2.46×10^{-12}m	6.1×10^{-13}m

The low values of $a_{Ce^{3+}}$ obtained support the stability evidence from the geologic data. Obviously monazite is more stable in warm alkaline environments. Increasing the phosphate content of the ground water would also further stabilize the monazite. Thus if $\Sigma PO_4 = 10^{-5}$ m (1 ppm), $a_{Ce^{3+}} = 4.0 \times 10^{-10}$ m at pH = 6, T = 25°C and the same for the other conditions.

Xenotime contains a high amount of yttrium rare earths. It is widespread in granites, pegmaties and metamorphic gneisses (Vlasov 1966). When granites weather, xenotime accumulates in placers (e.g. in New Zealand and USSR). Xenotime is very stable under surface conditions.

P.2.5 Iodine Hosts

P.2.5.1 Iodine Minerals

Iodine is a relatively rare element in rocks and minerals. It occurs in both the I^- and I^{5+} valence states. Iodine is easily oxidized to the 5-valent state and appears in many of its natural compounds as the iodate, IO_3^- ion. These are:

Lautarite	$Ca(IO_3)_2$
Bellingerite	$Ci(IO_3)_2 \cdot 2/3H_2O$
Salesite	$Cu(IO_3)OH$
Schwartzembergite	$Pb_5(IO_3)Cl_3O_3$
Dietzeite	$Ca_2(IO_3)_2CrO_4$.

The above compounds are at least slightly soluble in water, and all are soluble in solutions with low pH. The iodate minerals are found in evaporite deposits or as weathering products of ores in very dry environments.

Marshite, CuI, iodargyrite, AgI, and their solid solution, miersite, occur in nature and might be stable in a bedded salt type of repository but in general no natural mineral of iodine hints of very long-term stability.

P.2.5.2 Framework Structures for Iodine

Two candidate minerals that are composed of three-dimensional frameworks contain cavities sufficiently large to house the I^- ion: sodalite and the boracite family.

Sodalite, $Na_4Al_3Si_3O_{12}Cl$, is a member of the feldspathoid group. It is a three-dimensional framework and the essential Cl^- is locked in cage-like interstices. Iodine can be substitued for Cl^{-1} and maintained in this structure.

Boracite, $Mg_3B_7O_{13}Cl$ is a three-dimensional framework of B-O tetrahedra with the Cl^- locked in cage structure. Other minerals of the boracite family are ericaite, $(Fe,Mn)_3B_7O_{13}Cl$, and chambersite, $Mn_3B_7O_{13}Cl$. However, a very large number of synthetic materials with the boracite structure have been synthesized. Many of the synthetics contain I^- rather than Cl^-. They are stable under hydrothermal conditions.

P.2.5.3 Lead Oxyhalides

There exists a small group of minerals composed of the oxy- or hydroxy-halides of lead. These materials usually appear as oxidation products on lead-zinc ores which is evidence for their stability in the surface environment. The list includes:

Murdochite	$PbCu_6(O,Cl,Br)_8$
Mendipite	$Pb_3Cl_2O_2$
Penfieldite	$Pb_2Cl_3(OH)$
Yedlinite	$Pb_6CrCl_6(O,OH)_8$
Phosgenite	$Pb_2(CO_3)Cl_2$.

Little is known of the structures, solubilities, and ranges of stability of these materials. The substitution of iodine for chloride in the lead oxyhalide structures should be investigated.

P.2.6 Uranium Minerals

Uranium occurs in nature in both the U^{+4} and U^{+6} valence state. The U^{+5} valence state has been postulated, especially in U_3O_8 and other oxides intermediate between UO_2 and UO_3, but it has not really been verified. Its existence is not critical to our discussion.

P.2.6.1 U^{+4}Minerals

Uranium occurs as U^{+4} in only a small group of minerals. The most important and best known is uraninite, UO_2, which has the fluorite, CaF_2, structure. It is the principal mineral in most uranium deposits and is found in pegmatites, in sandstones and metasediments, and as an accessory mineral in some granites. Natural UO_2 is rarely stoichiometric and is better described as UO_{2+x} where x ranges between 0 and 0.25. Most uraninite from older sources is metamict and may be called pitchblende.

In sandstone deposits the uraninite has formed from circulating ground water by reduction of the U^{+6}. In the reduced form it is very stable and is common in the placer deposits of the Witwatersrand district in Africa. These uraninite grains were carried down streams and deposited in energetic depositional environments without chemical breakdown because the atmospheric conditions of the time were highly reducing. If uraninite could be maintained in its U^{+4} state it would be a good repository mineral. Unfortunately, it alters rapidly in present-day atmospheres.

Uraninite is usually only uranium bearing in sandstone deposits, but in pegmatites it may contain significant quantities of Ce and Th in solid solution. Actually, complete solid solutions of these elements can be prepared under laboratory conditions.

Some of the other U^{+4} minerals occur in quantities sufficient for them to be called ore minerals. Coffinite, $USiO_4$, brannerite, UTi_2O_6, and ningyoite, $CaU(PO_4)_2 \cdot 1.5H_2O$, occur primarily in sedimentary or metasedimentary environments probably as syngenetic minerals. Other U^{+4} minerals include lermontovite, $(U,Ca,Ce...)_3(PO_4)_4 \cdot 6H_2O$; sedovite, $U(MoO_4)_2$; uranopyrochlore, $U_2Nb_2O_6(O,OH,F)$; cliffordite, UTe_3O_8, and ishakowaite, $(U...)(Nb,Ta)O_4$. In addition U^{+4} occurs as a minor element in many minerals, mostly replacing other group IV elements or the rare earths. At the conditions existing at the earth's surface all these U^{+4} minerals readily alter by oxidation and weather by releasing the uranium into the ground water system. The U^{+6} may be fixed immediately in new minerals or may migrate for long distances before being redeposited.

P.2.6.2 Uranate Minerals

Uranium as U^{+6} forms a large group of oxides, hydrated oxides, and uranates. The uranates form compounds with Na, K, Mg, Ca, Ba and Pb. Some of these compounds are anhydrous, but most are hydrates. There are many crystalline modifications of UO_3 but none occurs naturally. Usually the hydrate schoepite, $UO_3 \cdot 2H_2O$, or one of its polymorphic forms occurs. If the other elements are present the tendency is to form the uranate minerals.

The uranates occur in the immediate vicinity of the source mineral, usually uraninite. They develop as a replacement aureole of poorly crystallized phases commonly called gummite. The Pb which is common in older deposits is primarily radiogenetic in origin.

The uranates do not survive further weathering and are replaced by uranyl compounds in the main oxidized zone of any ore body. It is doubtful if any uranate would be a good uranium repository.

P.2.6.3 Uranyl Minerals

Any uranium which finds its way into the ground water system migrates as the uranyl ion, UO_2^{+2} , or as some complex involving the uranyl ion. As the local conditions change the uranyl ion may precipitate as one of over 100 mineral species.

P.2.6.4 Urany Ion

The uranyl ion is a linear group with the uranium in the center and the oxygen ions on the ends. Because of this unique geometry uranyl compounds form their own series of compounds in nature with very little substitution of other ions.

Uranyl will form complex structures with almost any oxyanion, carbonate, sulfate, phosphate, arsenate, molybdate, selenate, vanadate and silicate. The crystal structure of the minerals is usually uranyl-oxyanion sheets or chains, which stack so as to contain interstitial low-charge cations and water molecules. Most of the carbonates, sulfates, molybdates and selenates and even the silicates are moderately soluble and will leach as the environmental conditions change. The phosphates-arsenates and vanadates appear to be very insoluble and may be potential repository compounds. The known minerals are listed in Table P.2.4.

The uranyl phosphates and arsenates are usually considered together because their crystal chemistry is very similar and in some cases there is even partial substitution of phosphorus and arsenic. In all compounds these ions exist in tetrahedral coordination. Vanadium is tetrahedral in a few vanadates, but in most vanadates complex V_2O_8 groups of pentagonal edge-shared VO_5 coordination polyhedra are formed.

As can be seen in Table P.2.4, the phosphates-arsenates-vanadates are usually classified by their U:X ratio where X is P, As, V. Several ratios exist but the most common is the U:X = 1. Within this group are several minerals that have great potential as repository minerals. This potential is suggested by the wide range of occurrence, the frequency of mineral formation and the extremely low solubility of the compounds.

TABLE P.2.4. Uranyl Phosphates, Arsenates, Vanadates

$UO_2:XO_4$		
4:2	Arsenuranylite	$Ca(UO_2)_4(AsO_4)_2(OH)_4 \cdot 6H_2O$
	Bergenite	$Ba(UO_2)_4(PO_4)_2(OH)_4 \cdot 8H_2O$
	Renardite	$Pb(UO_2)_4(PO_4)_2(OH)_4 \cdot 7H_2O$
3:2	Troegerite	$(UO_2)_3(AsO_4)_2 \cdot 12H_2O$ (see 2:2)
	Huegelite	$Pb_2(UO_2)_3(AsO_4)_2(OH)_4 \cdot 3H_2O$
	Dumontite	$Pb_2(UO_2)_3(PO_4)_2(OH)_4 \cdot 3H_2O$
	Phosphuranylite	$Ca(UO_2)_3(PO_4)_2(OH)_4 \cdot 7H_2O$
2:2	Carnotite	$K_2(UO_2)_2(V_2O_8) \cdot 3\text{-}5H_2O$
	Tyuyamunite	$Ca(UO_2)_2(V_2O_8) \cdot 5\text{-}8H_2O$
	Metatyuyamunite	$Ca(UO_2)_2(V_2O_8) \cdot 3H_2O$
	Curienite	$Pb(UO_2)_2(V_2O_8) \cdot 5H_2O$
	Francevillite	$Ba(UO_2)_2(V_2O_8) \cdot 5H_2O$
	Strelkinite	$Na_2(UO_2)_2(V_2O_8) \cdot 6H_2O$
	Autunite	$Ca_{1-2}(UO_2)_2(PO_4)_2 \cdot 8\text{-}12H_2O$
	Meta-autunite I	$Ca_{1-2}(UO_2)_2(PO_4)_2 \cdot 6\text{-}8H_2O$
	Meta-autunite II	$Ca_{1-2}(UO_2)_2(PO_4)_2 \cdot 4\text{-}6H_2O$
	Meta-vanuralite	$Al(UO_2)_2(VO_4)_2(OH) \cdot 8H_2O$
	Vanuralite	$Al(UO_2)_2(VO_4)_2(OH) \cdot 11H_2O$
	Vanuranylite	$(H_3O,Ba,Ca,K)_{1.6}(UO_2)_2(VO_4)_2 \cdot 4H_2O$
	Dewindtite	$Pb(UO_2)_2(PO_4)_2 \cdot 3H_2O$
	Sengierite	$Cu(UO_2)_2(V_2O_8) \cdot 8\text{-}10H_2O$
2:3	Coconinoite	$Fe^{3+}_2Al_2(UO_2)_2(PO_4)_2(SO_4)(OH)_2 \cdot 20H_2O$
2:4	Parsonsite	$Pb_4(UO_2)_2(PO_4)_2 \cdot 2H_2O$
	Przhevalskite	$Pb(UO_2)_2(PO_4)_4 \cdot 4H_2O$
	Pseudoautunite	$(H_3O)_4Ca_2(UO_2)_2(PO_4)_4 \cdot 5H_2O$
	Walpurgite	$(BiO)_4(UO_2)_2(AsO_4)_4 \cdot 6H_2O$
	Hallimondite	$Pb_2(UO_2)_2(AsO_4)_2$

The abundance of uranyl phosphates and arsenates results more from the stability of uranyl phosphate and uranyl arsenate complexes in ground water (Langmuir 1978) than from any abundance of P or As. The complex polymerizes readily into sheet-like crystal structures, which incorporate a variety of low-charge cations and water molecules between the sheets. Thus, they form a large number of mineral species depending on the available cation. The toxicity of As, however makes it less desirable additive.

The most important mineral family in the phosphates is the autunite minerals. The family is usually broken into three groups--autunite, meta-autunite I, and meta-autunite II, depending on the number of water molecules involved. Table P.2.5 lists all the members of the autunite family. The variation of water is common to the group but does not seem to affect the stability of the species.

Autunites are known to form compounds with Ca, Mg, Ba, Na, Cu, Fe^{2+}, K, Zn, Mn, Co, Pb, NH_4 Al, and H_2O. Many synthetic analogs can also be easily formed including Sr and even Li. The included cation is easily exchangeable in acid solutions but the autunite structure remains unaffected by the many substitutions.

TABLE P.2.5. The Autunite Family

Autunites, $R_{1-2}(UO_2)_2(XO_4)_2\cdot 8\text{-}12H_2O$		
Autunite, $Ca(UO_2)_2(PO_4)_2$ $8\text{-}12H_2O$		
Fritschelite	Mn	V
Heinrichite	Ba	As
Kahlerite	Fe	As
Novacekite	Mg	As
Sabugalite	H,Al	P
Saleeite	Mg	P
Sodium autunite	Na,Ca	P
Torbernite	Cu	P
Uranocircite	Ba	P
Uranospinite	Ca	As
Zeunerite	Cu	As
Meta-autinites, $R_{1-2}(UO_2)_2(RO_4)_2\cdot 6\text{-}8H_2O$		
Abernathylite	$K_2(UO_2)_2(AsO_4)_2\cdot 6\text{-}8H_2O$	
Bassettite	Fe^{2+}	P
Meta-ankoleite	K_2	P
Meta-autunite I	Ca	P
Metaheinrichite	Ba	As
Metakahlerite	Fe^{2+}	As
Metakirchleimerite	Co	As
Metalodevite	Zn	As
Metanovacekite	Mg	As
Metaforbernite	Cu	P
Meta-uranocircite	Ba	P
Meta-uranospinite	Ca	As
Metazeuerite	Cu	As
Sodium uranospinite	NaCa	As
Troegerite	$(H_3O)_2(UO_2)_2(AsO_4)_2\cdot 6H_2O$	
Uramphite	NH_4	P
unnamed	$(H_3O)_2$	P
Meta-autunite II	$Ca(UO_2)_2(PO_4)_2\cdot 4\text{-}6H_2O$	

In nature, autunite, $Ca(UO_2)_2(PO_4)_2{\cdot}8\text{-}12H_2O$, and meta-autunite I, $Ca(UO_2)_2(PO_4)_2{\cdot}6\text{-}8H_2O$, are very common anywhere uranium is found. They are found as a secondary mineral in all climates; and have been mined as ore minerals in several locations because of their abundance. In Cameron, Arizona, they occur in near-surface sandstone lenses and around Shoshoni, Wyoming. They are mined from bentonite pits where they form in the desiccation cracks of the clay. At Ningyo Prefecture in Japan they are found in sandstone, where they were mined extensively until the primary ningyoite zone was encountered. Some very noted specimen localities include the Daybreak Mine in Washington, and Cornwall, England. They are also common alteration products in uranium-bearing pegmatites. In all these localities they have proven to be very stable. The leaching characteristics under various conditions still must be tested.

Among the other uranyl phosphates several other candidates are also evident as possible repositories. In particular we should consider the phosphyranylite $Ca(UO_2)_4(PO_4)_2(OH)_4{\cdot}7H_2O$. It is a much rarer mineral than autunite but has a higher loading factor because the U:P ratio is 3:2. Considerably less is known about the stability of this phase. Its conditions of formation and synthesis are less well known but it occurs similarly to autunite.

One must not overlook the vanadates as potential repository minerals, in particular carnotite, $K_2(UO_2O_2V_2)_8{\cdot}3\text{-}5H_2O$; tyuyamunite, $Ca(UO_2)_2V_2O_8{\cdot}5\text{-}8H_2O$, and metatyuyamunite, $Ca(UO_2)_2V_2O_8{\cdot}3H_2O$. These three minerals occur extensively throughout the Colorado Plateau and have been mined for uranium. They usually occur in sandstone lensesand are found in intersticed among the sand grains. Once formed, they appear to resist weathering and alteration even at surface conditions. Strontium analogs might easily be made. Ion exchange, common in the autunites, does not seem to occur in the vanadates.

P.2.7 Technetium Hosts

Since the element technetium is not known in nature, it follow that no minerals exist with technetium as an essential element. Technetium exists mainly in valence states Tc^{4+} and Tc^{7+} with the latter forming the very soluble pertechnatate ion. $Technetium^{4+}$ forms stable solid oxide phases and, because of a similar ionic radius, behaves much like Ti^{4+}. Many titanium analogs have been synthesized (Muller et al. 1964) including spinels, pyrochlores, perovskites, and a stable solid solution between TiO_2 and TcO_2. Titanium minerals may be the best hosts for technetium if reducing conditions are maintained in the repository.

P.3 MINERAL TABLES

P.3.1 Hosts for Radionuclides

Table P.3.1 lists selected minerals which have potential as hosts for radionuclides. The entries in Table P.3.1 were selected according to the criteria listed below.

Approximately 2500 mineral species have been identified. These have been compiled into reference sources of which those of the Dana system (Palache et al. 1944, 1951), Deer, Howie and Zussman (1962), Strunz (1970), and Roberts, Rapp and Weber (1974) were consulted. Each of the 2500 minerals was reviewed and in a first sieving all minerals that were known to be water-soluble, chemically undesirable or crystal-chemically unsuitable as radionuclide hosts were eliminated. A much shortened list of about 100 minerals remained. A second sieving eliminated minerals of great chemical complexity that would be difficult to synthesize. The minerals that remained were separated according to the radionuclide for which they were to serve as host and these groups were then roughly ranked with the best candidates listed first.

Table P.3.2 is the final listing. In addition to mineral name and formula, the table lists some available information of the occurrence of these minerals in nature, which provides clues to their stability in the repository environment, and on alteration processes where known. it must be emphasized that the data on these later categories are very sparse although this study does not claim to be an exhaustive literature survey. Table P.3.2 is intended as a guide for future research rather than finalized data for engineering design.

P.3.2 Commentary on Table P.3.1

The lack of silicate minerals on the listing is perhaps unexpected. Silicates make up the bulk of the rocks on the earth and many of them are very stable. However, the common silicate structures utilize the most abundant elements of the earth and the critical radionuclides from nuclear waste are, with the exception of ^{90}Sr, unusual elements, either too large or too small to fit into available sites in the silicate minerals. Furthermore, silicates are relatively less resistant to weathering and only a few, or which zircon is an outstanding example, survive the weathering process to become detrital minerals. Even fewer survive to become placer minerals.

Phosphates and oxides are the first and second most stable minerals in a wide variety of geochemical environments from initial formation at high temperatures and pressures, through weathering transport, contact with salt water in oceanic depositional basins, burial, diagenesis, upheaval, and in some cases a complete second cycle of weathering.

A very large number of phases on the list occur in pegmatites or in alkaline rocks that are closely related. The minerals, by implication, are stable in the presence of aqueous solutions at temperatures to 600°C and pressures to several kilobars. Chemical compatibility with granite rocks is implied. Whether many of these minerals are compatible with other candidate repository rocks, basalts, and shales require research. The fact that the minerals do not occur in these rocks in nature means only that the chemistry for their formation was not correct, not that the minerals are necessarily incompatible.

TABLE P.3.1. Selected Host Minerals for Radionuclides

Element	Host Mineral	Formula	Substitution[(a)]	Occurrence in Nature	Alteration
Cs	pollucite	$Cs_{2-x}Na_xAl_2Si_4O_{12}\ H_2O$	E	granite pegmatites	
Sr	anorthite (feldspar)	$Ca_{1-x}Na_xAl_{2-x}Si_{2+x}O_8$	R	basalt	slow breakdown into clay minerals under surface weathering conditions
	Sr-apatite	$Sr_5(PO_4)_3(OH,F)$	E	alkalic pegmatites	
	belovite	$(Sr,Ce,Na,Ca)_5(PO_4)_3(O,OH)$	SS	alkalic pegmatites	breakdown at low pH
	celestine	$SrSO_4$	E	oxidation zones in sulfur deposits primary precipitation	
	Sr-autunite	$Sr(UO_2)_2(PO_4)_2$	E	strata-bound ore deposits	
	goyazite	$SrAl_3(PO_4)_2(OH)_5H_2O$	E	pegmatite	
	lamprophyllite	$Na_2(Sr,Ba)_2Ti_3(SiO_4(OH,F)_2$	SS	nepheline syenites alkali-rich pegmatites	
	lusangite	$(Sr,Pb)Fe_3(PO_4)_2(OH)_5 \cdot H_2O$	SS	pegmatite	
	bogildite	$Na_2Sr_2Al_2PO_4F_9$	E	cryolite	deposits
	danburite	$CaB_2Si_2O_8$	R	andesite	xenoliths
	attakolite	$(Ca,Mn,Sr)_3Al_6(PO_4,SO_4)_7 \cdot 3H_2O$	SS		
	cuspidine	$Ca_4Si_2O_7(F,OH)_2$	R	metamorphic rocks limestone contact zones	
	rankinite	$Ca_3Si_2O_7$	R	strain zones	gelatinizes readily at low pH
	melilite	$Ca_2Mg_{1-x}Al_{2x}Si_{2-x}O_7$	R	extrusive rocks	
	umbozerite	$Na_3Sr_4ThSi_8(O,OH)_{24}$	E		
	scheelite	$CaWO_4$	R	pegmatites	
	powellite	$CaMoO_4$	R	pegmatites	

TABLE P.3.1. (continued)

Element	Host Mineral	Formula	Substitution[(a)]	Occurrence in Nature	Alteration
I	sodalite	$Na_8Al_6Si_6O_{24}Cl_2$	R	nepheline-syenite rocks	
	boracite	$Mg_3B_7O_{13}Cl$	R	salt domes and salt deposits	occurs in the "water insoluble" fractions of salt deposits
	ericaite	$(Fe,Mn)_3B_7O_{13}Cl$	R		
	chambersite	$Mn_3B_7O_{13}Cl$	R		
	parahilgardite	$Ca_2B_5O_8Cl(OH)_2$	R	salt domes	occurs in "water insoluble" fraction
	murdochite	$PbCu_6(O,Cl,Br)_8$	R	oxidation zones of Pb-Zn deposits	
	mendipite	$Pb_3Cl_2O_2$	R		
	penfieldite	$Pb_2Cl_3(OH)$	R		
	yedlinite	$Pb_6CrCl_6(O,OH)_8$	R		
	phosgenite	$Pb_2(CO_3)Cl_2$	R		
	marshite	CuI	E	associated with copper ores	darkens on exposure to air
	iodargyrite	AgI	E	secondary mineral in silver ores	
	miersite	(Ag,Cu)I	E	associated with copper ores	
Tc	perovskite	$CaTiO_3$	R	basic igneous	rocks
	calzirite	$CaZr_3TiO_9$	R	carbonatite	partially dissolves in low pH solutions
	yttrocrasite	$(Y,Th,U,Ca)_2Ti_4O_{11}$	R		

TABLE P.3.1. (continued)

Element	Host Mineral	Formula	Substitution(a)	Occurrence in Nature	Alteration
Tc	batisite	$Na_2BaTi_2Si_4O_{14}$	R	nepheline syenite	
	brannerite	$(U,Ca,Ce)(Ti,Fe)_2O_6$	R	hydrothermal mineral	
Lanthanides, Actinides	monazite	$(Ce,La)PO_4$	E	granites, pegmatites, placers, hydrothermal deposits metamorphic	extremely stable
	cheralite	$(Ce,Ca,Th)(P,Si)O_4$	SS	rocks	sometimes yellow crust of rhabdophanite
	xenotime	YPO_4	E	granites, pegmatites, placers, hydrothermal deposits, sandstones	very stable alters to churchite
	rhabdophanite	$(Ce,La)PO_4 \cdot H_2O$	E	alkali pegmatites, hydrothermal deposits, sandstones	very stable forms from monazite but dehydrates to monazite on prolonged storage
	brockite	$(Ca,Th,Ce)PO_4 \cdot H_2O$	E		
	grayite	$(Th,Pb,Ca)PO_4 \cdot H_2O$	E		
	churchite	$YPO_4\ 2H_2O$	E	alkali massifs limonite ores	forms from zenotime
	zircon	$ZrSiO_4$	R	acid and alkali igneous rocks pegmatites, placers	metamict highly resistant to weathering
	baddeleyite	ZrO_2	R	carbonatites, gabbro, placers, basalts	highly stable

TABLE P.3.1. (continued)

Element	Host Mineral	Formula	Substitution(a)	Occurrence in Nature	Alteration
Lanthanides, Actinides	tacheranite	$(Zr,Ca,Ti)O_2$	R	alkali massifs	
	bazirite	$BaZrSi_3O_9$	R	granites	
	zirkelite	$Zr(Ca,Th,Ce)(Ti,Nb)_2O_7$	SS	magnetite deposits pyroxenites	
	thorite	$ThSiO_4$	E	greisens from granites	metamict
	huttonite	$ThSiO_4$	E	sands	alters to Y-bastnaesite
	thalenite	$Y_2Si_2O_7$	E	pegmagites	
	yttrialite	$(Y,Th)_2Si_2O_7$	E		
	throtveitite	$(Sc,Y)_2Si_2O_7$	E	pegmatites	
	bastnaesite	$(Ce,La)CO_3F$	E	hydrothermal deposits, pegmatites, granites	gradual alteration to lanthanite, rhadophanite or cerianite
	cordylite	$Ba(Ce,La)_2(CO_3)_3F_2$	E	alkali syenite	
	parisite	$Ce_2Ca(CO_3)_3F_2$	E	detrital, hydrothermal deposits, pegmatites, carbonate ore bodies	replaced by bastnaeisite
	synchysite	$CaCe(CO_3)_2F$	E	alkalie syenite pegmatite	
	röntgenite	$Ce_3Ca_2(CO_3)_5F_3$	E	pegmatite	
	cerianite	$(Ce,Th)O_2$	E	carbonates pegmatites	
	davidite	$(Fe,La,Ce,U)_2(Ti,Fe)_5O_{12}$	SS	granites skarns, pegmatites, with vein minerals	
	euxenite	$Y(Nb,Ti)_2(O,OH)_6$	E	pegmatites granites placers	can be altered but somewhat stable
	polycrase	$Y(Ti,Nb)_2(O,OH)_6$	E		
	delorenzite	$Y(Ta,Nb)_2(O,OH)_6$	E		
	fersmite	$(Ca,Ce)(Nb,Ti,Fe)_2(O,OH,F)_6$	SS		

TABLE P.3.1. (continued)

Element	Host Mineral	Formula	Substitution[a]	Occurrence in Nature	Alteration
Lanthanide, Actinide	columbite	$(Fe,Mn)(Nb,Ta)_2O_6$	R	granites, pegmatites, quartz veins, greisen deposits, placers	very resistant to weathering
	tantalite	$(Fe,Mn)(Ta,Nb)_2O_6$	R		
	perovskite	$CaTiO_3$	R	basic igneous rocks	can be altered to metaloparite but retains lanthanides
	loparite	$(Na,Ce,Ca)(Ti,Nb)O_3$	SS	alkali syenites	
	aeschynite	$(Ce,Nd,Th,Y)(Ti,Nb)_2O_6$	SS	alkali massifs pegmatites	usually weathers
	polymignyte	$(Ca,Fe,Ce)(Zr,Ti,Nb)_2O_6$	SS		
	sinicite	$(Ce,Nd,Th,U)(Ti,Nb)_2O_6$	SS		
	fergusonite	$YNbO_4$	E	granitoid formations, placers, granites, pegmatites	fairly stable often associated with monazite in placers
	formanite	$YTaO_4$	E		
	samarskite	$(Fe,Y,U,)(Nb,Ti,Ta)_2O_7$	SS	pegmatites, gold placers	
	pyrochlore	$(Na,Ca,U,Ce,Y)_{2-x}$ $(Nb,Ta,Ti)_2O_{6-x}(OH,F)_{1+x}$	SS		
	betafite	$(U,Ca_{2-x}(Nb,Ti,Ta)_2$ $O_{6-x}(OH_{1+x}$	SS	Alkali rock massifs	pervasively altered
	zirconolite	$CaZrTi_2)_7$	R		
	microlite	$(Ca,Na)_2Ta_2O_6(O,OH,F)$	R		
	obruchevite	$(Y,U,Ca)_{2-x}Nb_2O_6(OH)$	SS		
	djalmaite	$(Ca,Na,U)_2Ta_2O_6(O,OH,F)$	SS		
	pandaite	$(Ba,Sr)_{2-x}(Nb,Ti)_2O_{7-x}\cdot 7H_2O$	R		

TABLE P.3.1. (continued)

Element	Host Mineral	Formula	Substitution[a]	Occurrence in Nature	Alteration
U	uraninite	UO_2	E	pegmatites	rapid in oxidizing conditions but very stable in reducing conditions
	carnotite	$K_2(UO_2)_2(VO_4)_2$	E	sandstone	relatively insoluble
	tyuyamunite	$Ca(UO_2)_2(VO_4)_2$	E		
	autunite	$Ca(UO_2)_2(PO_4)_2$	E	pegmatites, sandstone, sedimentary breccia	insoluble
	K-autunite	$K_2(UO_2)_2(PO_4)_2$	E		
	Sr-autunite	$Sr(UO_2)_2(PO_4)_2$	E		
	phosphuranylite	$Ca(UO_2)_4(PO_4)_2(OH)_4\ 7H_2O$	E	U-schists, pegmatites	
	ningyoite	$(U,Ca,Ce)_2(PO_4)_2\ 1\text{-}2H_2O$	E	sedimentary rocks	
	lermontovite	$(U,Ca,Ce)_3(PO_4)_4\ 6H_2O$	E		
	coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$	E	sandstone, sedimentary breccia, U-schists	
	ekanite	$(Th,U)(Ca,Fe,Pb)_2Si_8O_{20}$	SS	pegmatite veins	
	weeksite	$K_2(UO_2)_2Si_6O_{15}\ 4H_2O$	E		
	soddyite	$(UO_2)_5Si_2O_9\ 6H_2O$	E	pegmatite	

(a) Substitution of radionuclide into host mineral: E = essential element; SS = solid solution; R = replacement of another element by radionuclide.

TABLE P.3.2. Systematic Tabulations of Metamict Minerals(a)

SIMPLE OXIDES

*Uraninite (UO$_2$)(b,c)

*Rutile (TiO$_2$)

PHOSPHATES

*Monazite (Conybeare and Ferguson 1948, Brooker and Nufield 1950)

*Xenotime (Sidorenko 1963)

*Griphite (Peacor and Simmons 1972)

SILICATES

Nesosilicates (Si:O = 1:4)

*Zircon

*Thorite

*Coffinite

*Titanite (Higgins and Ribbe 1976)

*Huttonite

*Steenstrupine-Cerite

*Britholite group

*Lessingite
Karnasurtite
Karnocerite
Tritomite
Spencite
Rowlandite
Gadolinite

Sorosilicate (Si:O = 2:7)

Thortveitite group

*Thalenite
Yttrialite
*Hellandite
*Rincolite
Epidote group
  *Allanite
  *Chevkinite
  *Perrierite

*Vesuvianite (Bouska 1970)

Cyclosilicates (Si:O = 1.3)

*Eudialyte
Cappelenite (Faessler 1942)

Nb-Ta-Ti OXIDES (A = U, Th, REE, Co, Na, K) Mg,Mn,Fe^{+2},Pb = Nb, Ta,Ti,Fe^{+3},W)

AB_3 (Perovskite structure)

*Loparite
Irinite
*Knopite

$A_{2-x}B_2O_{7-3}$ nH_2O (Pyrochlore structure)

*Pyrochlore
Betafite
*Microlite
Djalmaite
Obruchevite
*Zirconolite

$A_2B_5O_{15}$ (Davidite structure)

*Davidite

ABO_4 (Fergusonite structure)

Formanite
*Fergusonite
Risorite

AB_2O_6 (Columbite structure)

*Columbite (Hutton 1959, Ewing 1976b)

AB_2O_6 (Euxenite structure)

*Euxenite (Ewing 1976a)
Polycrase
Delorenzite
*Fersmite

AB_2O_6 (Priorite)

*Priorite
*Aeschynite
*Bloomstrandine
Polymignite

AB_2O_4 (Samarskite structure)

Samarskite
Chlopinite
Loranskite
Yttrocrasite

AB_2O_6 (Brannerite structure)

*Brannerite
Thorutile

AB_2O_7 (Zirkelite structure)

Zirkelite

(a) After Bouska (1970).
(b) The asterisk (*) indicates that the mineral also occurs as a partially or completely crystalline phase.
(c) A reference indicates that inclusion of the mineral in this table is based only on a single or poorly documented occurrence.

The rankings, except for the top few entries, are almost arbitrary. Although available mineralogical evidence suggests that these minerals are stable in the temperature and pressure regimes generally thought to exist around nuclear waste repositories, their relative stabilities are not known. Likewise, the relative solubilities of these generally insoluble phases are not known. Thus, detailed ranking or the construction of any sort of figure of merit cannot be done under the present state of knowledge.

Many of the oxide minerals are highly stable and insoluble because of a particular oxidation state. Lower oxidation states of the transition metals and of uranium form less soluble compounds than do the high oxidation states. The state of oxidation in a repository will be controlled by the oxidation potential and oxygen buffer capacity of the host rocks since these will be present in vastly larger volumes than the volume of the waste. Likewise the solubilities of many of the minerals are a sensitive function of the acidity of any circulating solutions. The fluorocarbonates are an example of minerals with low solubilities in neutral or alkaline solutions that become progressively more soluble as the ph decreases. The host rock in which the repository is formed will play an important role in buffering the oxidation potential and acidity of any circulating ground water that might contact the synthetic minerals of the waste form.

The large number of minerals that are listed as occurring in pegmatites is to be expected. Pegmatites are complex mineral assemblages that form from a residual high-water content fluid that remains after the crystallization of granitic rocks. Ions that are too big or too small or have the wrong charge or the wrong electronic structure to fit into any of the common granite minerals--quartz, feldspars, micas, and amphiboles, are concentrated in the residual fluid and finally crystallize into pegmatites. It is not the pegmatite-forming temperature and pressure regime that is critical but rather the complex solution chemistry that allows these minerals to be formed. Many of these minerals can be synthesized by entirely different methods but their occurrence in pegmatites does imply a substantial degree of mutual compatibility among the phases.

P.4 METAMICTIZATION

Metamict minerals are a special class of amorphous materials which were initially crystalline (Broegger 1893). Although the mechanism for the transition is not clearly understood, radiation damage caused by alpha particles and recoil nuclei is certainly critical to the process (Graham and Throber 1974, Ewing 1975). The study of metamicitzation of naturally occurring materials allows for the evaluation of the long-term effects that result from this type of radiation damage, particularly changes in physical properties. Comparison of metamict and non-metamict crystalline phases addresses the question of the susceptibility of different bonding and structure types to radiation damage and provides useful insights into defining radiation damage experiments.

P.4.1 Properties

The list below is an amplified tabulation of metamict mineral properties listed by Pabst (1952).

1. They are generally optically isotropic but may show varying degrees of anisotropy. Reconstitution of birefringence with heating is common.
2. Metamict phases lack cleavage. Conchoidal fracture is characteristic.
3. Some mineral species are pyronomic, that is, they glow incandescently on heating. In many cases, however, recrystallization may occur without observable glowing.
4. Crystalline structure is reconstituted by heating. The metamict material recrystallizes to a polycrystalline aggregate with a concomitant increased resistance to attack by acid. During recrystallization several phases may form, the particular phase assemblage is dependent on the conditions of recrystallization (e.g., temperatue and type of atmosphere). In many cases the original pre-metamict phase may not recrystallize due to compositional changes caused by post-metamict alteration.
5. Metamict minerals contain U and Th, although contents may be quite variable (as low as 0.41% ThO_2 in gadolinite from Ytterby, Norway). Rare-earth elements are also common (in some cases over 50 wt%). Water of hydration may be high (up to 70 mole%).
6. They are x-ray amorphous. Partially crystalline metamict minerals display distinct line broadening and decreased line intensities. A shift of lines to lower values of two-theta is observed in specimens with a reduced specific gravity.
7. Some phases occur in both the crystalline and metamict state, and in these cases there is little chemical difference.

The most common methods of analysis of the metamict state are x-ray diffraction analysis of annealed material (Berman 1955, Lima-de-Faria 1964, Mitchell 1972, Ueda and

Koreskawa 1954) and differential thermal analysis (DTA) (Kerr and Hollan 1951, Orcel 1953, Kurath 1957). Most of the effort by mineralogists has been directed at establishing identification criteria.

Elemental analysis is commonly completed by wet chemical means on mineral separates or by standard electron microprobe analysis. The presence of water, both structural and absorbed, and the preponderance of rare-earth elements make a complete chemical analysis a rarity in the literature.

Although radiation damage experiments are voluminous, there have been only limited and unsuccessful efforts to simulate the process of metamictization under laboratory conditions (Mugge 1922, Primak 1954).

P.4.2 Summary of Observed Metamict Phases

To understand the compositional and structural controls on the process of metamictization, it is useful to tabulate naturally occurring metamict phases. Table P.3.2 listed those phases described as being partially or completely metamict in a review of the literature by Bouska (1970). This tabulation lists only the major compositional end-member. As one might expect for mineral groups of complex compositions (e.g., compare the A:B ratios for fergusonite and samarskite) that are metamict and much altered, the nomenclature of any single mineral group is quite complicated and much confused by the proliferation of varietal names (Ewing 1976). For a more detailed listing and discussion of the mineralogical literature the reader is referred to Bouska (1970).

The asterisk by each mineral name indicates it also occurs as a partially or completely crystalline phase. In some cases (e.g., monazite, xenotime and vesuvianite) the inclusion of a mineral phases as metamict is based only on a single or poorly documented occurrence. In these instances the critical reference is indicated. In other cases (e.g., rutile) the radiation damage was not caused by constitutent uranium and thorium nuclides but rather occurred only along grain boundaries where the rutile was in epitaxial contact with radioactive davidite.

The uranium and thorium contents of phases that occur in both crystalline and metamict forms are interesting. Table P.4.1 gives the average U_3O_8 and ThO_2 contents of orthorhombic AB_2O-type Nb-Ta-Ti oxides. Although the data in the literature are limited, in general those specimens of euxenite, fersimite, aeschynite and lyndochite found in the crystalline state have distinctly lower uranium and thorium contents than their metamict euxenite and aeschynite counterparts. A similar relation has been demonstrated for zircons (Holland and Gottfried 1955, Krasnobayev et al. 1974).

Table P.4.2 is a compilation of radioactive minerals which are said to be always crystalline. Comparison of Tables P.3.2 and P.3.4 quickly reveals inconsistencies in the literature. Huttonite is listed as always crystalline (Pabst 1952) and partially metamict (Bouska 1970). Many of these inconsistencies may be resolved by very detailed and specific examinations of nomenclature. Also, note that among the phases listed as metamict (e.g., columbite and stitbiotantalite), their structures probably will not accommodate either

TABLE P.4.1. Uranium and Thorium Content (wt%) of Non-Metamict and Metamict AB_2O_6--Type Nb-Ta-Ti Oxides

	U_3O_8	ThO_2
Non-metamict		
euxenite (Nefedor 1956)	(a)	(a)
fersmite (Alexandrov 1966)	(a)	(a)
aeschynite (Alexandrov 1962 and 1966)	not detected	0.72
allanite (Čech, Vrana and Povondra 1972)	0.25(b)	2.26(b)
lyndochite (Gorzhevskaya and Sidorenko 1962)	0.08(c)	3.75
Metamict		
euxenite (mean value of 28 analyses)	9.31	3.08
aeschynites (mean value (of 22 analyses)	1.2	10.73

(a) Semiquantitative analysis, no U or Th reported.
(b) Analysis by R. C. Ewing, University of New Mexico.
(c) Reported as UO_3.

TABLE P.4.2 Radioactive Minerals Reported as Always Crystalline(a)

autunite	$Ca(UO_2)_2 \cdot 10\text{-}12H_2O$
bastnaesite	$(Ce,La)(CO_3)F$
carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$
columbite	$(Fe,Mn)(Nb,Ta)_2O_6$
gummite	$UO_3 \cdot nH_2O$
huttonite(b)	$ThSiO_4$
metatorbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 8H_2O$
monazite(b)	$(Ce,Th)PO_4$
stibiotantalite	$Sb(Ta,Nb)O_4$
thorianite(b)	ThO_2
thortveitite	$(Sc,Y)_2Si_2O_7$
tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot nH_2O$
uvanite	$U_2V_6O_{21} \cdot 15H_2O$
xenotime(b)	$(Y,U)PO_4$
yttrofluorite	Ca_3YF_9
titanite	$CaTiSiO_5$
uranite(b)	UO_2
baddeleyite(a)	ZrO_2

(a) After Ueda (1957).
(b) Primary phases which are invariably crystalline, even with high concentrations of uranium and throium. Note that in some rare caaes even these minerals have been reported as being partially metamict.

uranium or thorium. Reports of radioactive columbites are almost certainly mixtures of columbite and metamict microlite (Lima-de-Faria 1964). A number of the phases (bastnaesite and all hydrated phases) are alteration products. The primary phases that consistently occur in crystalline form, even with high concentrations of uranium or thorium, are indicated by asterisks.

P.4.3 Rate of Metamictization

The rate of metamictization of a given mineral to a first approximation, depends on: 1) the inherent stability of its structure and 2) the alpha particle flux resulting from the presence of uranium, thorium and their unstable daughter nuclides (Pabst 1952).

Pabst calculated that a minimum of 110,000 years is required for gadolinite, 0.4% Th, to become metamict. This figure, which could be low by a factor of 1000 (Ueda 1957, Lipova 1966, Hurley and Fairbain 1953), was obtained by assuming that all of that alpha decay energy was spent in disordering the structure and that this energy was measurable by DTA (Pabst 1952).

Most zircons become metamict upon receiving a radiation dose of about 10^{16} α/mg (Holland and Gottfried 1955). Using this dosage criterion, the following table gives estimates of the time required for some radioactive zircons to become metamict.

Initial radionuclide content	Estimate time (yrs)
1% Th	1.4×10^9
1% U	3.3×10^8
10% U	3.2×10^7
1% Pu^{236} (does not exist in nature)	2.0

There are, however, zircons and thorites (thorite has the zircon structure and is expected to show similar radiation effects) which show anomalous radiation effects. Some zircons that have had radiation doses of only 2.8×10^{15} α/mg are metamict (Krasnobayev et al. 1974). On the opposite extreme is a report of a non-metamict thorite containing 10% uranium that is at least 1.2×10^8 years old (Hutton 1950). If this age is correct, then the thorite specimen has withstood a radiation dose of about 9×10^{16} α/mg. These data suggest that factors other than structural stability and alpha particle flux are important in determining the rate of metamictization.

P.4.4 Alteration Effects

Minerals that occur in the metamict state are often severely altered, either as a result of hydrothermal alteration or surface weathering. The resulting complicated compositional variates are in part responsible for the very complex mineral nomenclature. Most of the available data on alteration effects pertains to various Nb-Ta-Ti oxides (Ewing 1975, Wambeke 1970) and zircon, $(Zr,U)SiO_4$. In both cases alteration may be extensive and followed by recrystalliztation of phases quite different from the original pre-metamict phase (Ewing 1974).

For metamict, AB_2O_6-type, Nb-Ta-Ti oxides (A = REE, Fe^{+2}, Mn, Ca, Th, U, Pb; B = Nb, Ta, Ti, Fe^{+3}) primary hydrothermal alteration causes a consistent increase in calcium content, generally a decrease in the uranium and thorium content, a decrease in total rare-earth concentrations, a slight decrease in B-site cations, and an increase in structural and absorbed water. Secondary alteration caused by weathering is similar in effect but produces a decrease in Ca content, an increased leaching of A-site cations and a relative increase in B-site cations. Refractive index, specific gravity and reflectance decrease with both types of alteration, but VHN_{50} remains approximately constant. It is important to note that although alteration effects in these natural materials have been carefully documented, there are no experimental data on hydrothermal alteration effects, solubility as a function of degree of metamictization, or the kinetics of these reactions.

There is an abundant literature on metamictization and alteration effects observed in zircon, $(Zr,U)SiO_4$, a phase commonly used by geologists in U/Pb radiometric dating. A summary of this literature is beyond the scope of this Appendix, but it should be the subject of future research. Discordant ages reported for metamict zircons indicate that the U/Pb rations can be changed or slightly disturbed by alteration (Krogh and Davis 1975). Laboratory experiments involving zircon have demonstrated that altered regions are more rapidly dissolved by 48% hydrofluoric acid. There are some data which suggest that zircons that have become metamict are susceptible to attack by solutions that can cause alteration (Krogh and Davis 1975; Larsen et al. 1953). However, Mumpton and Roy (1961) have recrystallized numerous metamict zircons by hydrothermal treatment at temperatures of 500°C and above, and found that the Zr:Si ratio remained close to 1:1. This is an indication that neither element was selectively dissolved. They also demonstrated that the water often found in metamict zircons was molecular H_2O and not the result of H^+ ion exchange leaching. The data are still too limited to draw broad conclusions regarding the effect of metamictization on solubility, even for metamict zircons. Yet, at worst, this does not seem to be a major problem. Monazite, a mineral that apparently does not metamictize, was chosen as the lanthanide and actinide synthetic mineral in the reference scenario (see Section 3.2.1.3).

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