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Foreign Programs for the Storage of Spent Nuclear Power Plant Fuels, High-Level Waste Canisters and Transuranic Wastes

K. M. Harmon
A. B. Johnson, Jr.

April 1984

Prepared for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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FOREIGN PROGRAMS FOR THE STORAGE OF SPENT NUCLEAR POWER PLANT FUELS, HIGH-LEVEL WASTE CANISTERS AND TRANSURANIC WASTES

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Richland, Washington 99352

PREFACE

This review of international practices for the interim storage of spent nuclear fuel and high-level waste from fuel reprocessing operations was prepared in support of the U.S. Department of Energy Commercial Spent Fuel Management and Monitored Retrievable Storage programs. The information presented herein came from widely varied sources such as topical reports, proceedings of international symposia, contacts with engineers and policy makers from other countries, and the news media.

SUMMARY

Worldwide activities related to the storage of spent (irradiated) nuclear power reactor fuel and highly-radioactive, long-lived wastes are summarized, with a review of the storage programs and plans of 26 nations:

Argentina	India	Sweden
Belgium	Italy	Switzerland
Brazil	Japan	Taiwan
Canada	Korea (ROK)	United Kingdom
Finland	Mexico	United States
France	Netherlands	U.S.S.R.
Germany (FRG)	Spain	

The focus of the report is on the application of dry storage techniques to spent fuel, although dry storage of long-lived wastes is also reviewed. Wet storage of spent fuel is also covered briefly as a point of reference.

Thirty-four nations at present have nuclear power stations operating, under construction or reasonably well committed for commissioning by the year 2000. Except for a few demonstration reactors that burn specialized fuel, the world's commercial power reactors are fueled with natural or slightly enriched UO_2 clad in Zircaloy, UO_2 clad in stainless steel or uranium metal clad in a magnesium or aluminum alloy. Estimates of spent fuel arisings through the year 2000 range from a few hundred tonnes for countries just starting their nuclear power programs to a high of 58,000 tonnes for the US. The uranium metal fuels are in general being reprocessed at plants in France and Great Britain after a relatively brief storage period, but the UO_2 fuels are accumulating in many countries and national plans for managing them include extended storage--until the fuel can be reprocessed or until it can be placed in a repository.

Water pools are used almost universally for initial storage of spent fuel from power and military plutonium-producing reactors, a notable exception being the Wylfa power station in Great Britain, where spent gas-graphite reactor fuels are stored dry (in a CO_2 atmosphere) immediately following discharge from the reactor. Pools are also in use in many countries for extended storage. In some cases, extra storage capacity is provided at the reactor site by reducing

the spacing between fuel assemblies or by constructing an independent facility. In other cases, fuel rod consolidation is planned as a means to increase fuel pool storage capacity. In a few instances, large-capacity pool-type AFR storage facilities have been constructed--e.g., at reprocessing plants in France and Great Britain and the 3000-tU CLAB facility in Sweden.

Several dry storage concepts are in use or being evaluated. Those currently favored are: emplacement in a dry well (subsurface caisson); use of an air-cooled vault; use of a silo (concrete cask, concrete canister or surface caisson); and storage in metal casks which in some cases are also qualified for transport.

National dry storage activities are tabulated below:

Country	Design	Testing	Construction	Operation
Argentina - SF	AFR-silo			
Canada - SF	AFR-silo	silo (concrete)		silo
France				
FBR SF	AFR-vault		AFR-vault	
HLW	vault			vault
Germany (FRG)				
LWR		metal casks	AFR-metal casks	AFR-metal casks
HTR (pebble bed)		metal cask vault		
India - HLW				vault
Italy - SF	silo			
Japan				
Test reactor fuel				vault
HLW	vault	vault		
Spain - SF	AFR-metal casks			

Country	Design	Testing	Construction	Operation
Switzerland				
Test reactor fuel				one cask other casks planned
SF & HLW	AFR-metal casks			
United Kingdom				
SF	AFR-vault			vault
HLW			vault	
US	MRS-silo	metal casks vault, dry wells, silo] E-MAD		vaults dry wells (used at INEL, but not licensed)
USSR				
SF		metal casks		
HLW		dry well		

SF - Spent Fuel

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GLOSSARY: ACRONYMS, ABBREVIATIONS AND SPECIAL TERMS

AECL	Atomic Energy of Canada, Limited
AFR	Away-from-reactor spent fuel storage facility
AGR	Advanced gas-cooled reactor, UO_2 fuel (UK)
ANDRA	National Agency for Radioactive Waste Management (France)
AR	At-reactor spent fuel storage facility
AVB	Atelier de Vitrification de Belgique (Belgium)
AVM	Atelier de Vitrification de Marcoule (France)
BNFL	British Nuclear Fuels Limited (UK)
BWR	Boiling water reactor
CANDU	Canada Deuterium Uranium reactor
CEA	French Atomic Energy Commission
CEGB	Central Electricity Generating Board (UK)
CMEA	Council for Mutual Economic Assistance (Eastern bloc countries)
COGEMA	French nuclear fuel cycle company
DBE	Germany Company for Construction and Operation of Waste Disposal Facilities
DOE	U.S. Department of Energy
Dry well	Also known as subsurface caisson
DWK	German nuclear fuel reprocessing company
DWPF	Defense Waste Processing Facility (Savannah River)
EDF	Électricité de France - French utility
ENEA	National commission for energy research and development (Italy)
ENEL	National electric energy agency (Italy)
FBR	Fast breeder reactor
FRG	Federal Republic of Germany
FRP	Fuel reprocessing plant
GCR	Gas-cooled, graphite-moderated reactor
GNS	GNS Company for Nuclear Service (FRG)
GWd/t	Gigawatt days per metric ton
GWe	10^9 watts of electricity (1000 MWe)
GWe•yr	Gigawatt years (electric)

HM	Heavy metal (uranium, plutonium, etc.)
HLW	High-level waste (first cycle waste in a reprocessing plant)
HTGR	High-temperature, gas-cooled reactor
HTR	High-temperature reactor
HWR	Heavy water reactor
ILW	Intermediate-level waste
INFCE	International Fuel Cycle Evaluation
Interim/extended storage	Retrievable storage
ISFSF	Independent Spent Fuel Storage Facility
JAERI	Japan Atomic Energy Research Institute
JEN	Spanish Nuclear Energy Agency
KfK	Nuclear research center at Karlsruhe (FRG)
KW	Kilowatt
LGR	Water-cooled, graphite-moderated reactor
LLW	Low-level waste
LMFBR	Liquid metal fast breeder reactor
Long-term storage	Intended to continue beyond the period of human administration
LWR	Light water reactor
MAGNOX	Magnesium-aluminum alloy used for GCR fuel cladding (UK)
MFRP	Midwest Fuel Recovery Plant (US)
MOX	Mixed (plutonium/uranium) oxide
MRS	Monitored retrievable storage
MWd/t	Megawatt days per metric ton
MWe	Megawatts electric
NTL	Nuclear Transport Limited
OCL	Ocean Cask Lease (Japan)
ONDRAF/NIRAS	National waste management company (Belgium)
NRC	U.S. Nuclear Regulatory Commission
PNC	Power Reactor and Nuclear Fuel Development Corporation (Japan)
PNL	Pacific Northwest Laboratory
PNTL	Pacific Nuclear Transport Limited (Japan/UK)
PTB	Federal science and engineering laboratory (FRG)

PWR	Pressurized water reactor
RBMK	Water-cooled, graphite-moderated, channel-tube reactor (USSR)
Silo	Also known as concrete cask, concrete canister, surface caisson
SS	Stainless steel
t	Metric ton (tonne)
Temporary storage	Short-term (weeks or months), pending transfer
tHM	Metric tons of heavy metal
THORP	Thermal Oxide Reprocessing Plant (UK)
TOR	Breeder fuel reprocessing pilot plant at Marcoule (France)
TRU	Transuranic
tU	Metric tons uranium
UKAEA	United Kingdom Atomic Energy Authority
WIP	Waste Immobilization Plant (India)
WNRE	Whiteshell Nuclear Research Establishment
WVNS	West Valley Nuclear Services

INTRODUCTION

The production of nuclear power is associated with a series of manufacturing operations known collectively as the nuclear fuel cycle. These operations start with the mining of uranium (or thorium) ores, include the processes required to produce the fuel elements that go into the nuclear reactor, and end with the treatment and disposal of wastes. The fuel cycle scheme varies from country to country. Some nations are already committed to a closed fuel cycle, which includes interim storage of spent (irradiated) fuel in a water basin until the short-lived radioactive fission products have decayed; reprocessing to recover plutonium and uranium; recycle of plutonium and uranium to an appropriate nuclear power reactor system; and immobilization, interim storage and disposal of the fuel cycle wastes. Some nations regard the spent fuel as a waste, and hence plan direct disposal following an interim storage period of 10 to 100 years. In many cases, the fuel is stored retrievably until a final decision can be made between the once-through and reprocessing schemes and the necessary facilities to implement that decision can be put in place.

Overall storage requirements for spent fuel and HLW vary markedly from country to country, reflecting the national strategy for managing spent fuel. Specific storage requirements are also a function of the type of reactor system adopted, and hence depend upon the fuel characteristics, e.g., fuel composition, dimensions and burnup.

Spent fuel storage needs thus far have been met primarily with at-reactor storage in a water pool, and such wet storage (i.e., under water) will continue to be necessary for freshly-discharged fuel. For fuels which have aged for at least several months and for which extended storage is required, dry storage looks attractive and several countries (including the US) are developing and evaluating this type of technology. Wet and dry storage are both being considered for HLW packages pending their transfer to a repository.

Two types of fuel cycle waste are regarded as requiring safe storage until they can be placed in a geologic repository: reprocessing plant high-level waste (HLW), highly radioactive, heat producing and contaminated with long-lived radionuclides; and a variety of waste materials which are neither very radioactive nor heat-producing but do contain significant levels of transuranic elements (TRU waste). Interim storage for transuranic wastes is usually provided in a warehouse or other surface facility, but more highly radioactive TRU wastes and high-level waste packages require specialized storage arrangements.

This report summarizes the various national programs for developing and applying technology for the interim storage of spent fuel, HLW and TRU wastes. Primary emphasis of the report is on dry storage techniques for uranium dioxide (UO_2) fuels, but data are also provided concerning pool storage.

STORAGE SYSTEM DESIGN BASIS

Design and safety analysis of a storage system for spent fuel or long-lived wastes is a very complex process, which must take account of many factors. Some of the most important factors (typical spent fuel and waste package characteristics and rates of arisings) are reviewed in this section.

NUCLEAR FUELS

Nine distinct types of nuclear power reactor are either in current commercial use or in the demonstration stage. In a discussion of the fuel cycle, it is convenient to divide them into four major classes, according to fuel type:

1. Reactors fueled with uranium metal or alloys. These include the graphite-moderated, gas-cooled reactor (GCR), built in significant numbers by the UK and France and tried on a one-time basis by several other countries, and the water-cooled, graphite-moderated reactor (LGR). The US has one LGR (the Hanford NPR), while the Soviet Union has built several of them.
2. Reactors fueled with natural or enriched UO_2 fuels. These are found in several versions: the light-water reactor (LWR), cooled and moderated by normal water and in use in large numbers around the world; the heavy-water reactor (HWR), heavily exploited by Canada and in use in several other countries; and two second-generation graphite-moderated reactors, Great Britain's Advanced Gas Reactor (AGR) and the Soviet Union's oxide-fueled LGR.
3. Reactors fueled with PuO_2-UO_2 (MOX) fuels. MOX fuels were developed primarily for fast breeder reactor (FBR) use, but their application in LWRs and Japan's HWR has also been demonstrated.
4. Reactors fueled with graphite-matrix uranium/thorium fuels, developed for the high-temperature gas reactor (HTGR).

Selected reactor parameters for a few typical non-US nuclear power stations are listed in Table 1. Selected characteristics of LWR, HWR, AGR and

TABLE 1. Reactor Parameters--Selected Power Stations[1]

Fuel Type	Reactor Type	Country	Power Station	Fuel: Material	Fuel: Cladding	Moderator	Coolant
U metal and alloys	GCR	France	Chinon 3	Natural U	Mg-Zr	Graphite	CO_2
		UK	Oldbury 1	Natural U	Magnox	Graphite	CO_2
	LGR	USSR	Beloyarsk 2	Enriched U-Mo	Zr-Nb	Graphite	H_2O
Natural and enriched UO_2	AGR	UK	Dungeness B1	Enriched UO_2	SS	Graphite	CO_2
	BWR	FRG	Kruemmel KKK	Enriched UO_2	Zr-2	H_2O	H_2O
	HWR	Canada	Bruce 4	Natural UO_2	Zr-4	D_2O	D_2O
		India	Kalpakkam	Natural UO_2	Zr-2	D_2O	D_2O
		Japan	Fugen	Enriched UO_2 and MOX	Zr-2	D_2O	H_2O
	PWR	France	Paluel 1	Enriched UO_2	Zr-4	H_2O	H_2O
		USSR	Novo-Voronezh 3	Enriched UO_2	Zr-Nb	H_2O	H_2O
	RBMK	USSR	Smolensk 1	Enriched UO_2	Zr-Nb	Graphite	H_2O
UO_2/PuO_2 (MOX)	FBR	France	Phenix	UO_2/PuO_2	SS	None	Na
Graphite-matrix	HTR	FRG	THTR 300	Enriched $(U,Th)O_2$	Graphite	Graphite	He

uranium metal fuels are summarized below. More detail on fuels is provided in Table 2, and Table A-1 (Appendix A) shows fuel parameters for individual reactors in other countries.

Fuel Characteristics[1]

LWR Fuels

Two types of LWR are in wide-spread use: the PWR and the BWR. The fuel rods, which are about 0.6 cm in diameter for PWRs and 1 cm in diameter for BWRs, contain low-enriched UO_2 pellets in a Zircaloy cladding[a] and are combined into square-lattice fuel assemblies (Figure 1). PWR and BWR fuel assemblies are about the same length (approximately 4 m), but the rods of a typical BWR assembly are arranged in an 8 x 8 array compared with a 16 x 16 or 17 x 17 rod array for the typical PWR assembly, and the BWR fuel assemblies are correspondingly smaller in cross-section and weight. Uranium content of a PWR assembly is about twice that of a BWR assembly. Current target burnup is generally smaller for BWRs than for PWRs, roughly 28,000 versus 33,000 MWe·d/tHM.[2,3]

HWR Fuels

CANDU reactors are fueled with natural UO_2 pellets stacked in Zircaloy tubes. Typically, the fuel rods are assembled into circular cross-section bundles that are 10 cm in diameter and about 50 cm long (Figure 1). Target burnup is about 7,500 MWe·d/tHM.[1,2] One day after discharge from the reactor, the fuel has a decay heat output of less than 2 kW per bundle and will not go critical in light water regardless of storage density or age of the fuel.

AGR Fuels

AGR fuel rods, slightly-enriched UO_2 clad in stainless steel, are assembled 36 to a fuel assembly. The fuel bundles, about a meter in length and 24 cm in diameter, contain about 45 kg U. Design burnup is currently about 18,000 MWe·d/tHM.[1,2]

(a) Three US reactors and two European LWRs use stainless steel cladding.

TABLE 2. Characteristics of Typical UO_2 Fuels[2]

Characteristics	PWR	BWR	HWR (CANDU)	AGR
Reactor size (MWe net)	1000	1000	540	660
Approximate fuel assembly dimensions (cm)				
Length	320-483	447	49.5	105
Cross-section				
Side (square)	19-23	14-15.3		
Diameter (circle)			8.1-10.3	24
Weight per assembly (kg)				
Total	480-840	250-307	16.6-24.7	83.5
Heavy metal (HM)	122-548	172-194	13.4-19.8	42.7
Rods per assembly	126-331	47-64	19-37	36
Design burnup (GWd/t)	26-40	27.5-30	6.5-8.1	10-25
Fuel enrichment				
Initial % ^{235}U	3.0-4.4	2.5-3.5	Natural (0.71)	2.01-2.55
Final % ^{235}U	0.8-1.26	0.8-1.0	0.205-0.282	0.5-1.2
Total activity (Ci/kg)				
After 150 d	4.6×10^3	3.8×10^3	NA[a]	$1.2\text{-}3.1 \times 10^3$
After 1 yr	2.3×10^3	1.9×10^3	7.9×10^2	$6.1\text{-}15 \times 10^2$
After 10 yr	3.2×10^2	2.9×10^2	8.4×10^1	$1\text{-}2.5 \times 10^2$
Decay heat (W/kg)				
After 150 d	24.3	18.7	NA	4.9-12.4
After 1 yr	10.4	8.2	3.15	2.4-6.1
After 10 yr	2.3	2.2	0.22	0.3-0.7
Calculated fuel discharge, tU/GWe•yr[b]	32-38	38-40	150	49

(a) NA--information not available.
(b) Actual discharge depends on reactor operating efficiency.

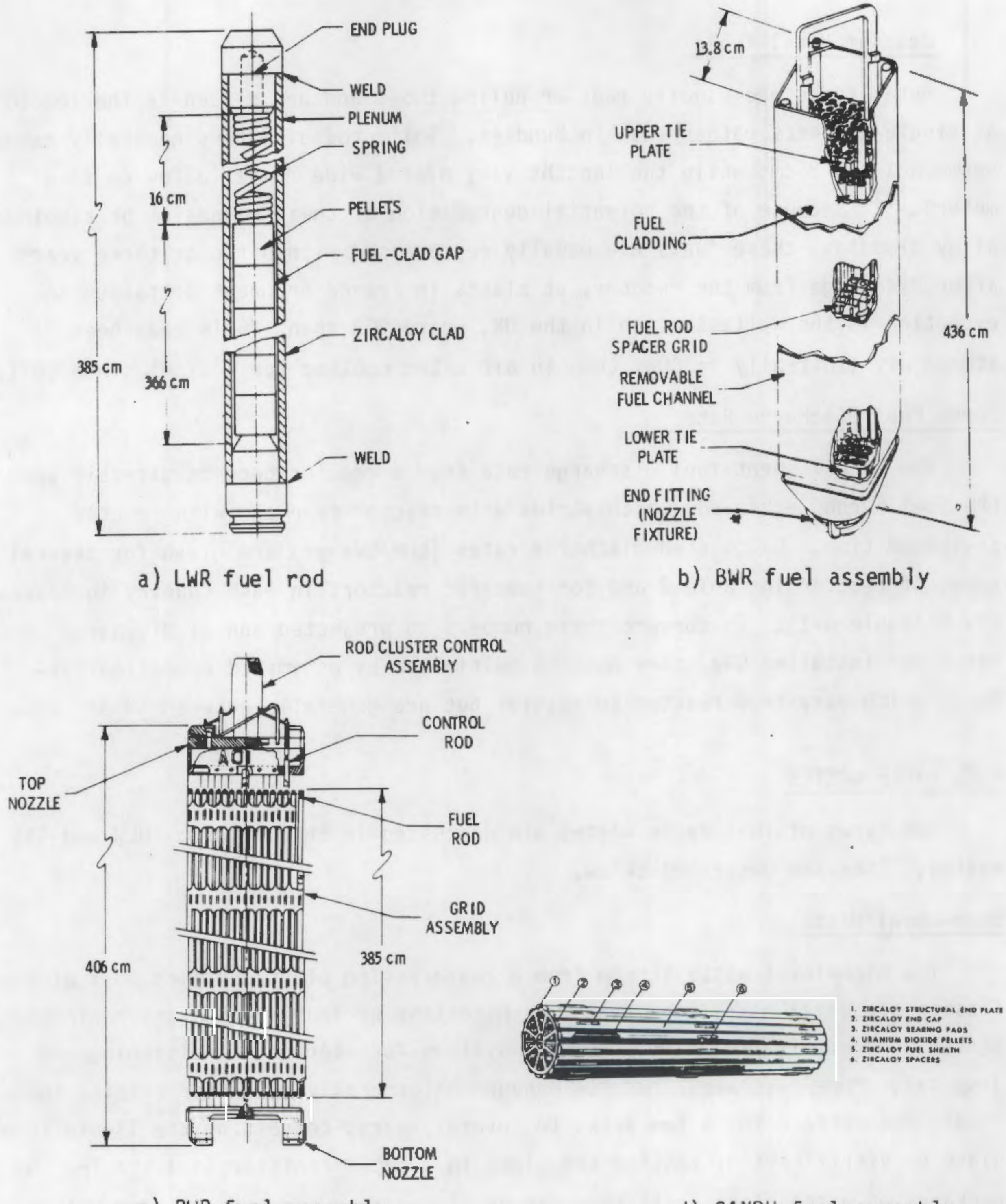


FIGURE 1. Typical Geometries for a LWR Fuel Rod and BWR, PWR, and CANDU Fuel Assemblies[4]

Uranium Metal Fuels

Metal fuels are usually rods or hollow tubes and are placed in the reactor as single elements rather than in bundles. Solid rod diameters generally range between 1 and 3 cm, while the lengths vary over a wide range (a few cm to a meter).[1] Because of the potential degradation of their magnesium or aluminum alloy cladding, these fuels are usually reprocessed within two or three years after discharge from the reactor, at plants in France or Great Britain. An exception is the Wylfa station in the UK, where GCR spent fuels have been stored dry (initially in CO_2, then in air after cooling for a time) since 1971.

Spent Fuel Discharge Rates

The annual spent fuel discharge rate from a reactor depends directly upon the fuel burnup achieved, which varies with reactor type and with reactor on-stream time. Calculated discharge rates (tHM/GWe•yr) are given for several types of reactor in Table 2 and for specific reactors in each country in Appendix A (Table A-1). To convert these numbers to projected annual discharge rates per installed GWe, they must be multiplied by estimated operating factors, which vary from reactor to reactor but are generally between 60 and 80%.

FUEL CYCLE WASTES

Two types of fuel cycle wastes are discussed in this report: HLW and TRU wastes. They are described below.

High-Level Waste

The high-level waste stream from a reprocessing plant contains most of the fission products; has significant concentrations of long-lived transuranic elements; and requires relatively complex systems for storage, conditioning and disposal. Modern strategy for HLW management generally calls for storing the liquid concentrate for a few weeks to several years; converting the liquid to a glass by vitrification; casting the glass in a metal canister; and storing the packages of waste glass until they can be placed in a repository. The volume of HLW glass from one tonne of spent fuel depends largely upon the fuel reprocessing flowsheet, the type of fuel, its exposure level, and the limits set on heat output from the waste package by waste repository specifications. In a "typical" vitrification process,[5] the fission products from 1 tHM of LWR fuel are incorporated in 80-90 ℓ of glass. One canister, 0.3 m in diameter and 3 m in height, holds 0.21 m^3 of glass, equivalent to 2.5 tHM of fuel. Waste packages from the vitrification plants currently planned or in operation are described in Table 3.

Calculated heat generation rates and dose rates from the "typical" HLW canister (described in the preceding paragraph) are summarized in Table 4.

Long-Lived (TRU) Wastes

Non-HLW that require long-term control or disposal in a geologic repository include a number of long-lived fission products and a wide variety of TRU-bearing materials--MOX fuel fabrication residues, cladding hulls, incinerator ash and other reprocessing plant waste streams. The wastes may be packaged in various ways, although many countries incorporate them in concrete or bitumen matrices, typically in 200-ℓ drums. Estimates for rates of TRU waste arisings vary widely. An average rate of 150 m^3/GWe•yr was estimated in Reference 10.

TABLE 3. HLW Packages

Country	Plant/Site	Start of Hot Operations	Waste Package Dimensions	Waste Oxide Loading	Waste Form
Argentina	NA	NA	0.6 m dia x 1.6 m h	10%	Glass blocks
Belgium	AVB/Mol		0.4 m dia x 1.5 m h[6]	NA[a]	Glass blocks
France	AVM/Marcoule	1978	0.5 m dia x 1.0 m h[6]	9%	Glass blocks
	AVH/La Hague	1986	0.43 m dia x 1.9 m h[6]	9%	Glass blocks
Germany (FRG)	Pamela/Mol	1986	0.3 m dia x 1.2 m h[6]	11-13%[7]	Glass or "Vitramet" blocks
India	WIP/Tarapur	1983	0.325 m dia x 0.75 m h[8]	NA	Glass blocks
Japan	PNC/Tokai	1990	0.43 m dia x 1.5 m h	12%	Glass blocks
US	DWPF/ Sav. River	1990	0.61 m dia x 3 m h[9]	28%	Glass blocks
	WVNS/ West Valley	1988	0.61 m dia x 1.2 m h	25%	Glass blocks
UK	Sellafield	1987	NA	NA	Glass blocks

(a) NA - information not available.

TABLE 4. Heat Generation and Dose Rates--HLW Glass Canister

Time Out of Reactor (yr)	Heat Generation Rate (kW)	Dose Rate One Foot from Surface (R/hr)
1	22	1×10^{8}
5	~4.4	
10	3.1	6.2×10^{4}
100	0.36	5.8×10^{3}
1000	0.02	1.6

TRANSPORT AND STORAGE MODES AND CONCEPTS

Spent fuel is transported in special casks, usually after a previous cooling period of a year or more. Most fuel is currently transported dry, in an air, nitrogen or helium atmosphere, but in some cases the cask is filled with water as a heat transfer medium. Transport time varies from a few days to months, e.g., up to 100 days for sea transport from Japan to European fuel reprocessing plants.

Spent fuel transport casks are designed and built to maintain full integrity even under severe accident conditions. If they are to be used for transport across international boundaries, they must satisfy IAEA standards. These require that a test cask withstand sequential tests simulating the stresses which could occur during accidents (e.g., drop test, puncture tests, exposure to fire and immersion in water). Most countries have patterned their national regulations after the IAEA standards.

Transport casks in common use are fabricated from stainless steel or carbon steel by a forging technique. An example is the TN-12 family, produced by Transnuklear (FRG) and currently being used for dry transport of spent fuel within Europe and between Japan and Europe. These casks have a forged, carbon steel body for gamma shielding and structural strength; a solid, borated resin for neutron shielding; fins welded to the body for convective and radiative heat rejection; and a removable fuel basket. They can be evacuated and backfilled with a gas such as helium or nitrogen, to provide a nonreactive atmosphere, and the cask sealing system is designed to provide two independent leakage barriers.

A new type of spent fuel cask, constructed of ductile, nodular cast iron, has been developed in West Germany. One line, the "Castor" casks, manufactured by GNS, has been licensed for transport and storage within Germany and is to be used for AFR storage at Gorleben. A Castor cask is in use in Switzerland for storing spent test reactor fuel, and Castor casks have been shipped to the USA and the USSR for evaluation. Transnuklear (FRG) has built and licensed a similar cask (TN-1300) for use by several utilities in Germany, and is to provide transportable, forged carbon steel storage casks to be used in removing spent fuel from the decommissioned Nuclear Fuel Services reprocessing plant at West Valley, New York. US manufacturers are also designing spent fuel transport/ storage casks. One US storage cask (REA 2023) has been built.

Characteristics of typical casks are listed in Table 5.

The INFCE Working Group 6 study (Spent Fuel Management) references two modes of irradiated fuel storage: AR (at-reactor) and AFR (away-from-reactor).[2] By the INFCE definition, AFR facilities include all storage facilities not integrated within a reactor plant, e.g., those located at reprocessing centers, fuel cycle centers or disposal sites. Freshly discharged fuels are held in water-filled AR pools at least until radioactive decay and thermal cooling are sufficient to facilitate safe transport elsewhere. AFR facilities may be either wet or dry and, in the US, are licensed by NRC for 20-year (renewable) periods.

The United States has defined a third storage mode, to be used for spent fuel or packages of long-lived radioactive wastes (HLW or TRU waste): monitored retrievable storage (MRS). MRS facilities are to be dry and are being designed to be licensable for 40-year (renewable) periods.

WET STORAGE

Extensive operating experience has shown that the storage of spent fuel assemblies in water-filled pools can be considered a proven technology. Water reactor fuel has been in wet storage for periods exceeding 20 years.[11]

Most LWR fuel storage pools are rectangular (10-20 m long and 7-15 m wide) and 12-13 m deep--deep enough to keep at least 3 m of water over the tops of the fuel assemblies during fuel handling operations. Fuel assemblies are placed in storage racks or baskets located at the bottom of the pool. These racks hold the assemblies vertically and maintain the required spacing between assemblies for criticality control. In many pools, the first-generation racks have been replaced with racks having neutron absorbers, e.g., boron-impregnated aluminum, to allow more fuel to be stored in a given space.[11] In general, LWRs had first-generation AR fuel storage capacities for one full core plus

TABLE 5. Characteristics of Selected LWR Spent Fuel Transport Casks[2]

Country	France	FRG	UK	UK/Japan	US	Japan
Type	TN 12	Castor IIa & IIc	NTL 4	Exl 4	NLI-10/24	HZ-75T
Owner	COGEMA	GNS	NTL	PNTL		UCL
Capacity						
PWR Assemblies	12	9 (IIa)	7	5	10	7
BWR Assemblies	30	25 (IIc)	19	14	24	17
Thermal Capacity (kW)	100	50	35	40	74	84
Total Weight (t)	95	100	65	100	86.6	80
Payload (tU)	5.7	4.8	2.3	2.7		3.3
Primary Coolant	Air (water)	Gas	Water	Water	Helium	Air (water)
Primary Mode of Transport	Rail	Rail	Rail	Rail/Sea	Rail	Sea/Road

(a) Castor IIc is qualified for both transport and storage.

room for one or two years' operating discharges. Reracking typically increases the pool storage capacity by a factor of 4-8, and most US reactor pools have been reracked.

Pool walls and floors are constructed of reinforced concrete and are painted or lined with stainless steel or with a fiberglass-base material. Auxiliary facilities include fuel and transport cask handling equipment, a water purification system to remove fission and corrosion products, and a system to remove decay heat.

Typical pool storage facilities for HWR and GCR fuels are described in this report in the sections on Canada and UK, respectively.

HLW glass canisters may be stored in water pools, as in the Swedish CLAB. The Midwest Fuel Recovery Plant (MFRP), which never operated as a reprocessing plant, also had a water basin for storage of HLW glass canisters.

DRY STORAGE CONCEPTS

Theoretical and experimental work has been done on the dry storage of spent fuels and HLW packages in several countries, the concept has been tested,[4,12] and several concepts for storage facilities have been defined.[2,4,13] In this report, the following storage modes are discussed: dry well (caisson), vault, silo and metal storage cask.

Dry Well (subsurface caisson)

Dry wells are cylindrical holes in the ground that are lined with concrete and/or metal. They may be placed just below the surface of the ground (see Figure 2) or in the floor of an underground rock tunnel. The fuel is stored inside sealed metal containers. Heat is removed by radiation to the liner and by conduction through the liner and the surrounding earth, while shielding is provided by shield plugs, the soil and the concrete structure.[4] Dry well spacing depends on expected heat generation rates, thermal conductivity of the soil, criticality requirements and maximum allowable temperatures.

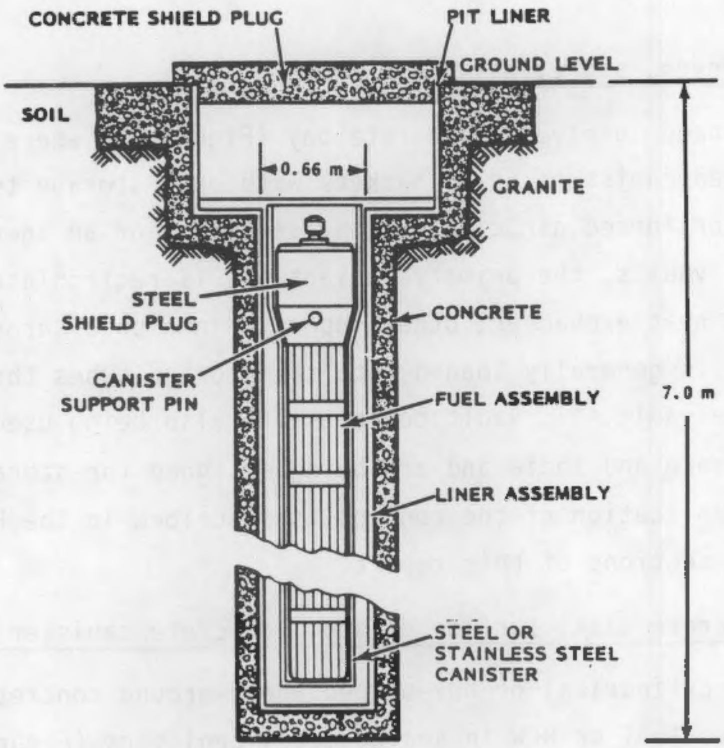


FIGURE 2. Schematic of Near-Surface Dry Well[4]

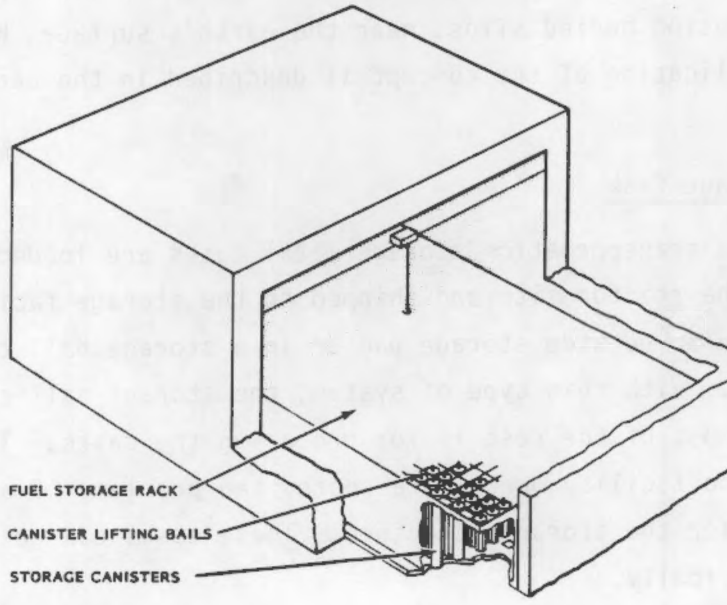


FIGURE 3. Schematic of Dry Storage Vault[4]

Vault (canyon, store, bay)

Vault storage involves a concrete bay (Figure 3), where the fuel or HLW is stored in sealed canisters or in baskets with open storage tubes. Cooling may be by natural or forced air circulation, using air or an inert cover gas. In "closed-cycle" vaults, the primary coolant gas is recirculated and gives up its heat to an air heat exchanger; others operate in a once-through mode, using air cooling. Fuel is generally loaded into the storage tubes through plug-holes in the roof of the vault.(4) Vault concepts are also being used for HLW glass packages in France and India and are being designed for storage of defense HLW in the USA. Application of the concept is described in the France, Japan and United Kingdom sections of this report.

Silo (concrete cask, surface caisson, concrete canister)

Silos are cylindrical or box-shaped above-ground concrete structures that store irradiated fuel or HLW in sealed metal canisters (Figure 4). Two silo designs are in use: one involves heat removal by conduction through the concrete walls and one involves natural convection past metal liners inside the silo. Shielding is provided by the concrete walls and the top shield plug.(4) The concept of using buried silos, near the earth's surface, has also been evaluated. Application of the concept is described in the Canadian section of this report.

Metal Storage Cask

Combination transportation/storage metal casks are loaded with spent fuel assemblies at the reactor site and shipped to the storage facility where they can be placed on an outside storage pad or in a storage hall cooled by passive air circulation. With this type of system, the storage hall can be a simple warehouse, and most of the cost is for procuring the casks. These can be built as needed, so the facility owners are spared the problems of a large initial capital outlay for the storage structure. These casks can be stored horizontally or vertically.

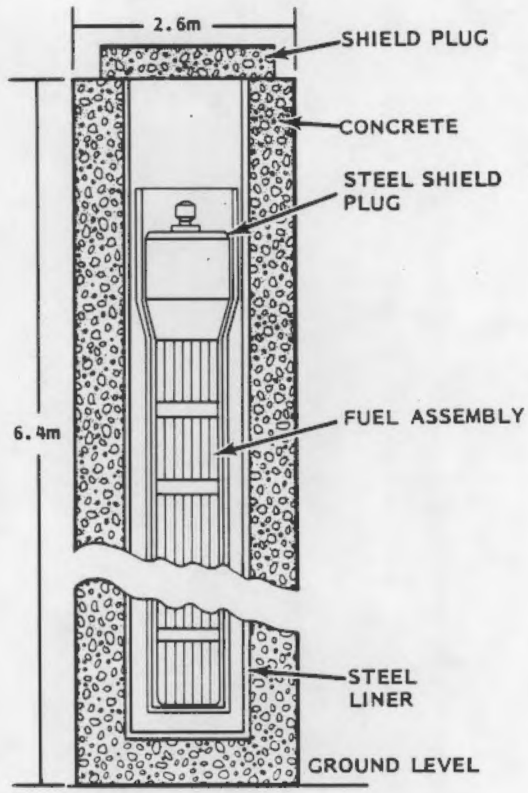


FIGURE 4. Schematic of Silo for Dry Storage of a PWR Fuel Assembly[4]

West Germany has built one 1500-tonne cask storage facility and plans another, both using the new German ductile cast iron casks (see FRG section for more details).

Dry storage concepts have both advantages and disadvantages compared with wet storage. They require less maintenance; cooling by natural convection is possible; and less secondary radioactive waste is generated. On the other hand, the fuel assemblies may have to be encapsulated and/or sealed prior to storage, for some storage concepts; they experience higher temperatures and thus may be more susceptible to degradation of the cladding (and the fuel, if the cladding is breached) during extended storage; and the technology is not as thoroughly demonstrated as it is for wet storage. However, dry storage has now been licensed in several countries.

NATIONAL STORAGE PROGRAMS

National programs for storing spent fuel and long-lived radioactive wastes are summarized in the following sections. Additional information may be found in the following tables, located in the Appendix:

Table A-1. Spent Fuel Characteristics for Selected Reactors in 26 countries

Table A-2. Country-by-Country Estimates of Installed Nuclear Power Capacities, Annual Spent Fuel Discharge Rates and Cumulative Spent Fuel Arisings as of the Year 2000

Table A-3. Summary of National Wet and Dry Storage Programs

Table A-4. National Plans for Geologic Disposal of Spent Fuel and Radioactive Wastes

ARGENTINA

Argentine authorities place a high priority on developing a self-sufficient nuclear power industry based on the HWR, which is fueled with natural uranium and moderated with D_2O. All nuclear power plants are owned and operated by the government, through the National Atomic Energy Commission (CNEA).

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity, HWR (GWe/ No. of Reactors)[1,14]	0.3/1	0.9/2	1.6/3	2.3/4	3.7/6
Spent Fuel Arisings (tHM)[a]					
Annual	58	160	280	400	650
Cumulative	416	940	1,900	3,300	5,800

(a) From data in Reference 15, modified by the authors to fit current nuclear power forecasts in Reference 14.

Spent Fuel Management

Fuel management strategy calls for AR and possibly for AFR storage until a domestic reprocessing plant is established in the 1990s.

AR Pools. Capacity is equivalent to 10-15 years of reactor operation. Two-tier storage was installed at Atucha during recent pool expansion.[16]

AR Dry Storage

Dry storage has apparently been considered for the Atucha expansion.[17] The facility would consist of four independent modules with 108 silos in each module. The silos were to be lined with a carbon steel tube 45 cm in diameter with holes in the lower end.

Monitored Retrievable Storage (MRS)[16]

Interim storage of spent fuel awaiting reprocessing may be provided in a HLW repository in granite host rock, currently in the planning stages and tentatively sited in the Sierra del Medio, Chubut Province, 350 km from Rawson. Preliminary plans for the repository call for sinking shafts to the -800 m level, where the storage chambers would be constructed. Spent fuel transport would be required from the nuclear plant sites to the repository and back to the reprocessing plant near Buenos Aires, a greater than 2400-km round trip.

BELGIUM

Belgium has five operating PWRs and two under construction. When all are operating in late 1984 or 1985, nuclear power will account for about 60% of the country's total electric generating capacity. The utilities hope to build additional nuclear stations, and the country is working towards FBR capability through participation in the Kalkar SNR-300 project (300 MWe FBR demonstration) in West Germany.

The country has an extensive fuel cycle program, which includes AR storage of spent fuel, foreign reprocessing of 500 tU, operation of the Eurochemic fuel reprocessing plant (120 tU/yr), and construction of a geologic repository in a plastic clay formation.

Management of spent fuel in Belgium is the responsibility of SYNATOM, established originally by the private utilities but now under split ownership--50% private, 50% government. Unloading of the fuel from the reactor and its initial storage in cooling ponds is handled by the utilities. SYNATOM takes over as soon as the fuel leaves the reactor ponds. Companies or agencies involved in waste management activities include:

- NIRAS/ONDRAF, the national waste management company (transport and disposal of radioactive waste)
- Minister of Health and Minister of Labour (overall control of radioactive operations)
- CEN/SCK, the nuclear research center at Mol (waste disposal R&D).[18]

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity, PWR (GWe/ No. of Reactors)[1,14]	1.7/3	5.4/7	5.4	6.7/8	8.0/9
Spent Fuel Arisings (tHM)[a]					
Annual	44	150	150	180	220
Cumulative	196	560	1,300	2,100	3,000

Spent Fuel Management

Successive AR water pool expansions seem to be keeping up with spent fuel storage requirements. Use of the Eurochemic fuel storage pool (150 tU capacity) as an AFR has been considered.[17] Transport of spent fuel to the COGEMA reprocessing plant at La Hague, France, is principally by truck.

Waste Storage and Disposal

Germany (FRG) is building a pilot plant (Pamela) in the Eurochemic plant space at Mol, to demonstrate the German HLW vitrification process. Pamela is to produce two waste forms: borosilicate glass blocks and blocks containing glass beads embedded in a lead matrix. Canisters for both are to have the same

(a) Based on data in Reference 15, modified by the authors to reflect current nuclear power forecasts.

dimensions, 30 cm diameter and 120 cm height.[7] They are to be stored in a vault until the Belgian repository (potentially, plastic clay host rock) can accept them.

Intermediate-level wastes, including cladding hulls and other TRU-bearing wastes from the Eurochemic reprocessing operations, are incorporated in bitumen and loaded into 220-ℓ drums. The drums are being stored in ventilated concrete bunkers until they can be transferred to a repository.[19]

BRAZIL

The government is promoting an ambitious program to develop a complete, government-owned nuclear industry, based upon PWRs and including fuel reprocessing capability.

Institutional responsibility for nuclear programs in Brazil rests with the Nuclear Energy Commission, CNEN (R&D, safety, regulatory, program planning) and Nuclebrás, a federal nuclear power enterprise (fuel cycle and waste management process demonstration, design and construction of plant facilities).

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity, PWR (GWe/No. of Reactors)[1,14]	--	0.6/1	1.9/2	3.1/3	4.4/4
Spent Fuel Arisings (tHM)[a]					
Annual	--	16	50	80	120
Cumulative	--	32	180	500	1,000

Spent Fuel Management

Spent fuel management strategy calls for AR storage in water pools until a domestic reprocessing plant can be built and placed in operation. Angra-1 pool capacity is adequate for 10 years' reactor operation.[17]

(a) From data in Reference 15, modified by the authors to fit current nuclear power forecasts in Reference 14.

CANADA

Canada has invested heavily in the development, domestic use and export of the CANDU (HWR, fueled with natural UO_2 and moderated with D_2O) reactor system and its associated fuel cycle. Although CANDU fuel is discharged after relatively low burnup, Canada has sufficient uranium reserves to continue operating its reactors without fuel recycle well into the next century, and there has been little incentive as yet to reprocess spent fuels. However, a decision to recover plutonium is possible in the future, and AECL may turn to a Th-^{233}U fuel cycle.

Commercial nuclear power activities in Canada are handled primarily by two organizations: Atomic Energy of Canada Limited (AECL), which also manages and performs most of the country's nuclear research and development, and Ontario Hydro, the utility which owns and operates most of Canada's nuclear power reactors. The Canadian spent fuel management program is divided between AECL and Ontario Hydro: AECL manages the immobilization and disposal R&D, while Ontario Hydro is concerned with technology for storage and transportation.[20] Regulatory and environmental reviews are handled by the Atomic Energy Control Board (AECB).

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity, PHWR (GWe/ No. of Reactors)[1,14]	5.2/9	10.1/17	13.4/21	15.1/23	14.9/22
Spent Fuel Arisings (tHM)[21]					
Annual	830	1,040	1,600	2,400	2,400
Cumulative	3,650	8,800	18,900	28,000	38,000

Spent Fuel Management

Authorities are preparing to dispose of either CANDU fuels or reprocessing wastes in a crystalline rock repository. Current spent fuel management strategy is to depend on AR storage until reprocessing or spent fuel disposal facilities are established (after 2010). Also, in the event that the choice between fuel disposal is deferred for many years, concepts for the storage of spent fuel for extended periods (>50 years) are being evaluated.

AR Storage[20,22-25]

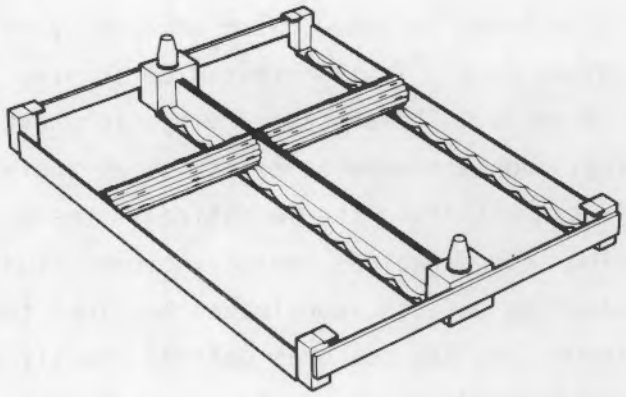
Except for storage of WR-1 (Whiteshell) spent fuel in silos (concrete canisters), at-reactor storage for CANDU spent fuels is provided in water-filled concrete pools lined with stainless steel or fiberglass-reinforced epoxy paint. Because of their low heat output and low ^{235}U-Pu content, the fuel bundles can be closely packed, hence are stored in simple baskets or trays stacked on the floor of the pool (Figure 5). New designs for storage modules have been developed that will allow stacking densities of about 110 bundles/m^3 (Figure 5). Total pool depth is 8-9 m.[23]

Early Canadian generating stations were provided with storage capacity of 5-10 station-years. Experience with water-pool storage of CANDU irradiated fuels has been very good, with no evidence of any deterioration after 15-20 years,[20] and current opinion is that the fuels can be left in a water basin safely for 50 years. Now that utilities must plan to store their spent fuel for an indefinite period, new power stations are being designed to provide storage capacity for their life times, and auxiliary wet storage facilities are being installed at the older reactors. Meanwhile, alternatives to pool storage are being investigated for both interim and long-term applications, and Ontario Hydro is currently considering use of concrete canisters to extend the interim storage capacities at their newer nuclear generating stations, beginning around 1994-95.[25]

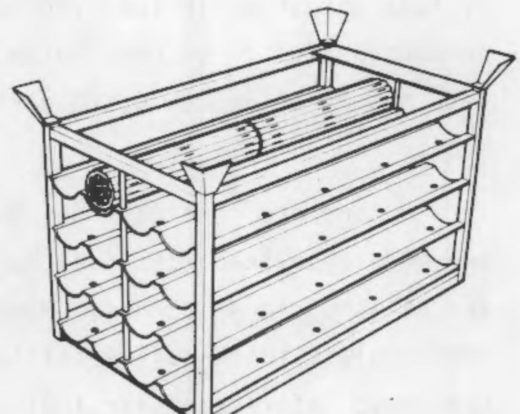
Research and Development

Transportation[26]

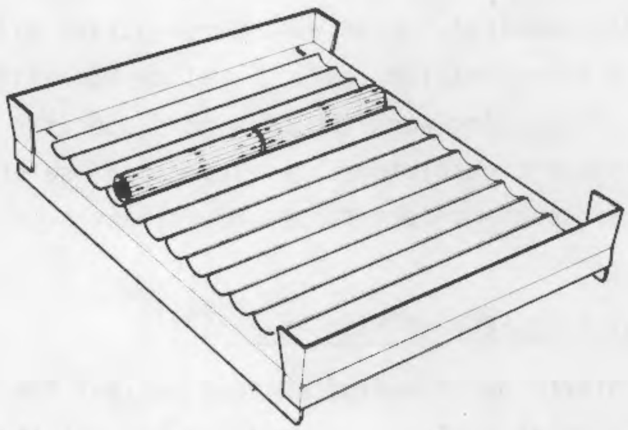
Assigned the responsibility for developing transportation technology for spent nuclear fuel, Ontario Hydro has initiated a program to design, acquire and demonstrate a full-size road cask system by 1989-90. This is to be followed by acquisition of a fleet of road, rail or barge casks as required for large-scale transport to reprocessing and/or permanent disposal facilities. The program has focused on a) development and testing of a module for storing and shipping irradiated fuel bundles, b) investigation of the response of CANDU fuel and the storage module to shock and vibration arising during normal transport, and c) feasibility studies on shipping spent fuel in a dry environment.



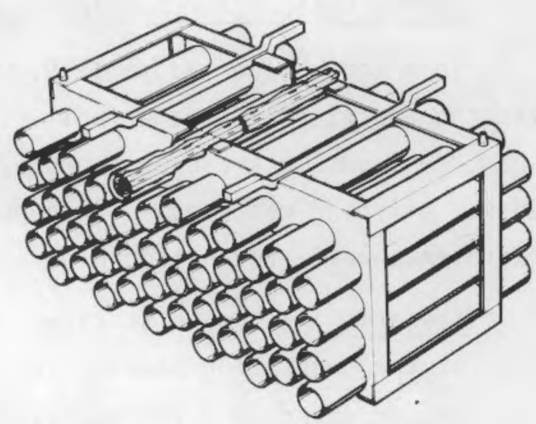
Bruce GS
Storage Tray for Irradiated Fuel



Pickering GS
Fuel Storage Basket



Darlington GS
Storage Tray for Irradiated Fuel



Shipping and Storage Module

FIGURE 5. Containers for Water Storage Ontario Hydro Spent Fuel[24]

The module design depicted in Figure 5 was selected, with a capacity of 96 fuel bundles. Constructed of stainless steel, it is intended to survive pool storage conditions for at least 50 years. The shock and vibration test program consisted of combined analytical and experimental tests, which indicated that the fuel bundles and module can withstand the mechanical stresses occurring during shipping. Dry shipping investigations, which included studies of fuel oxidation in fuel rods with cladding defects, concluded that fuel temperatures need to be kept below a maximum that has not been defined exactly as yet, but is below 200°C, to avoid oxidation-induced damage to breached fuel rods.

A concrete road cask has been designed to stand vertically and to handle a two-module payload (192 fuel bundles), one module above the other. Estimated weight is up to 40 tonnes. Preliminary design analysis appears to favor a dry, rectangular, thick-wall metallic cask rather than a circular cask (because of the choice of rectangular fuel bundle modules). Cask wall construction will be cast, forged, welded or laminated in steel/uranium/lead. Final design will be selected after further evaluation. Supporting work includes more specific studies of fuel durability under transport conditions, development of safety design criteria, analysis of performance characteristics, and estimates of shipping costs.

Siting Options for Supplemental Fuel Storage Facilities[24]

In a study reported in 1979, Ontario Hydro evaluated four options for siting the additional storage facilities that will be required for the utility's spent fuel until it can be reprocessed or placed in a repository. In all cases, only the wet storage concept was considered, presumably because it represents well-proven technology.

Scenario 1 - Onsite storage. All the irradiated fuel is accumulated at the generating power plant (about 50 years is assumed) until it can be moved to a reprocessing plant or repository site. The fuel-packaging facility is located at the repository site.

Scenario 2 - Centralized storage at a specific site, either at a nuclear power plant or an independent site. The fuel-packaging facility is collocated with the repository.

Scenario 3 - Centralized storage, with the fuel-packaging facility at the same site and the geologic repository located at a different site.

Scenario 4 - Centralized storage and fuel-packaging at the repository site.

The study concluded that irradiated fuel can be stored safely in water pools for long periods, that there is enough space at the power stations to build the bays required to store their fuel until the year 2025, that no clear advantage can be seen for the centralized storage option, and that continuation of onsite storage appears to be the most logical approach.

In a study of interim storage options, Ontario Hydro investigators compared various combinations of at-surface and underground sitings, using the water pool, convection vaults, borehole emplacement and concrete silo (storage canister) concepts.[27] Three configurations (Figure 6) were considered for most of the concepts: location at the surface, near the surface (depth <50 m), and deep underground (500 m depth). The following assumptions were used in the evaluation:

1. Water pools
   - Construction - typical for pool storage
   - Fuel package - sealed canister
   - Shielding - water layer in the pool
   - Heat removal - double heat-exchange system, dumping to the atmosphere through forced-draft dry cooling towers.
2. Convection vaults
   - Construction - steel tubes fixed within a rectangular concrete structure
   - Fuel package - sealed canisters, stacked in sealed storage tubes
   - Shielding - structural materials, host medium (if underground)

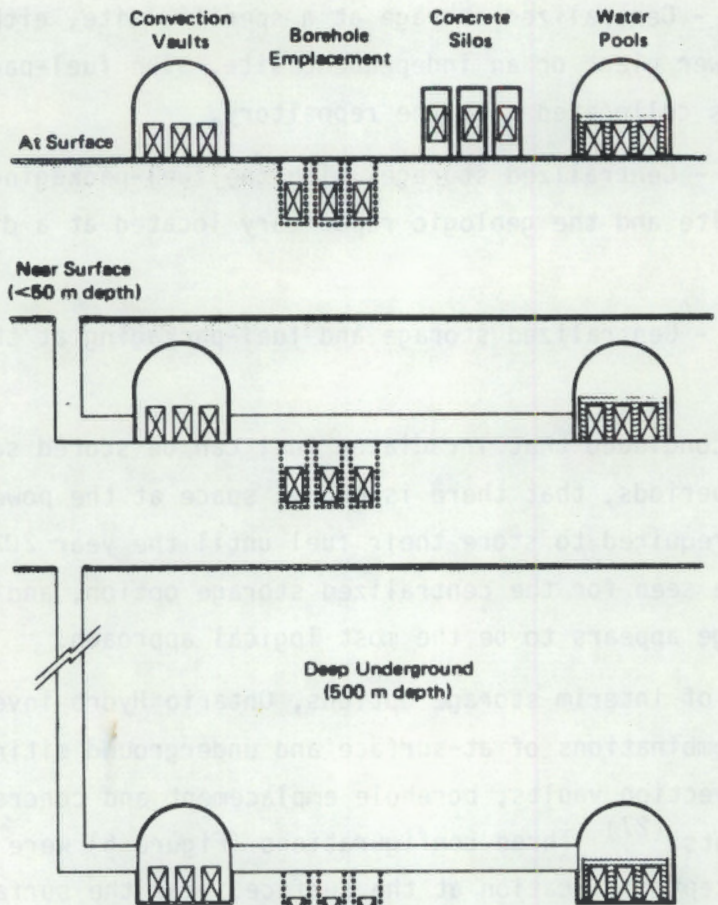


FIGURE 6. Interim Storage Options[27]

- Heat removal - passive air cooling for surface facilities; forced air cooling if underground.

3. Borehole emplacement
   - Construction - prepared boreholes in the host medium
   - Fuel package - sealed canister
   - Shielding - backfill and host medium
   - Heat removal - passive air cooling for surface facility; forced air cooling if underground.
4. Concrete silos (concrete storage canisters, surface caissons or surface casks)

- Construction - large concrete monolith with inner cavity for irradiated fuel
- Fuel package - sealed canister in a carbon steel silo liner
- Heat removal - heat conduction through the concrete, natural convection to the atmosphere.

After applying a pairwise comparison technique to engineering, safety, environmental, cost and social impact assessments of the alternatives, the results summarized in Table 6 were obtained by the Canadian authors.

The preferential ranking for the at-surface siting is associated with decreased engineering complexity, lower construction costs and safer construction. The only consistent drawback against the at-surface options is in the radiological environmental assessment, which concludes that the surface options provide smaller but acceptable safety margins against radionuclide emissions to the biosphere than do the underground sitings.

TABLE 6. Ranking of Interim Storage Options for Spent Fuel in Canada[27]

Option		Ranking[(a)] Favorable: Unfavorable	Pairwise Totals
Convection Vaults	AS	7:0	16.0
Concrete Silos	AS	5:0	14.0
Water pools	AS	5:1	10.0
Boreholes	AS	2.5:1	12.5
Convection Vaults	NS	1:1	5.5
Convection Vaults	DU	1:1	6.0
Boreholes	DU	0.5:1	5.5
Waterpools	NS	0.25:1	4.5
Boreholes	NS	0.25:1	3.0
Waterpools	DU	0:1	2.0

(a) Ratio of favorable to unfavorable ratings.
AS At the surface
NS Near surface
DU Deep underground

The fundamental conclusions of this study were that interim storage of CANDU fuel would be best accomplished by dry storage facilities sited at the surface and that passive heat removal should be applied. Based on this, the convection vault and the concrete silo concepts were recommended.[27]

Dry Storage Concepts

1. Concrete silo development.[28] In 1974, AECL started a program to develop and demonstrate the concrete silo concept for storage of CANDU spent fuels. Four silos were designed and constructed at the Whiteshell Nuclear Research Establishment (WNRE), two to be tested with electrical heaters and two with irradiated fuel loads, one from the Whiteshell research reactor and one from the Douglas Point Generating Station. One of each is cylindrical; the other two are essentially square in cross-section, with the outer corners rounded. Testing started in 1975.

   The electrically heated cylindrical container was tested at power levels ranging from 0-10 kW, the square one at power levels from 0-11 kW. Hairline cracks were observed at 1.5-2.0 kW, as expected. These opened up slightly as the temperature differential increased, but even at a heat load of 11 kW, the cracks did not affect the structural or shielding integrity of the walls, and it was concluded that heat loads to at least 11 kW can be tolerated by the silo design. Based on the satisfactory performance of the test canisters, WNRE elected to use concrete silos for storage of fuel from the Whiteshell test reactor, WR-1, and several silos were built and loaded with fuel, starting in 1977. Since 1975/76, 138 WR-1 and 360 HWR fuel assemblies have been in storage.[4]

   The WR-1 concrete canister is a steel-lined, reinforced-concrete monolith, 5.3 m high and 2.6 m in diameter. It has a central cavity 3.5 m high and 0.8 m in diameter, weighs about 70 t, and holds 216 bundles of standard CANDU fuel (4.3 tU), 36 bundles to a basket (Figure 7). It is designed to stand outdoors on a concrete pad. The carbon steel fuel containers (baskets) are loaded with fuel bundles

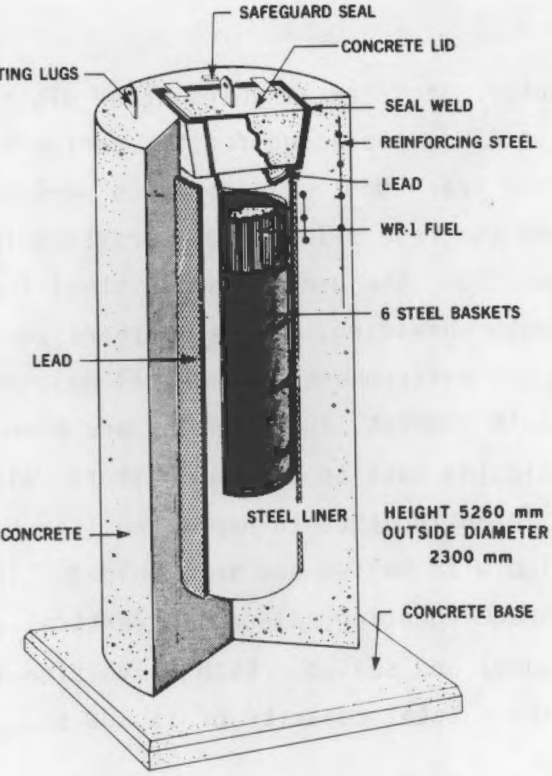


FIGURE 7. Cylindrical Silo #2 Containing WR-1 Fuel[29]

in a hot cell, covered with a lid which is seal-welded, and transported to the canister. Once the canister has been loaded (six fuel baskets), it is filled with helium and sealed by welding a plug to the steel canister liner; the annulus is filled with lead shot and a concrete plug is sealed in place.

The dual use of concrete canisters for transport as well as storage has been considered, and drop and puncture tests were conducted with 1/8-scale models. These indicated concept feasibility: no detectable breaching or deformation of the liner occurred, although about 20% by weight of the shielding concrete had spalled off by the time the series of tests had been completed.[28]

2. Conceptual design studies. In 1982, Canadian investigators reported a conceptual design study[28,30] for a central dry-storage facility for 80,000 tU in spent CANDU fuel. The fuel was to be stored in

pools at the reactor sites for 10 years after discharge, and retrievable storage in an AFR was planned for the period between startup (year 2000) and the year 2060. Two concepts were considered: convection vaults and concrete silos. Both provided for cooling by natural air circulation, the use of carbon steel fuel baskets and containers, concrete shielding, double barriers against release of radioactivity to the environment and minimal maintenance.(30) With the convection vault concept, fuel bundles are transferred under water from the shipping cask to storage baskets, air-dried in a hot cell, and placed in an inner containment can (six baskets to a can), which is backfilled with helium and seal welded. The cans are transferred to the storage location, placed in vertical storage tubes (four cans to a tube) and sealed. Each convection vault has 704 storage tubes, with a total capacity of 11,200 tU. Eight vaults are required.

The silo storage facility is self-contained, with its own plant for fabricating concrete silo, service and fuel transfer facilities, and a storage field for the loaded canisters. Fuel bundles are placed in baskets which can be sealed; three baskets are loaded into each canister can, which is backfilled with helium and sealed by welding a cover in place; the canister is loaded into the silo, which is sealed with a plug and grout; and the loaded silo is moved to the storage field. Each silo can hold 216 bundles; 20,000 silos are required for the 80,000 tU of spent fuel.

Ontario Hydro is currently reviewing their spent fuel management program to the year 2025, and considering the possibility of using concrete casks (silos) to extend the interim storage capacity at their newer generating stations, beginning around 1994-95.(25)

<u>Extended Durability of Irradiated Fuel in Dry Storage</u>(23,31)

A joint AECL-Ontario Hydro program was initiated in 1978 to collect experimental data on the behavior of breached and non-breached irradiated CANDU fuel in dry storage. Concrete silo storage experiments were set up at WNRE, also a laboratory test program to investigate cracking of fuel sheathing and UO_2

oxidation. In the in-silo tests, irradiated fuel bundles from the Bruce and Pickering power stations, with both defected and non-defected pins, are being held at 150°C, in moist and dry air. The tests started in 1981; the first interim examinations are scheduled for 1984/85.

Immobilization of Spent Fuels for Disposal[32]

Canadian investigators are developing techniques for immobilizing spent CANDU fuels in preparation for their emplacement in a deep geologic repository. Their studies are concentrating on placing spent fuel in cylindrical containers that have a high-integrity, corrosion-resistant metal wall, designed to isolate the fuel for about 500 years. They are also considering concepts that offer much longer isolation by using materials such as ceramics.

Several container concepts are being studied. One was a "stressed shell" design that provides a shell thick enough to withstand the hydrostatic pressure in a flooded vault. Other concepts call for the use of some form of internal support (a cast metal matrix, packed particulate material, or structural supports), permitting the use of thinner-walled containers. The development program includes design, fabrication, testing and assessment.

Storage of Transuranic Wastes

Canada's low- and intermediate-level wastes, which include small amounts of TRU, are stored in three types of systems, depending on the radiation level and the toxicity. The lowest levels of waste are stored in boxes or drums, in warehouse-type structures which may have parapet walls for shielding. Higher levels are stored above grade in concrete boxes ("quadricells") or in concrete dry wells. The dry wells may either be maintained for ultimate retrieval of the waste or backfilled with concrete.

FINLAND

Finland has four nuclear power plants, two PWRs supplied by the USSR and two BWRs obtained from Sweden, and energy planners are considering the installation of a fifth. Finland has no commercial fuel cycle capability.

The Finnish nuclear power stations are operated by two state-owned power companies, IVO and TVO. These companies have established the Nuclear Waste

Commission of Finnish Power Companies, YJT, to coordinate studies related to the management of their nuclear wastes. The government oversees IVO and TVO through the Finnish Atomic Energy Commission.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe/ No. of Reactors)(1,14)					
PWR	0.8/2	0.8	0.8	3.2	3.2
BWR	1.3/2	1.3	1.3		
Spent Fuel Arisings (tHM)[a]					
Annual, LWR	30	60	60	60	100
Cumulative, LWR	48	350	650	950	1,400

Spent Fuel Management

Spent fuel from the USSR-built PWRs (440 MWe each) is to be returned to the Soviet Union for handling and disposal, with no wastes to be returned to Finland. The first shipment, of fuel cooled for three years, occurred in the fall of 1981. Spent fuel from the Swedish BWRs (660 MWe each) may be sent to another country for reprocessing or placed in terminal storage by Finland. In either event, Finland anticipates the need for a geologic repository for spent fuel or for solidified high-level waste from these two reactors.(33)

AR Pool Storage(33,34)

- IVO (Loviisa) power station--auxiliary water pool storage capacity is being installed to accommodate the USSR requirement that Finland hold its spent fuel for 5 years.
- TVO (Oikiluoto) power station--water pool storage is to be provided for all fuels discharged during the reactor lifetime. Existing pools have capacity until about 1990; new pools, with dense racks (using boron steel as a neutron prison), are to be ready by 1988. The new facility will be at the surface, but the spent fuel pools will be

(a) Based on data in Reference 15, modified by the authors to reflect current nuclear power forecasts.

excavated in rock and designed for a 60-year life. The designers assumed a 40-year fuel residence time in the pool. Construction cost: about $55 million.

Research and Development

Several options for increasing IVO and TVO capacity were evaluated, with the following conclusions:

- Dry vault--cheapest, but technology is considered unproven
- Dry casks--more expensive than pool storage
- Auxiliary wet storage--proven technology, considered cost-effective.

FRANCE

France is very aggressive in developing nuclear power capability. A few GCRs were built in the 1950s and 1960s, but present emphasis is on installation of PWR power stations and on LMFBR development and demonstration.

The French Atomic Energy Commission (CEA) controls all nuclear R&D, while its semi-autonomous subsidiary, COGEMA, handles all industrial fuel cycle activities, including reprocessing and the conditioning of fuel cycle wastes. Long-term management and disposal of radioactive wastes is handled by another CEA subsidiary, ANDRA. Electricité de France (EdF) is the major producer and sole distributor of electricity in France, and retains title to used nuclear fuel and all by-products. Fuel cycle and waste management R&D is handled principally at the Marcoule, Cadarache or Fontenay-aux-Roses nuclear research centers of the CEA.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe/ No. of Reactors)(1,14)					
GCR	2.2/7	2.2/7	2.2	1.9	--
PWR	9.9/12	32.2/38	47.2/52	54.1	60
FBR	0.25/1	1.4/2	1.4	1.4	25

Spent Fuel Arisings (tHM)[a]					
Annual, PWR	250	800	1,200	1,300	1,500
Cumulative					
GCR (metal fuels)	5,600	8,000	10,000	13,000	15,000[b]
PWR	250	2,700	8,000	14,000	22,000
Waste Arisings, Cumulative					
Vitrified HLW, m^3		300	750	1,900	3,000
Packaged TRU, m^3		13,000	15,000		45,000

Spent Fuel Management

France has been reprocessing GCR fuels for many years and does not have a significant backlog of this type of fuel.[b] Furthermore, the government is committed to reprocessing and recycle of LWR fuels. Thus, spent fuel management plans call for relatively short storage times, either at the reactor or in large-capacity pools at the reprocessing plant.

Wet Storage

Spent fuel is cooled in AR pools until it can be transported to storage facilities at the reprocessing plant. AR storage time is at least 9 months for LWR fuels, usually less than a year for GCR fuels, and LWR fuels are stored at the reprocessing plant for at least an additional 27 months before reprocessing. Wet storage capacity for LWR fuels at the La Hague reprocessing plant is to be increased to 8,000 tU by 1987. Both "wet" and "dry" casks are used for spent fuel shipment, but the French plan to shift essentially to dry transportation and unloading at La Hague.[19,35]

Because of delays in building a large reprocessing plant for breeder fuels, the Superphenix FBR needs additional storage capacity to supplement the internal (in sodium) storage drum. This is to be provided by a 1300 tHM water basin, selected in preference to a cask facility because the Superphenix fuel will require liquid-type cooling for three years after discharge.[36]

(a) Data obtained from Reference 15, modified by the authors to fit current nuclear power forecasts.
(b) France reprocesses GCR fuels soon after discharge, hence has only a small inventory.

Dry Storage[37]

The CEA has gained experience with dry storage and transport of highly radioactive materials through the following activities: use of dry casks for transport of PWR spent fuels; installation of a facility for dry storage of spent LMFBR fuels; and vault storage of canisters of HLW glass.

1. Transport

   Transnucléaire, a COGEMA subsidiary, has participated with its Nuclear Transport, Ltd., partners in shipping LWR spent fuel from European and Japanese utilities to the COGEMA and BNFL reprocessing plants and has had very good results. Dry transport casks were chosen for this service because they were considered safer and more economical.

2. Storage of LMFBR Fuels[38]

   A dry storage facility for spent Phenix and Superphenix fuels is being installed as part of the new TOR FBR fuel reprocessing pilot plant at Marcoule. The storage module (3.9 m by 4.5 m by 11 m high) has 77 wells, each cooled by forced air ventilation. Each well has a diameter of 300 mm and a height of 9.85 m and will hold five Phenix or three Superphenix 93-pin fuel assemblies. The assemblies are to be cooled at the reactor for 6 to 24 months and placed in an air-tight canister prior to storage at TOR. The thermal load from each well is expected to be between 1 and 4 kW, and the maximum canister temperature is not to exceed 640°C.

   The dry storage mode was selected for the facility because it is small and because the designers wished to avoid immersing the shipping cask in water.

Storage of HLW Glass[37,38]

France has produced and stored tonnage quantities of HLW glass in two facilities at Marcoule, Piver and AVM. In operation between 1969 and 1973, the Piver pilot plant produced 130 glass blocks, each weighing 90 kg and with activity levels as high as 100 kCi/block. The blocks are stored in 32 pits, sunk in concrete to a depth of 10 m each. The capacity of each pit is 20 canisters of glass, cooling is by air pumped between the pit walls and the containers, and the air is filtered before it is exhausted to the atmosphere.

The AVM plant at Marcoule, in hot operation since 1978, had produced about 840 canisters (ca 285 t) of HLW glass by March 1983. AVM canisters are stainless steel, 1 m high by 50 cm in diameter, and contain about 0.4 tonne of glass (150 ℓ).

The AVM glass storage facility comprises three underground concrete vaults with overall horizontal dimensions of 28.5 m by 20.2 m and a depth of 15.2 m underground, surmounted by a metal shed for handling the waste canisters. With 220 storage pits, the three vaults can hold a total of 2,200 HLW canisters. The pits are 10-m-long stainless steel pipes, 60 cm in diameter, suspended vertically on a metal frame and loaded through plug-holes in the concrete roof.

A forced-air ventilation system has been installed, sufficient to keep the exit air temperature below 100°C when the heat generated in the glass is at the 50 W/ℓ maximum. These conditions limit the temperature of the concrete to 60°C and the centerline temperature of the glass to 500°C under forced-air cooling, 600°C under natural convection conditions. The air is exhausted through absolute filters and a chimney, but experience to date has shown the filters to be unnecessary.

The HLW glass storage facilities being installed at La Hague are similar to the Marcoule vaults. Five storage vaults, each with 100 pits, will hold 4,500 glass canisters. Each storage pit, 11 m deep, will hold nine waste logs with a total heat output as high as 31.5 kW. Cooling air circulates along the concrete walls, floor and ceiling before it flows into the storage pits. The maximum temperature of the effluent air will be 110°C under forced-circulation conditions, 140°C when the blowers are not working.

Until recently, French authorities planned to store their vitrified HLW in surface facilities for up to 100 years, then transfer the waste-glass canisters to a geologic repository. There are indications that this policy is changing and that HLW storage times may be much shorter.

TRU Waste Storage[10]

Transuranic wastes are reduced in volume by various techniques (incineration, decontamination, crushing, etc.) and packaged in metal drums or boxes. Some are immobilized by admixture with bitumen or concrete. If the TRU content of the package does not exceed 1 Ci/m^3 (1,000 nCi/g), the package may be shipped to the La Manche LLW site for disposal. Otherwise, it is stored onsite in a warehouse or a subsurface caisson until it can be transferred to a geologic repository.

Waste packages at La Manche are placed in either of two types of structure, depending on the radiation level of the package. Low-level materials are stacked on concrete platforms inside a concrete block wall, covered with backfill which fills the gaps between the drums, then covered with a thick layer of impermeable clay and with earth. Waste containers that require additional shielding are disposed of in concrete monoliths. These structures are formed by stacking the packages on a concrete foundation inside reinforced concrete walls and then filling the structure with concrete. The storage structures may be either below grade or built on the surface of the ground.

GERMANY (FRG)

The Federal Republic of Germany (FRG) has a strong nuclear program, embracing the construction of BWRs and PWRs and the demonstration of advanced reactor technology (HTR and FBR). The commercial fuel cycle program has been based for many years on the concept of recycling plutonium to breeder reactors and possibly to LWRs.

The federal government supports an extensive nuclear R&D program, administered through the Ministry for Science and Technology, but requires participation by private industry in major demonstration projects. Commercial activities for the back end of the fuel cycle are handled by DWK, the nuclear fuel reprocessing company (spent fuel storage and reprocessing; treatment and storage of reprocessing wastes) and ALKEM GmbH (PuO_2/UO_2 mixed oxide fuel fabrication and the treatment of alpha-contaminated wastes from fuel fabrication), while PTB, the Federal Physical-Technical Institute, has legal responsibility for radioactive waste storage and disposal. Together with other industrial and public institutions, PTB established another company, DBE, to build and operate repositories. Fuel cycle and waste management R&D is handled by the Karlsruhe, Jülich and Hahn-Meitner research institutes (KfK, KFA and HMI, respectively) and the Institute for Underground Storage (GSF/IfT) at Braunschweig, with the assistance of many other research organizations. KfK, assisted by DWK, NUKEM GmbH and DBE, has the lead for the evaluation of direct disposal of spent fuel.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe/ No. of Reactors)(1,14)					
LWR	8.6/10	16.1/17	23.6/22	26.0	28.0
HTR		0.3/1	0.3	0.3	0.3
FBR			0.3	0.3	0.3
Spent Fuel Arisings (tHM)[a]					
Annual, LWR	200	390	530	600	700
Cumulative, LWR	960	2,200	4,500	7,400	11,000

Spent Fuel Management

Current FRG fuel cycle strategy includes: 1) indefinite dry storage of spent fuels at one or more AFRs, in metal casks; 2) interim reprocessing of FRG fuels (2700 t) by COGEMA at La Hague; 3) construction of one or more small (350-t/yr) reprocessing plants; and 4) construction of a salt dome repository at Gorleben for HLW, TRU wastes and possibly spent fuels. Final storage of irradiated LWR fuels as an alternative to reprocessing is also being thoroughly evaluated.

AR Storage for LWR Spent Fuels

After discharge, spent fuel is cooled for at least one year in the reactor pools. Reactor pools at the older reactors in Germany are generally sized to accommodate two years at reactor discharge, while maintaining a full core reserve. Capacities could be expanded significantly by using existing dense rack designs, but utilities in some German states have encountered licensing

(a) Data obtained from Reference 15, modified by the authors to reflect current power station construction schedules.

problems with this approach. New reactors are having their pools fitted with compact racks which could provide storage capacity for eight or nine years.(17,18) Problems from the limited AR storage capacity are being avoided by shipping spent fuel to COGEMA (France) for reprocessing and by building supplemental dry storage facilities.

Industrial-Scale Dry Storage Activities

DWK has elected to meet FRG needs for supplemental LWR fuel storage capacity by using the metal storage cask concept, with helium-filled combination transport/storage casks developed in Germany. Four facilities have been planned: a 1,500 tU AFR at Gorleben, has received an operating license and is ready to receive spent fuel; a second 1,500-tU AFR is planned for Ahaus, near the Netherlands border; and two AR facilities, one each at the nuclear power plants of Würgassen (120 tU) and Stade (240 tU), are in the licensing procedure stage.(39,40)

The AFR storage hall at Gorleben is 180 m long by 38 m wide and will hold about 420 casks, stored vertically. The facility is designed for a maximum heat load of 8 MW and is cooled by passive convection, the air entering the building at the floor level and exiting through openings near the ceiling. Instrumentation is to be installed at each cask station, to monitor temperature and helium pressure. Construction was completed in 1984.(39)

Two German companies, GNS and Transnuklear, have developed and received FRG operating licenses for spent fuel transport and storage casks. The GNS "Castor" casks are fabricated by a process that produces a ductile cast iron and are reported to have high strength, good thermal conductivity and low cost. Neutron shielding materials are contained within borings in the cask body; the cooling fins are cast together with the body. GNS estimates that in 1985 dollars the 20-year cost of storing spent fuel in their cask would be about $96/kgHM.(41)

Cask design criteria include the following requirements:(40)

- A two-barrier containment system
- Type B(U) properties for each barrier containment system

- Continuous monitoring of gas leakage from the cask
- Safety under severe accident conditions (e.g., aircraft crash, building collapse)
- Design of the containment system to meet the hypothetical assumption of 100% rod failure
- Prevention of a nuclear criticality accident
- Limitation of dose rate
- Satisfactory dissipation of the decay heat under both standard and accident conditions, to be provided by the cask's geometry and structural design. (Limits of 390°C for PWR fuel and 420°C for BWR fuel have been set on fuel assembly surface temperatures at the time of loading to minimize the effects of fuel cladding degradation.)

Transnuklear has two series of storage casks: TN-1300 and TN-2400. The TN-1300 series, developed at the request of several West German utilities, was designed to transport and store short-cooled (1.5-2.4 year) fuel from the Biblis 1300 MW class of LWRs and has a ductile cast iron body similar to the GNS Castor casks. Casks in the TN-2400 series have forged carbon steel bodies sized for a large payload, but intended primarily for interim (many years) storage at the reactor plant site.[42-44]

Some of the design parameters of the Castor, TN-1300 and TN-1400 casks are shown in Table 7.[43,44] Figure 8 shows two Castor cask views: an artist's drawing that shows the structure of the cask, with four PWR assemblies in place; and a cask being drop-tested.

Dry Storage of HTGR Fuels

Spherical graphite-matrix fuel elements from the Jülich HTGR test reactor have been stored in tubes in a vault since 1981. The fuel elements, about nine years out of reactor and packaged in stainless steel canisters, generate only about 30 W/canister. Heat is removed by a natural convection air cooling system that maintains canister surface temperatures at 30-32°C. Storage of these fuels in transport casks is also being tested.

TABLE 7. Selected Parameters of German Spent Fuel Storage Casks[43,44]

Cask Model	Capacity, No. of Assemblies BWR	Capacity, No. of Assemblies PWR	Cask Weight, tonne	Fuel Design Age, yr	Design Thermal Load, kW
Castor 1A	--	4	79	>1	22
Castor 1B	--	4	60	>1	22
Castor 1C	16	--	82	>1	22
Castor 2A	--	9	106	>1.5	45
Castor 2B	--	9	85		45
Castor 2C	25	--	98	>1.5	45
Castor 3	16	4	<80	>1.5	
Castor 4	25	9	<110	>1.5	
Castor 5 (B,C)	50-52	21-26	100-120	>5	45-55
TN-1300	33	12	116.5 (PWR) 108 (BWR)	>2	50
TN-2400	52	24	<100	>5	24

Dry Storage Cask Research and Development

The German cast-iron storage cask development and testing program has been extensive. A partial list of these activities follows:

- Multi-assembly cast iron casks were licensed in the FRG for shipment early in 1981 and for a dry storage demonstration at the Würgassen power station later in 1981. The licensing process included thermal assessments (using electrical heating), drop tests, crash tests, and fire tests.[4]
- The first demonstration of irradiated fuel storage in a metal cask was completed in February 1984 at Würgassen. Two years earlier, after about a year's storage in the reactor fuel storage pool, 16 uncanistered BWR assemblies with a burnup of about 27,000 MWd/t had been placed in a Castor 1C cask with a helium cover gas. The cask was instrumented to measure fuel rod temperatures and the pressure of the nitrogen gas between the cask lids. The leak tightness of the cask was demonstrated; no failed fuel rod claddings were detected.

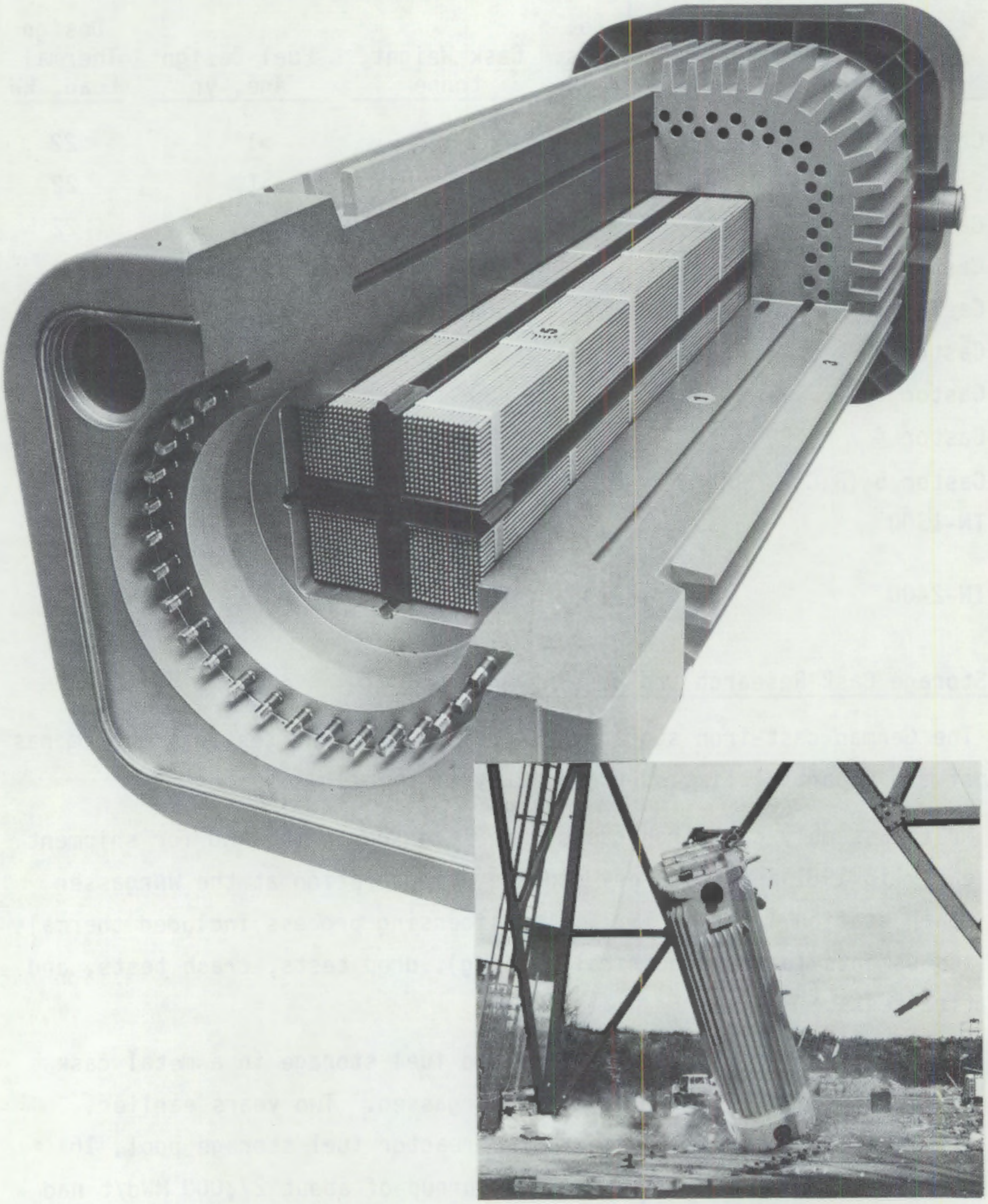


FIGURE 8. Views of Castor Cask: Interior, with 4 PWR Assemblies in Place; Drop Test[a]

(a) Pictures taken from STEAG Kernenergie GmbH brochure.

Over the demonstration period, the maximum cladding temperature (on a few center rods) dropped gradually from about 380°C to 220°C. The cask surface temperature decreased from about 60°C to less than 50°C.[4,45,46]

- Instrumented Zircaloy-clad irradiated fuel capsules and rods with exposures as high as 33,000 MWd/t have been held in helium at temperatures as high as 450°C for 150 days and longer, at Ispra, without failure. These tests were terminated and are being evaluated.[12,47]
- Theoretical evaluations of the heat transfer and shielding problems of dry storage facilities.[48]
- A Castor SPX cask was subjected to a test in which the cask was insulated on the outside to simulate conditions if it were buried in rubble. After seven days, the temperature of the neutron moderator material, an epoxy resin, reached 320°C and the resin decomposed, leaking from the cask. The cask's hermetic seal was unaffected.[49]

Direct Disposal of Spent Fuel[50,51]

A $20 million, four-year project to evaluate direct disposal of spent fuel as an alternative to reprocessing was started at KfK in January 1981. During the first phase of the project, which ended in June 1982, technical concepts for conditioning the fuel elements, for disposal packages and for final disposal were identified and evaluated. The following waste forms were investigated: unmodified fuel assemblies; fuel assemblies with the end fittings removed; individual close-packed fuel rods; fuel rods with the fission gas released by venting; fuel rods shortened by folding or chopping; fuel vitrified after voloxidation; and fuel incorporated in a glass after dissolution. Ten types of final disposal casks were studied, including ceramic and graphite monoliths as well as metal canisters. Disposal in galleries in either vertical or horizontal boreholes was considered.

At the end of the first phase, a reference concept was selected: packaging of complete fuel assemblies in corrosion-resistant metal casks and disposal in a gallery.

In the second phase, detailed engineering and experimental studies of the reference concept are being carried out, leading to the final evaluation during the second half of 1984.

Storage of HLW Glass Canisters and TRU Wastes

DWK engineers have completed a conceptual design for air-cooled vault storage of canisters of HLW glass. The concept, based on once-through, natural-draft heat removal, provides space for 3,500 canisters, eight per storage tube. Design specifications include a maximum heat output of 1.9 kW per canister and the following maximum temperatures: 146°C air outlet temperature from the vault; 170°C at the storage tube wall; and 158°C at the concrete.

TRU wastes are stored in heavily reinforced concrete bunkers until they can be placed in a repository.

INDIA

India depends heavily on a growing nuclear power capacity to augment the nation's electric power generating capacity. Their nuclear program, started with the installation of two BWRs, is continuing with CANDU-type HWRs fueled with natural uranium and is to proceed to FBRs fueled with plutonium and eventually to self-sustaining thorium-uranium cycle reactors. National objectives continue to emphasize development of complete fuel cycle self-sufficiency.

Essentially all activities concerned with the back end of the fuel cycle are conducted by the various divisions of the Department of Atomic Energy. Major components include the Bhabha Atomic Research Center at Trombay (near Bombay), the Nuclear Fuels Division (fuel manufacture) and the fuel reprocessing organizations at the Tarapur and Kalpakkam power stations.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe/ No. of Reactors)[1,14]					
BWR	0.4/2	0.4	0.4	0.4	0.4
HWR	0.2/1	0.8/4	1.5	2.6	4.0
Spent Fuel Arisings (tHM)[a]					
Annual, HWR	30	85	180	210	420
Cumulative					
BWR	200	290	380	470	600
HWR	160	500	1,200	2,300	4,400

Spent Fuel Management

India is developing a closed fuel cycle, with domestic reprocessing (100 tU/yr capacity in 1983). The country lacks a modern interstate road system, and the railroads are multigage, requiring frequent transloading of cargo. Consequently, the Indian AEC is attempting to minimize the need for transport of highly radioactive materials, and the country's reprocessing requirements are to be met with small (100 tHM/yr) reprocessing plants located near each major nuclear power center. Hence, there is little need for major facilities for either extended storage or transport of nuclear fuels. The nuclear industry depends on AR pools to handle interim storage requirements.

Dry Storage of HLW Glass

Each reprocessing plant is to have its own HLW vitrification plant and a facility for interim storage of HLW glass until a national repository is ready. India's first industrial vitrification plant is now in operation in the Waste Immobilization Plant (WIP) at Tarapur, and the Solid Storage Surveillance Facility (SSSF) for HLW glass canisters is scheduled for completion early in 1984.[52]

The SSSF, intended to store HLW from Tarapur and Trombay (Bombay) for 20 years, is a partially-underground storage vault which is cooled by a

(a) Data obtained from Reference 15, modified by the authors to fit current nuclear power forecasts.

stack-induced natural-draft cooling system. The canister storage tubes, 356 mm in diameter and 2 m deep, are arranged vertically on a triangular pitch 825 mm by 825 mm (distance between centers), and each contains two HLW canisters. The HLW canisters are 0.375 m in diameter, 0.75 m long and constructed of SS 304L. Each contains about 125 kg of HLW glass, and the initial heat release rate is about 2.5 kW. Cooling air enters the vault through a screen to an inlet air corridor, is distributed through air supply ducts and is exhausted through a 100-m-high stack. Waste canisters are loaded into the storage tubes through plug-holes in the top of the vault (Figure 9).[8,52]

TRU Waste Storage

Plutonium-contaminated intermediate-level waste solutions are bituminized and collected in custom-built containers or 200-ℓ carbon steel drums coated on the inside with an acid resistant material. Both types of waste packages are stored in engineered underground steel-lined tile holes.[52]

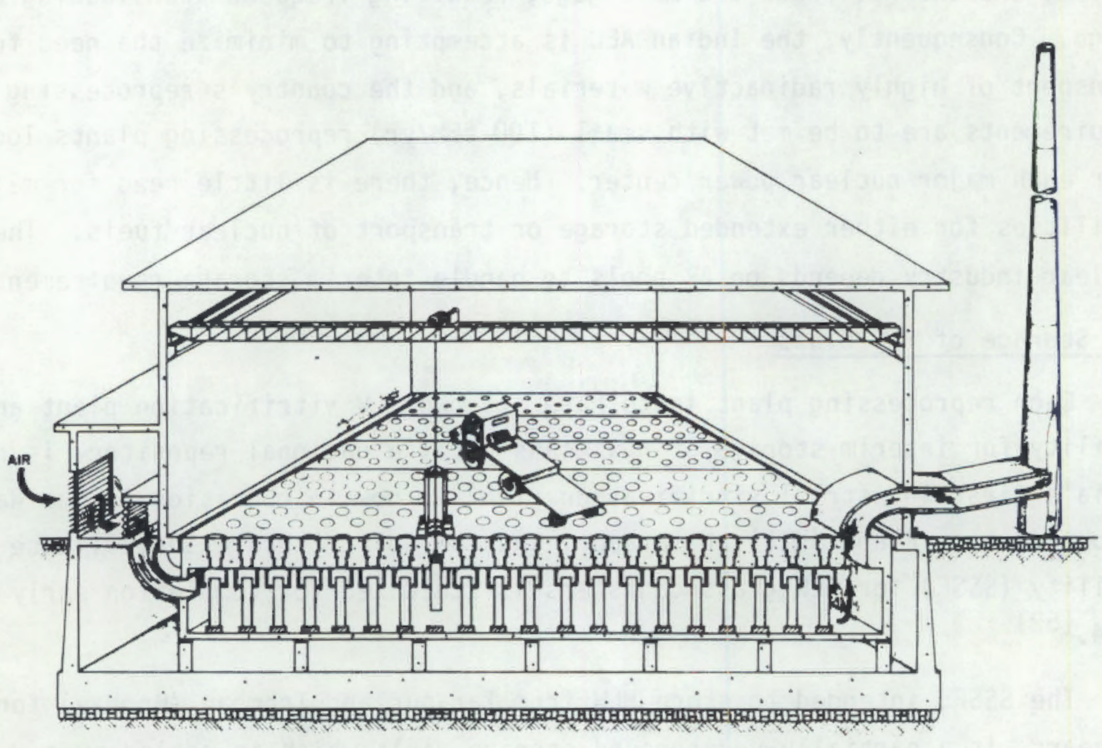


FIGURE 9. Schematic View of the Air-Cooled Storage Facility at Tarapur[52]

ITALY

Italy has an ambitious, diversified nuclear program that is based primarily upon light-water reactors but includes construction of two advanced reactors, a HWR and a test breeder. The country is aiming for self-sufficiency in the nuclear fuel cycle, with domestic reprocessing of spent fuels and recycle of plutonium to a fast breeder reactor.

The nuclear industry is state-owned to a great extent, major responsibilities being handled by: ENEL, operation of power plants; Ansaldo, reactor plant construction; AGIP Nucleare, fuel cycle; and ENEA (formerly CNEN), R&D and regulatory matters. ENEA operates nuclear research centers near Rome, Turin (northern Italy) and Rotondella (southern Italy).

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe/ No. of Reactors)(1,14)					
GCR	0.15/1	0.15	0.15	0.15	--
LWR	0.3/1	1.1/2	1.1	4.8	6.7
Spent Fuel Arisings (tHM)[a]					
Annual, LWR	12	40	100	170	240
Cumulative					
GCR (metal fuels)	900	1,200	1,400	1,400	1,400
LWR	160	320	500	1,000	2,000

Spent Fuel Management

Two small, special-purpose reprocessing plants have been built and operated successfully, and the construction of a commercial fuel reprocessing plant is being considered for the late 1990s; and an Italian HLW vitrification process has been developed and tested in a nonradioactive pilot plant. Current nuclear strategy assumes that, for the time being, there is no need to provide large-scale AFR spent fuel storage; that HLW will be vitrified and stored for

(a) Data obtained from Reference 15, modified by the authors to reflect current power station construction schedules.

upwards of 50 years prior to emplacement in a repository; and that a geologic repository, probably in a clay formation, can be developed by the time it is needed.

Spent Fuel Storage

Spent fuel from Italy's Latina (GCR) reactor is being sent to the UK for reprocessing. By installing high-density racks in the Caarso pool, by modifying the Avogadro swimming-pool reactor for spent fuel storage, and by designing the Mantalto station storage pools to yield a 10-year capacity, storage space is being provided for Italy's LWR fuels until the end of the present decade.(17,53) Authorities believe that a large AFR storage facility will be needed by 1995, and are considering installation of a 1000-tU-capacity pool, probably at the site of the commercial reprocessing plant. As an alternative to the pool facility, dry storage is also being evaluated.

In 1978, ENEL designed a dry spent fuel storage facility for installation at the Trino Vercellese PWR site. A modular concept was used, each module consisting of a metal container, sized for 12 PWR assemblies, and its housing, a concrete box assembled in situ. External dimensions of the module are 5 x 2.5 x 3 m (high) and the walls 0.35 m thick. Heat is removed by natural circulation. With a carbon-steel fuel basket and fuel assemblies cooled for four years (5 kW total heat output per module), the calculated fuel rod temperature is 388°C and the fuel assembly sheath 324°C.(54)

JAPAN

The Japanese government actively supports nuclear power as the primary means of reducing dependence upon foreign energy sources and considers it the top priority energy source. The government's strategy is to install LWRs for near-term power production; develop an advanced thermal reactor (ATR), based on a LW-cooled, HW-moderated concept; aim for commercial operation of fast breeder reactors by the year 2010; and eventually depend heavily on fusion power.

Development of fuel cycle and waste management technology is handled primarily by the government-owned Power Reactor and Nuclear Fuel Development Corporation (PNC) and the Japan Atomic Energy Research Institute (JAERI), supported by other government institutes and private industry. Construction and operation of commercial fuel reprocessing facilities is the responsibility of Japan Nuclear Fuel Service, Limited (JNFS).

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe/ No. of Reactors[1,14]					
GCR	0.19/1	0.19	0.19	0.19	--
LWR	14.1/20	21/30	31/37	40	50
HWR	0.15	0.15	0.15	0.15	0.15
FBR	--	--	0.28	0.28	0.28
Spent Fuel Arisings (tHM)[a]					
Annual, LWR	450	620	960	1,100	1,400
Cumulative					
GCR (metal fuels)	690	900	1,150	1,300	1,500
LWR	1,400	4,100	8,200	13,000	20,000

Spent Fuel Management

With only very limited indigenous uranium resources, and with a national commitment to become self-sufficient with regard to their nuclear fuel supply, the Japanese are leaning heavily on fuel reprocessing and plutonium recycle--to breeder reactors in the long term, to thermal reactors (ATRs and LWRs) in the near term. In keeping with these objectives, Japan is developing domestic industrial capability for reprocessing and waste treatment. Since a commercial-scale reprocessing plant will not be in operation in Japan before 1990, the utilities have arranged to have over 4,600 t(U) of their fuel treated by foreign reprocessors, under contracts which in general require return of the HLW to Japan. Waste management strategy calls for vitrification of HLW, volume reduction and immobilization of other wastes, and surface storage of waste packages until provision can be made for disposal.

(a) Data obtained from Reference 15, modified by the authors to fit current nuclear power forecasts.

Storage and Transport

The nuclear power and spent fuel reprocessing plants in Japan are sited beside the ocean, harbor facilities are easily accessible, and spent fuel is transported to reprocessing facilities in Japan and abroad by ship directly from the reactor site. Other radioactive materials are moved within the country by road. Facing widespread public concern about transport safety, the nuclear industry and the government both sponsor major programs to improve and demonstrate the safety of the transport system.(55)

Current Japanese policy is to store spent fuels in water pools at the reactor site (with rod consolidation) until they can be moved to a foreign or domestic reprocessing plant, and the nuclear utilities depend on AR pool storage. This policy is now being reassessed,(56) and consideration is being given to constructing AFR storage facilities. A 3000-tU AFR is planned for the first commercial reprocessing plant.

Japanese Zircaloy-clad fuel has been kept in dry casks during sea transport for as long as 3.7 months, at estimated temperatures as high as 385°C. Each cask holds 12 PWR assemblies and each ship carries 10 to 20 casks. Cask atmospheres have been inert in some cases, air in others. Several hundred assemblies have been shipped from Japan to Europe in this way without any evident cladding failure due to handling and shipping.(4,37)

A dry storage facility for test reactor fuel has been in operation at JAERI's Tokai site since early 1982. The fuel is low-exposure (800 MWd/t) uranium metal clad in an aluminum alloy, with a maximum heat generation rate of 0.5 watt. The fuel rods are sealed in helium-filled, stainless steel canisters that are stored in stainless-steel-lined dry wells in a concrete box. Heat is removed by natural convection, with no cooling system provided.(57)

Interim Storage of HLW Glass

PNC expects to commission a HLW vitrification/glass storage facility at Tokai in 1990. Preliminary design studies(58) assumed that the waste would be vitrified 5-1/2 years after fuel discharge from the reactor and that it would arise from reprocessing LWR fuel with an exposure level of 28,000 MWd/tU. The HLW storage room was designed to meet the following overall specifications:

storage capacity, 500 canisters (30 cm dia x 1.7 m high, 12.2% waste loading); glass centerline temperature, below 450°C; canister surface temperature, below 350°C; and cooling air outlet temperature, below 65°C.

A storage pit-vault concept is used that provides for 100 stainless steel cylindrical pits, held in place by a rack system. Cooling air is blown through the annuli between the pits and the stainless steel canisters and discharged through filters to the atmosphere.

PNC also reports a design study of a pilot plant for long-term (up to 100 years) storage of HLW canisters.[58] This facility would also follow the vault-storage pit concept, with capacity for 4,000 HLW glass canisters in four vaults, but would be cooled by a natural air convection system.

The PNC HLW storage concept has been tested experimentally by Kobe Steel investigators in a one-fifth scale nonradioactive mockup, which has a matrix of electrical heaters simulating waste canisters in 144 positions in a 12 x 12 array. The purpose of the test is to measure cooling effectiveness, temperatures and fluid flow data for forced convection, natural convection, and transition from forced to natural convection.

Interim Storage of TRU Waste

PNC has an engineered storage facility at Tokai for solid, contact-handled TRU wastes. The warehouse has a capacity for 6,000 drums (200 ℓ). Waste packages are assayed with a system capable of detecting 20 mg ^{239}Pu and are segregated to facilitate treatment when PNC's new Plutonium Waste Treatment Facility (PWTF) becomes available (early 1987). Several immobilization processes are being evaluated for the PWTF, including electroslag and microwave melting of residues and incorporation of wastes in bitument and resins.[10]

KOREA (REPUBLIC OF KOREA)

South Korea has seven PWRs and one HWR installed or under construction, in a nuclear program aimed at lessening the country's dependence upon foreign oil as an energy source. The country is moving toward domestic fuel cycle capability, but has not yet established a policy concerning spent fuel storage and reprocessing.

Responsibility for nuclear energy development belongs to the Atomic Energy Bureau and Atomic Energy Commission. Nuclear R&D is carried out at the Korea Institute of Energy and Resources.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe/ No. of Reactors)(1,14)					
PWR	0.6/1	2.1/3	6.8/9	8.7	10.6
HWR	--	0.6/1	0.6	0.6	0.6
Spent Fuel Arisings (tHM)[a]					
Annual, LWR	18	60	200	230	310
Cumulative					
LWR	17	240	1,000	2,100	3,200
HWR	--	160	510	860	1,200

Spent Fuel Management

South Korean nuclear power plants have AR pool storage capacity until the early 1990s. Plans for the future are indefinite, with their formulation awaiting the outcome of current technical and economic studies evaluating the reprocessing option. If reprocessing is not adopted, the country will probably install AFR storage facilities.(59)

MEXICO

At one time, the government of Mexico was working toward a national goal of 20 GWe installed nuclear capacity by the year 2000, and several fuel cycle R&D facilities were reported to be under construction at the Salazar Nuclear Center near Mexico City. One of these facilities was thought to be a pilot-scale reprocessing plant. At present, the country has two 650 MWe BWRs under construction at the Laguna Verde station, scheduled for completion in 1986 and 1988, and the nuclear power goals are being re-evaluated.

(a) Data obtained from Reference 15, modified by the authors to reflect current forecasts of nuclear power capacity.

Responsibilities for nuclear matters are divided among the National Atomic Energy Commission, a state company charged with exploration and exploitation of national reserves (URAMEX), and a National Nuclear Research Institute (ININ) charged with R&D. Nuclear power plants are owned and operated by the Federal Electricity Commission (CFE). Responsibility to review and approve the design, construction and operation of nuclear facilities is assigned to the National Institute for Nuclear Research (CNSNS).

Nuclear Power Projections

	1985	1990	1995	2000
Capacity (total) (GWe/No. of Reactors)[14]	--	1.3/2	1.3	1.3
Spent Fuel Arisings (tHM)[a]				
Annual	--	105	300	500
Cumulative				

Spent Fuel Storage

The Mexican nuclear power plants, scheduled to start up in 1986 and 1989/90, will have pool storage capacity for 2.8 cores (7 years). The national regulatory body has recommended that plans be started at once for an AFR and a repository for spent fuel.

NETHERLANDS

The Netherlands has a 50-MWe BWR and a 445-MWe PWR, but implementation of plans to build other nuclear plants is awaiting resolution of the country's waste management problems and the completion of a public debate over energy policy.

Overall responsibility for nuclear energy matters is spread through three ministries, with their decisions subject to approval by Parliament. Other organizations with major roles include the energy research institute at Petten (ECN) and the Geological Survey.

(a) Data obtained from Reference 15, modified by the authors to fit current nuclear power forecasts.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity, LWR (GWe/No. of Reactors)[14]	0.5/2	0.5	0.5	0.5	0.5
Spent Fuel Arisings (tHM)[a]					
Annual	16	16	16	16	16
Cumulative	100	190	270	350	420

Spent Fuel Management

The country contracted to have spent fuel reprocessed in France and England; recent contracts require return to the Netherlands of the resulting HLW immobilized in glass or ceramic clad with stainless steel. The government is, therefore, looking for sites for a salt dome repository for disposal of these high-level wastes.

The Dodewaard (50 MWe) AR storage pool has capacity for about two annual discharges, while the Borssele (445 MWe) storage pool, after reracking, has capacity for four or five years. Both reactor plants, however, are covered by foreign reprocessing contracts through the end of the present decade. There is no near-term need for a centralized storage facility.

SPAIN

The Spanish government has promoted the development of nuclear power as part of its effort to reduce national dependence on oil imports, and the utilities have built BWRs, PWRs, and one GCR. In 1983, the new Socialist government announced their intention to reduce the previous government's goal of 11.5 GWe nuclear by 1987 to no more than 7.5 GWe by 1990, and cancelled earlier plans to develop domestic fuel recycle capability.

Nuclear activities in Spain are controlled by the government through the Nuclear Energy Agency (JEN), now primarily an R&D organization; EMPRESA, a fuel

(a) Data obtained from Reference 15, modified by the authors to reflect current forecasts of nuclear power capacity.

cycle services company; the Nuclear Safety Council, safety and licensing; and ENRESA, the new waste management company.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe/ No. of Reactors)(1,14)					
GCR	0.48/1	0.48	0.48	0.48	0.48
LWR	0.6/2	5.0/6	7.0	7.9	9.7
Spent Fuel Arisings, LWR, (tHM)[a]					
Annual	18	135	190	210	260
Cumulative	175	490	1,300	2,300	3,400

Spent Fuel Management

As a result of a recent governmental decision, Spain has dropped earlier plans to develop domestic reprocessing capability and now intends to dispose of spent LWR fuel directly in a salt or granite host rock repository. The AR spent fuel storage pools, largely because of dense racking, have capacities equivalent to 7 to 16 years of reactor operation. Interim storage needs are to be met with independent dry-storage facilities, located at the proposed repository site or at the reactor sites. Current intentions are to use metal storage casks. Spent fuel from Spain's GCR is being reprocessed by COGEMA, and Spanish LWR fuels have been accepted for reprocessing by BNFL.

In 1981, JEN joined with ENUSA (Spanish fuel cycle company) and ENSA (Spanish nuclear equipment company) in a project to develop a metal storage cask that would satisfy the following requirements: capacity for 17 PWR fuel assemblies of the standard 17 x 17 matrix design, with a burnup as high as 40,000 MWd/tU and cooled for a minimum of five years; total cask weight not to exceed 120 t, fully loaded; fuel cladding temperature not to exceed 250°C; and external dose rates not to exceed 40 mrem/hr at the cask surface. In initial studies,[60] nodular cast iron was selected as the cask material and aluminum

(a) Data obtained from Reference 15, modified by the authors to reflect current power station construction schedules.

for the basket; a concept was developed (internal diameter, 1.5 m; external diameter, 2.5 m; and length, 5.0 m); and analytical work confirmed the feasibility of the basic design concept.

SWEDEN

Sweden has seven BWRs and two PWRs installed, producing about 30% of the country's electricity, while two BWRs and one PWR are under construction.

Present nuclear power policy, mandated by a majority of the voters in a March 1980 referendum, calls for completion of a total of 12 power stations (9.4 GWe) by 1985-86, to provide about 45% of Sweden's electricity. Thereafter, the government plans no more growth in nuclear power and, in fact, intends to phase out all nuclear plants by the end of the year 2010, decommissioning each nuclear plant at the end of a 25-year operating life.

Swedish national law makes the Swedish power utilities responsible to plan and implement the waste management program. The utilities have delegated responsibility for executing waste management activities to the jointly owned Swedish Nuclear Fuel Supply Company, SKBF. The work of SKBF in waste management is supervised by a special governmental body, the National Board for Spent Nuclear Fuel (NAK), which was organized in July 1981. One of NAK's special functions is to administer the waste management program funds accruing from fees paid by the nuclear power producers in proportion to the electric power they produce.

Through its KBS Division, SKBF manages Swedish waste disposal R&D programs, which are carried out at the Studsvik Energy Technology Center, at the Stripa Mine, at various universities and institutes, and in ASEA-Atom laboratories. The federal laboratory at Studsvik and a number of universities and institutes handle the supporting R&D.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity, LWR (GWe/No. of Reactors)[a]	4.6/7	7.4/10	9.4/12	9.4	9.4
Spent Fuel Arisings (tHM)[a]					
Annual	127	210	260	260	260
Cumulative	465	1,330	2,350	3,650	5,000

Spent Fuel Management

Current fuel cycle plans assume that total spent fuel arisings by the year 2010 will amount to 7,000 tU. Of this, 870 tU will be reprocessed by COGEMA (France) and the resulting HLW will be returned to Sweden, as glass, for disposal. The HLW glass and the rest of the fuel will be stored 30-40 years, after which the fuel may be reprocessed or fuel and HLW may both be placed in a repository.

Spent Fuel and HLW Transport

All Swedish nuclear power stations, as well as CLAB (Central Temporary Storage Facility) are built on the coast, and spent fuel and radioactive wastes are transported by sea. A new ship (M/S SIGYN), built for this purpose, is currently devoted to transporting spent fuel from the Swedish reactor plants to France for reprocessing. In 1985, the vessel is also to start transporting spent fuel from the reactors to CLAB and HLW glass from France back to Sweden. SIGYN has a double hull, double bottom and several watertight bulkheads, ensuring high floatability. The single hold, 57 m x 10 m x 5.6 m deep, is designed to accommodate ten TN17 Mk 2 transport casks holding a total of 70 PWR or 170 BWR fuel assemblies (about 32 tU).[61]

(a) Data obtained from Reference 15, modified by the authors to reflect current power station construction schedules.

Spent Fuel and HLW Storage

The Swedish reactors have AR spent fuel storage capacity in pools equivalent to 4-5 years reactor operation--sufficient until 1985, when CLAB is to be ready. In some cases, dense racks have been installed.

Located near the Oskarshamn nuclear station, CLAB is a manmade cavern mined out of granite bedrock. It lies beneath 30 m of rock, is designed for wet storage of up to 3,000 tU of spent fuel as long as 40 years, and is sited to allow expansion to 9,000 tU if needed. It also is designed to store canisters of HLW glass from foreign reprocessing of Swedish spent fuel until the final repository is ready. CLAB, scheduled for commissioning in early 1985, is designed for a life of 60 years, when its contents will have been transferred to a reprocessing plant or to a repository. Construction cost is about $250 million,[62,63] and fuel storage costs are estimated at $50/kg in 1980 dollars.

Sweden's waste disposal concept calls for encapsulation of spent fuel assemblies in copper or in lead and copper, and HLW canisters in lead and titanium, at the end of the 40-year storage period and before emplacement in a repository.[64]

SWITZERLAND

Four LWRs have been built in Switzerland, a second BWR is under construction, and the utilities want to install additional nuclear capacity. The government has been pro-nuclear, but has encountered much public opposition to requests for approval of specific power plant sites, and the future of nuclear power is in doubt. Furthermore, federal law now requires that the nuclear utilities establish a project guaranteeing the long-term safety of waste management and disposal before any new reactor project can receive a general permit. The Minister of Energy has stipulated that if a satisfactory project has not been established by December 31, 1985, the existing plants may lose their operating licenses. In response, NAGRA (the radioactive waste producers' waste disposal cooperative) has launched a major repository development program.

Several agencies in Switzerland have major roles in nuclear fuel and waste management: the Federal Institute for Reactor Research (EIR) at Würenlingen, waste management R&D; the National Cooperative Association for the Storage of Radioactive Wastes (NAGRA, German language acronym, or CEDRA, French acronym), development and construction of repositories; Lucens Studies Consortium (CEL), intermediate storage of spent fuel and reprocessing wastes; and the Nuclear Energy Inspectorate, licensing of repositories.[18]

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity, PWR (GWe/No. of Reactors)[1]	1.9/3	2.9/4	2.9	3.8/5	3.4
Spent Fuel Arisings (tHM)[a]					
Annual	55	55	85	105	140
Cumulative	380	660	1,090	1,530	2,000

Spent Fuel Management

The Swiss nuclear utilities have selected a fuel cycle based on reprocessing and recycle of plutonium to either LWRs or FBRs, but are also evaluating a once-through fuel cycle and disposal of their spent fuel. They would like to participate in a multi-national reprocessing plant, but do not anticipate that option becoming available in the foreseeable future. Hence, they have placed contracts for foreign reprocessing--165 tonnes going to BNFL (UK) and 599 tonnes to COGEMA (France). HLW glass, to be returned by the reprocessors starting in 1992/93, is to be stored in a surface facility for 30 years before emplacement in a repository.

Transport and AR Storage

Switzerland has shipped more than 100 t of spent fuel abroad for reprocessing via rail, truck and ship. With COGEMA and BNFL accepting spent fuel for storage until they can reprocess and with all operating reactor pools

(a) Data obtained from Reference 15, modified by the authors to reflect current power station construction schedules.

equipped with dense storage rocks, Swiss authorities estimate that they have adequate AR storage capacity until the mid-1990s.

AFR Storage

CEL is expected to apply in 1984 for a general permit for a combined AFR storage facility for spent fuel, vitrified HLW and other reprocessing wastes. This facility is expected to be operational by 1992.[18] Since the Swiss interim storage requirements are estimated at only 300 to 500 tU of spent fuel by the year 2000, current plans are to use GNS (Castor) storage casks.

The Castor cask storage concept has been applied by EIR for storage of fuel from the Diorit test reactor until the Swiss repository is ready. Three tonnes of Zircaloy-clad fuel, with a maximum burnup of 17,000 MWd/t and having been stored in water for 6-10 years, were loaded by a dry transfer method into a Castor 1C cask in May 1983. At the time of loading, total heat output from the fuel was 10.5 kW. The cask atmosphere is helium; maximum cladding temperature is estimated at 180°C.[12]

Swiss engineers (Electrowatt Engineering) have collaborated with US investigators (GA Technologies) in developing the "MODREX" closed-cycle vault-storage concept, which uses heat pipes to exchange heat from the air that circulates over the fuel canisters. In the MODREX system, the spent fuel (7 PWR or 17 BWR assemblies) is sealed in a helium atmosphere in a stainless steel canister. The canisters are placed in storage modules, each an individually poured concrete monolithic structure containing nine individual silo positions. The silos are 6 m long, 1.7 m in diameter, lined with steel and capped with shield plugs. Additional storage modules are built as needed.[65]

TAIWAN

Taiwan has an ambitious nuclear power program based on both BWRs and PWRs. The government wishes to develop LWR fuel fabrication capability, and spent fuel reprocessing is being considered. Nuclear power plants in Taiwan are government-owned and operated by Taiwan Power (Taipower), which generally depends on foreign vendor organizations for technical help. The Atomic Energy

Council has functions similar to those of the US NRC, but also is responsible for waste disposal. Research in the nuclear field is handled by the Institute of Nuclear Energy Research.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity, LWR (GWe/No. of Reactors)(1,66)	1.2/2	4.0/5	4.9/6	5.8/7	8.7/8
Spent Fuel Arisings (tHM)[a]					
Annual	18	120	145	170	260
Cumulative	70	430	1,140	1,770	2,600

Spent Fuel Management

Original pool storage capacity of Taiwan's four operating reactors has been nearly doubled by installing high-density storage racks. These pools will be filled by 1988. New reactors are to be provided with lifetime spent fuel pool capacity.(67) Taipower authorities are evaluating dry storage techniques to supplement pool capacities. They estimate a need for 500 to 1000 tU additional storage capacity by the year 2000.

UNITED KINGDOM (UK)

The United Kingdom has developed its nuclear-generating capacity around gas-cooled reactor technology for three decades. Calder Hall, the world's first commercial sized nuclear power station, was opened in 1956. Through 1982, 21 similar gas-cooled reactor (GCR) plants and nine advanced gas-cooled reactor (AGR) plants have been added with six more AGRs under construction. At present, hearings are under way on a proposal to introduce the pressurized water reactor (PWR) system into the UK. The United Kingdom has also aggressively pursued the development of the fast breeder reactor (FBR).

(a) From data in Reference 15, modified by the authors to fit current nuclear power forecasts in Reference 14.

The UK fuel cycle/waste management organization is quite complex: the United Kingdom Atomic Energy Authority (UKAEA) is in general responsible for nuclear research; the Department of the Environment has the charter for developing waste management strategy and for coordinating waste management R&D; British Nuclear Fuels Limited (BNFL) handles the commercial fuel cycle for the British nuclear utilities and for foreign customers; and a new organization, NIREX, attends to the disposal of LLW and ILW. These organizations are supported by a variety of regulatory, safety and research agencies. Power-generating nuclear plants are owned and operated by the Central Electricity Generating Board (CEGB), the South of Scotland Generating Board, and BNFL. The reactor operators are responsible for unloading spent fuel from the reactors, storing it at the reactor site and transporting it to the reprocessing plant at Sellafield.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe/No. of Reactors)[1,14]					
GCR (Metal fuels)	4.1/26	4.1	1.6	--	--
AGR (Oxide fuels)	2.1/4	5.8/10	8.2/14	8.2	8.2
PWR	--	--	1.2/1	2.4	5.1
Spent Fuel Arisings (tHM)[a]					
Annual					
GCR (Metal fuels)	1,200	1,200	2,500	--	--
AGR (Oxide fuels)	80	190	270	270	270
PWR	--	--	--	60	270
Cumulative					
GCR (Metal fuels)	20,000	27,000	37,000	40,000	40,000
AGR (Oxide fuels)	250	550	1,400	2,500	3,600
PWR	--	--	30	200	630

(a) Data obtained from Reference 15, modified by the authors to reflect current power station construction schedules.

Spent Fuel Management

BNFL handles spent fuel from three types of reactor: GCR, AGR and LWR. GCR fuel rods, about 2.5 cm in diameter and a meter in length, are placed in the reactor fuel channels singly. With a magnesium alloy (Magnox) cladding, they are subject to corrosion under pool storage conditions and are reprocessed as soon as possible after discharge from the reactor.[68] Fuel pins in the 36-pin AGR circular assembly (about one meter long) are comprised of UO_2 pellets clad in stainless steel. AGR cladding also has been found susceptible to corrosion in wet storage, developing leaks after only 3-4 years.

Heat output at discharge from GCR reactors ranges as high as 1 kW per fuel rod (ca 12 kgU) and drops to a maximum of 46 watts per rod after 150 days.

AGR and foreign LWR fuels are being stored until the new THORP reprocessing plant is completed (ca 1990). Waste management strategy calls for vitrification of HLW in a French-technology plant, interim storage of HLW glass for at least 50 years, and shallow-land burial or sea dumping of LLW and ILW. Authorities expect to build a repository at some time, but have decided that this is not an urgent matter for the UK.

Wet Storage of Spent Fuel

Used GCR and AGR fuel is stored in AR pools and in an AFR water storage complex at Sellafield. New water basin storage, under construction at Sellafield, has three main storage pools, each filled with water to a depth of 7 m. One pool can store up to 1,000 tU of Magnox fuel double-stacked; a second is designed for 600 tU of triple stacked AGR fuel in its original state, or 1,800 tU if consolidated; and the third pool is to be held in reserve.[69] If PWR stations are built in the UK, they are to be equipped with spent fuel storage pools that will have space for about 18 years worth of fuel arisings.

Dry Storage of GCR Fuel

The Wylfa GCR power station was designed with three vault-type dry storage modules, each with an 83 tU capacity. Fuel rods are moved directly from the reactor to storage tubes in the modules, where they are stored for at least 150 days in a CO_2 atmosphere. Removal of decay heat occurs by radiation from the fuel rod to the tube wall, conduction through the tube wall, then by natural (passive) thermosyphon air cooling. The system has worked very well since 1971: the cooling system has been completely reliable, and examination has shown the fuel to be still in pristine condition after four years.

Because of the small capacity of the original Wylfa spent fuel vaults, two additional cells (350 tU each) were built, to provide interim storage in air after the initial period (at least 150 d) in CO_2. Design criteria included:

- maximum fuel element temperatures of 150°C under normal operating conditions, 200°C under the worst credible fault conditions
- no condensation of moisture upon the fuel surface under the lowest credible temperature conditions
- moisture level less than 30,000 ppm and 50% relative humidity during normal operating conditions.

The Wylfa air-cooled store is a concrete box 60 m long, 11 m wide and 4.5 m high, with walls that are 2 m thick. Fuel is stored in skips positioned on the floor of the store, each skip comprising a matrix of blind tubes in a 12 x 16 array. Heat is removed by radiation from the fuel elements to the tube walls and by convection from the tube walls to the naturally recirculating room air and from the air to a cooling water system through heat exchangers. Part of the room air is exhausted from the store, through filters, to keep the air pressure below atmospheric.

The first of the two stores was commissioned in September 1979 and filled to capacity by September 1981. Operational experience has been very good.[70]

Dry Storage of Oxide Fuels and Vitrified HLW Canisters

CEGB and National Nuclear Corporation engineers have designed a central dry storage facility that is adaptable to AGR and LWR spent fuels and to canisters of HLW glass. The basic specifications were that it accommodate the lifetime discharge from 10 AGR reactors (7,200 tU) for a total storage period of 50 years; that it be cooled by natural convection; that the 36-pin fuel assemblies be enclosed in individual steel containers; and that the facility accept either dry or wet transport casks.

The storage vault consists of several solid concrete cells, each provided with an array of 650 cooling channels which can each hold two AGR fuel containers. The passive cooling system is designed to limit maximum fuel temperatures to 250°C. The fuel containers have an inert gas atmosphere to prevent oxidation of the UO_2 in any failed fuel rods during the period that the fuel may exceed the oxidation threshold temperature. Special precautions are taken to ensure that the fuel assemblies are dried thoroughly before the containers are sealed and that the containers are maintained at a high enough temperature, through recirculating part of the heated air, to prevent moisture condensation on their surfaces.[71]

Storage of TRU Wastes

TRU waste packages that exceed the limits permitted for sea dumping are placed in interim surface storage at the production sites.

UNITED STATES

For many years, nuclear power received widespread popular and governmental support in the United States and the US nuclear industry led the world in domestic application and foreign export of nuclear technology. Recent years have seen an erosion of popular support, cancellations of nuclear plant orders, and termination of construction projects actually in progress. In 1979, at the time of the INFCE Study,[72] the US utilities were planning to have between 255 and 295 GWe of installed nuclear power capacity by the year 2000. Today, the projection for the year 2000 (by the DOE Energy Information Administration) is for 121.8 GWe installed nuclear capacity.

US nuclear power plants are nearly all LWRs, with about 2:1 mix of PWRs versus BWRs. The country has also conducted major LMFBR and HTGR development programs.

At present, federal government nuclear power interests are administered by the Department of Energy (R&D, uranium enrichment, waste disposal), the Nuclear

Regulatory Commission (regulation and licensing) and the Environmental Protection Agency (environmental protection criteria). Commercial power generation, fuel fabrication, reprocessing and waste treatment activities are the responsibility of private industry.

Nuclear Power Projections

	1980	1985	1990	1995	2000
Capacity (GWe)[73]	50.8	77.9	110.2	114.3	114.4
Spent Fuel Arisings (tHM)[74](a)					
Annual LWR	1,149	1,904	3,238	2,995	3,110
Cumulative					
BWR	2,856	5,495	10,326	15,698	21,405
PWR	3,779	8,317	16,748	26,304	36,482

Spent Fuel Management

United States strategy for the back-end of the commercial nuclear fuel cycle is shown conceptually in Figure 10. The basic intent is to hold the fuel in storage at the reactor until the fuel can be reprocessed, immobilize the reprocessing wastes and place the HLW glass and TRU waste packages in a geologic repository. However, there is a strong possibility that commercial reprocessing service will not be available in the US when the utilities' AR storage capacity is exhausted. There is also a possibility that commercial reprocessing will not happen at all in the US--in which case, direct disposal of the irradiated fuel will be necessary. The mandate of the Nuclear Waste Policy Act (NWPA) of 1982 is to have the geologic repository available to receive immobilized HLW and/or spent fuel in 1998. If the repository is not ready in time to receive HLW or spent fuel beginning in 1998 the waste packages would be sent to a federal monitored retrievable storage (MRS) facility should Congress authorize such a facility.

The owners of nuclear power stations are expected to store their spent fuel at reactor sites until the repository or federal storage facilities are

(a) Projections of spent fuel arisings assumed 128.6 GWe installed in the year 2000, versus current estimates of 121.8 GWe.

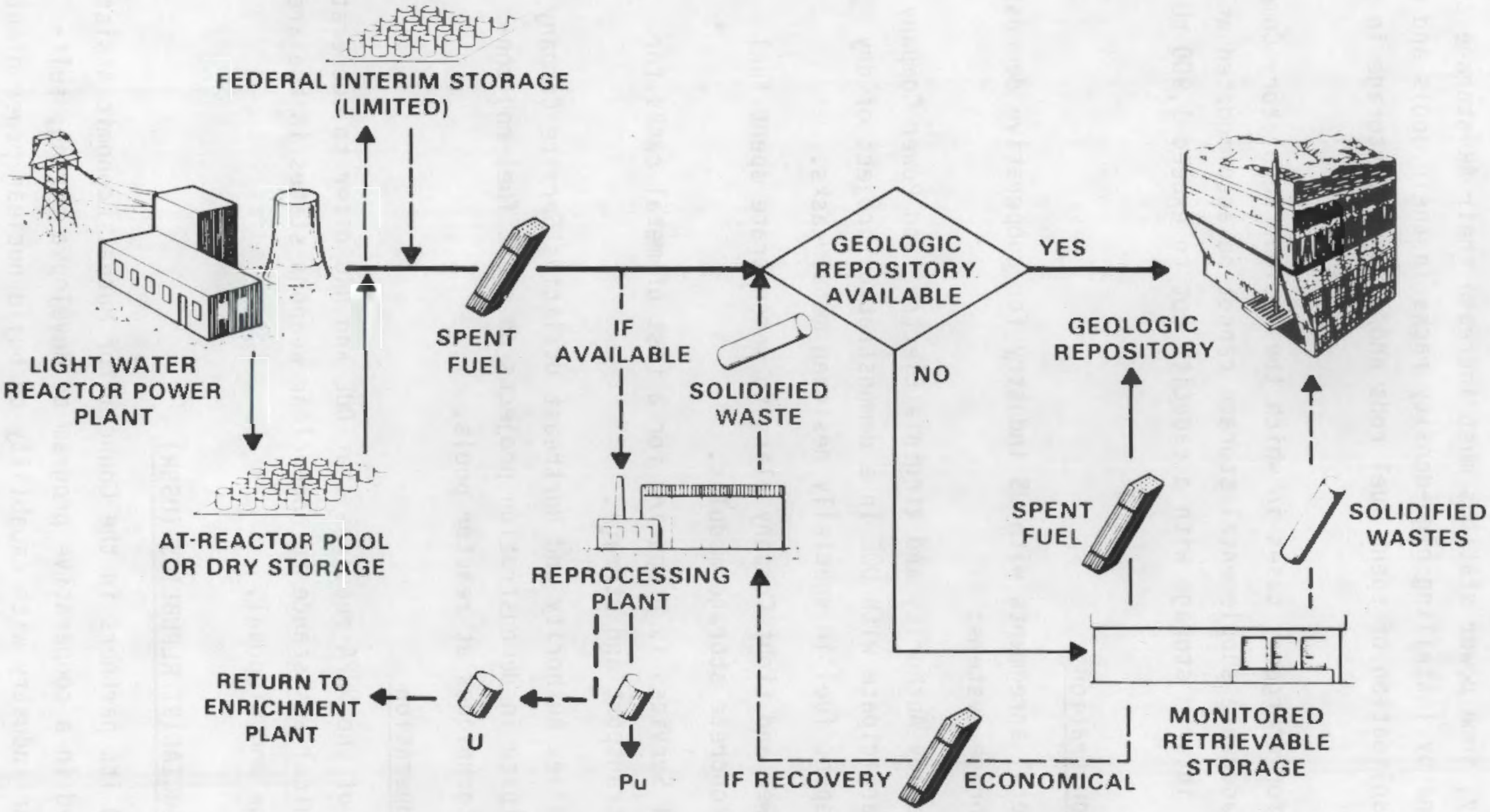


FIGURE 10. Commercial Nuclear Fuel Cycle

ready. To comply, some power stations must increase their AR storage capacity. This is being done by installing high-density racks in their pools and may be augmented by consolidation of spent fuel rods and/or by dry storage in metal casks.

To provide for emergency cases in which the Nuclear Regulatory Commission determines that adequate supplemental storage cannot be accommodated at a power station, federal interim storage with a capacity not to exceed 1,900 tU would be provided.

Fuel Storage Demonstration

DOE has several agreements with US industry for cooperative demonstrations of spent fuel storage systems:

1. Tennessee Valley Authority and Virginia Electric and Power Company will each participate with DOE in a demonstration project of dry storage of spent fuel in specially designed metal casks.
2. Carolina Power and Light Company plans to demonstrate spent fuel storage in concrete storage modules.
3. Nuclear Fuel Services is preparing for a test of metal casks for spent fuel transport and storage.
4. Tennessee Valley Authority and Northeast Utilities Service Company will participate in demonstration projects on spent fuel rod consolidation techniques at reactor pools.

International Cooperation

Section 223 of the NWPA requires that DOE and NRC offer to cooperate with and provide technical assistance to nonnuclear weapons states in the area of spent fuel storage and disposal.

UNION OF SOVIET SOCIALIST REPUBLICS (USSR)

The USSR and its partners in the Council for Mutual Economic Assistance (CMEA) have joined in a cooperative program to develop a strong, self-sufficient nuclear industry with capability to build nuclear power plants and provide complete fuel cycle services. The Soviet Union's complex of nuclear power stations includes two models of LGR (light-water cooled, graphite-moderated reactor), the early one fueled with uranium metal, and an advanced model (the RBMK) fueled with uranium oxide; PWRs of various sizes; and demonstration LMFBRs. Other CMEA nations (Bulgaria, Cuba, Czechoslovakia, East Germany, Hungary and Poland) and Finland have chosen to install Russian-developed PWRs. Rumania has turned to Canada for reactor technology and is installing a generation of HWRs.

Nuclear Power Projections

	1980	1985	1990
Capacity (GWe)(2,75)			
LGR (Metal fuels)	0.9	0.9	0.9
LGR (Oxide fuels)	8.0	16.0	31.9
PWR	3.1	8.9	39.9
Spent Fuel Arisings (tHM)[(a)]			
Annual			
LGR (Metal fuels)	50	50	50
LGR (Oxide fuels)	360	920	1,400
PWR	95	260	1,000
Cumulative			
LGR (Metal fuels)	1,000	1,200	1,500
LGR (Oxide fuels)	1,200	3,800	9,000
PWR	600	1,600	4,500

Projections of Spent Fuel Arisings--USSR Fuel Services Customers

	1980	1985	1990
Spent Fuel Arisings, USSR Customers[(b)]			
PWR (tHM)	370	1,100	2,900
Annual	100	210	420
Cumulative	390	1,295	3,140

(a) Estimated by the authors from current projections of nuclear power capacity.

(b) Estimated by the authors from current projections of nuclear power capacity.

Spent Fuel Management

The USSR controls most of the nuclear fuel cycle for the CMEA group, providing uranium enrichment, fuel fabrication and spent fuel management services for nuclear plant customers. Spent fuel is returned to Russia following interim storage at the reactor sites. Plans for the future call for construction in the Soviet Union of facilities for AFR fuel storage, reprocessing (for plutonium recycle to USSR FBRs), HLW vitrification, and geologic disposal of HLW glass canisters.

Wet Storage

Original fuel recycle plans of the Soviet Union called for spent fuel to be reprocessed three years after discharge from the reactor. However, because of delays in the construction of additional fast reactors, the interim storage period in reactor pools is being stretched out to 10 years and construction of a series of AFR storage facilities, each with capacity for the 10-year output of four 440-MWe PWRs (600 tU), is under consideration.(76,77) The fuel is stored in stainless steel baskets which hold 30 fuel assemblies each and which are also used for transport. Pool walls and floor have two metal liners, one of carbon steel and one of stainless steel.

Dry Storage

USSR authorities appear to be evaluating dry storage of spent fuel assemblies in metal casks, having purchased a Castor V transport/storage cask from GNS in Germany.(77)

The Soviet system for managing HLW provides for vitrification and interim storage of the HLW glass logs, in 200-ℓ containers, in air-cooled vertical concrete pipes.(78)

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APPENDIX A

SPENT FUEL CHARACTERISTICS, ARISINGS AND STORAGE

TABLE A-1. Spent Fuel Characteristics of Representative Reactors(1)

Country	Reactor Type	Power Station Name	Reactor Size Net, MWe	Reactor Size MWt	Fuel Rods Per Assembly	Kg HM Per Fuel Assembly	Expected Burnup, MWd/tHM	Calculated Fuel Discharge Per GWe•yr, tHM[a]
Argentina	HWR	Atucha 1	319	1,100	36	153	5,600	222
Belgium	PWR	Tihange 1	870	2,660	204	457	33,700	33
Brazil	PWR	Angra 2	1,245	3,765	236	534	34,000	33
Bulgaria	PWR	Kozloduy 2	405	1,375	126	120	28,600	46
Canada	HWR	Bruce 4	740	2,519	37	17.3	8,167	152
Czechoslovakia	PWR	Bohunice 1	380	1,375	126	135	28,600	46
Finland	PWR	Loviisa 1	440	1,375	126	120	28,600	38
	BWR	TVO 1	660	2,000	63	178	27,500	40
France	PWR	Paluel 1	1,290	3,817	264	538	33,000	33
	GCR	Chinon 3	480	1,560	1	9.4	3,500	338
Germany (FRG)	PWR	Biblis A	1,146	3,517	236	534	31,500	35
	BWR	Kruemmel KKK	1,260	3,690	63	186	27,500	39
India	BWR	Tarapur 1	200	661	36	139	23,000	55
	HWR	Kalpakkam 1	220	790		15.3	6,700	195
Italy	PWR	Trino Vercellese	260	870	208	329	25,000	49
	BWR	Caorso	875	2,651	63	186	20,000	55
	GCR	Latina	150	647	1	11.4	2,900	543
Japan	PWR	Ohi 1	1,120	3,423	264	461	29,400	37
	BWR	Hamaoka 2	814	2,436	63	188	27,500	40
	GCR	Tokai 1	159	587	1	11.4	3,300	410
	HWR	Fugen	148	557	28	152	17,000	81
Korea (South)	PWR	Kori 2	605	1,876		220	33,000	32
	HWR	Wolsung 1	629	2,180	29	18.4	7,500	170
Mexico	BWR	Laguna Verde 1	654	1,931	62	182	28,445	38
Netherlands	PWR	Borssele	452	1,366	205	310	29,000	38
	BWR	Dodewaard	51	163	36	58	22,600	51
Pakistan	HWR	Kanupp	125	433	19	15.1	7,000	180
Philippines	PWR	PNPP 1	620	1,876	235	411	33,000	34
Poland	PWR	Zarnowiec 1	465		126	135	28,600	46
South Africa	PWR	Koeberg 1	922	2,782	264	462	NA	33
Spain	PWR	Asco 1	887	2,696	264	459	33,000	34
	BWR	Valdecaballeros 1	930	2,735	62	183	25,000	42
	GCR	Vandellos 1	480	1,750		10.2	6,500	200
Sweden	PWR	Ringhals 3	915	2,783	264	460	33,000	34
	BWR	Forsmark 1	900	2,700	63	181	27,600	40

TABLE A-1. (contd)

Country	Reactor Type	Power Station Name	Reactor Size Net, MWe	Reactor Size MWt	Fuel Rods Per Assembly	Kg HM Per Fuel Assembly	Expected Burnup, MWd/tHM	Calculated Fuel Discharge Per GWe·yr, tHM(a)
Switzerland	PWR	Gösgen	920	2,806	205	403	35,000	32
	BWR	Leibstadt	942	3,012	62	183	28,500	41
Taiwan	PWR	Maanshan 1	907	2,785	264	462	50,000	22
	BWR	Kuosheng 1	940	2,894	63	189	27,500	39
UK	GCR	Oldbury 1	416	1,500	1	11.0	5,000	267
	AGR	Dungeness B1	600	1,480	36	42.8	18,000	49
USSR	LGR	Smolensk 1	1,000	3,200	NA	106	18,500	63
	PWR	Novo-Voronezh 3	440	1,375	125	120	28-30,000	38
		Novo-Voronezh 5	1,000	3,000	331	437	26-40,000	27-42
Yugoslavia	PWR	Krsko	615	1,876	235	220	33,000	33

(a) Calculated from expected burnup and, where available, published reactor efficiency data. Estimated reactor efficiencies were used when published data were not at hand.

TABLE A-2. Nuclear Power and Spent Fuel Arisings

Country	Reactor Type[a]	First Commercial Power Plant (MWe)	Projections for Year 2000: Nuclear Power Capacity,[a] GWe	Spent Fuel Arisings, tHM[b]: Annual	Spent Fuel Arisings, tHM[b]: Cumulative
Argentina	HWR	1974 (344)	3.7	650	5,800
Belgium	PWR	1975 (393)	8.0	220	3,000
Brazil	PWR	1982 (626)	4.4	120	1,000
Bulgaria	PWR	1974 (440)	7.8	200	2,500
Canada	HWR	1968 (206)	14.9	2,400	38,000
China	PWR	1987 (300)	10	270	1,300
Cuba	PWR	1987 (440)	1.8	50	420
Czechoslovakia	PWR	1978 (440)	11-14(79)	350	3,800
Egypt	PWR	1990 (900)	2.7	70	360
Finland	LWR	1977 (420)	3.2	100	1,400
France	GCR	1959 (40)	--	--	15,000[c]
	PWR	1967 (305)	60	1,500	22,000
	FBR	1973 (233)	1.5		
Germany-East	PWR	1966 (80)	9	270	2,100
Germany-West	LWR	1968 (328)	28	700	11,000
	HTGR	1985 (296)	0.3		
	FBR	1987 (280)	0.3		
Hungary	PWR	1983 (440)	4.8(80)	150	1,400
India	BWR	1969 (200)	0.4	18	600
	HWR	1973 (202)	4.0	560	4,400
Israel	LWR	1994 (900)	4.6	110	400
Italy	GCR	1964 (150)	--	--	1,700[c]
	LWR	1965 (260)	6.7	240	2,000
Japan	GCR	1966 (159)	--	--	1,500
	LWR	1970 (341)	50	1,400	20,000
	HWR	1979 (149)	0.15		
	FBR	1990 (280)	0.28		
Korea (South)	PWR	1978 (556)	10.5	310	3,200
	HWR	1983 (629)	0.6	70	1,200

TABLE A-2. (contd)

Country	Reactor Type[a]	First Commercial Power Plant (MWe)	Projections for Year 2000: Nuclear Power Capacity,[a] GWe	Spent Fuel Arisings, tHM[b]: Annual	Spent Fuel Arisings, tHM[b]: Cumulative
Mexico	PWR	1986 (654)	1.3	40	500
Netherlands	LWR	1969 (58)	0.5	16	420
Pakistan	HWR	1972 (125)	0.13	12	290
	LWR	1990 (1,000)	1.0	30	150
Phillippines	PWR	1985 (620)	1.2	32	270
Poland	PWR	1989 (465)	5.9	175	1,000
Romania	PWR	1983 (440)	0.44	13	220
	HWR	1986 (700)	6.6[81]	750	8,000
South Africa	PWR	1984 (922)	3.8	115	1,200
Spain	GCR	1972 (480)	0.48	60	1,740[c]
	LWR	1968 (160)	9.7	260	3,400
Sweden	LWR	1972 (440)	9.4	260	5,000
Switzerland	LWR	1969 (350)	3.4	140	2,000
Taiwan	LWR	1978 (606)	8.7	260	2,600
UK	GCR	1956 (50)	--	--	35,000[c]
	AGR	1976 (520)	8.2	220	3,600
	PWR		5.1	140	630
	FBR	1975 (250)	0.25		
USA[d]	LWR	1957 (60)	117	3,600	58,000
USSR	LGR	1958 (100)	0.9	50	1,500[c]
	Advanced LGR	1973 (1,000)	17.0	720	7,400
	PWR	1964 (210)	23.9	640	3,700
Yugoslavia	PWR	1981 (632)	2.6	70	420

(a) Unless otherwise indicated, nuclear power forecasts were obtained from References 14 and 66.

(b) Projections of foreign spent fuel arisings were based on data in Reference 15, modified by PNL to fit current forecasts of nuclear power capacity.

(c) The cumulative values for arisings of GCR and LGR (uranium metal) spent fuels do not represent inventories, since this type of fuel is usually reprocessed soon after its discharge from the reactor.

(d) The projections of US capacity were taken from Reference 74.

TABLE A-3. Spent Fuel/HLW Storage

Country	Fuel Type	Wet Storage of Spent Fuel	Spent fuel	HLW Glass
Argentina	HWR	AR pool storage pending transfer to FRP[a]	R&D/AFR design	
Belgium	PWR	AR pool storage pending transfer to FRP		
Brazil	PWR	AR pool storage pending shipment to USSR		
Bulgaria	PWR	AR & AFR pool storage pending transfer to USSR		
Canada	HWR	AR pool storage pending transfer to FRP or repository	Concrete silo R&D and full-scale tests; convective vault evaluation	
Czechoslovakia	PWR	AR pool storage pending transfer to USSR; a 600 t (pool) ISFSF to be provided at each power plant site		
Finland	PWR	AR pool storage pending transfer to USSR		
	BWR	AR & auxiliary pool storage pending final disposition	Concept evaluation	

(a) FRP - fuel reprocessing plant.

TABLE A-3. (contd)

Country	Fuel Type	Wet Storage of Spent Fuel	Spent fuel	HLW Glass
France	GCR, PWR	Pool storage AR and AFR (8000 tU at La Hague) pending reprocessing		Vault storage of HLW glass at Marcoule since 1978
	FBR	Short-term storage in sodium	Vault storage at Marcoule	
Germany (FRG)	LWR	AR pool storage pending transfer to AFR or FRP	Dry cask storage at Gorleben AFR (1984) and Ahaus AFR	R&D/design of air-cooled storage vault
Hungary	PWR	AR & auxiliary pool storage pending transfer to USSR		
India	BWR, HTR	AR pool storage pending transfer to FRP	Evaluation of vault/cask concepts	Air-cooled vault to be commissioned in 1984
Italy	LWR, GCR	AR pool storage pending transfer to dry storage or FRP		Modular surface facility designed in 1978
Japan	LWR, GCR, HWR	AR pool storage pending transfer to FRP	Passive-circulation vault for test reactor fuels (1983)	R&D/design of air-cooled storage vault; scale-model tests
Korea (ROK)	LWR	AR pool storage pending transfer to FRP or AFR		
Mexico	BWR	AR pool storage pending disposition	R&D	
Netherlands	BWR, PWR	AR pool storage pending transfer to FRP		

TABLE A-3. (contd)

Country	Fuel Type	Wet Storage of Spent Fuel	Spent fuel	HLW Glass
Pakistan	HWR	AR pool storage pending transfer to FRP		
South Africa	PWR	AR pool storage pending transfer to repository		
Spain	GCR	AR pool storage pending transfer to FRP		
	BWR, PWR	AR pool storage pending transfer to AFR at repository site	R&D: development of dry cask for AFR	
Sweden	BWR, PWR	AR pool storage pending transfer to FRP or pool-type AFR (CLAB, 1985)		
Switzerland	BWR, PWR	AR pool storage pending transfer to FRP or AFR	Castor cask storage of test reactor fuel; concept developed for dry cask AFR for spent fuel & HLW. R&D/ Modrex vault concept	
Taiwan	BWR, PWR	AR pool storage pending final disposition	Evaluation of techniques	
United Kingdom	GCR, AGR	AR pool storage pending transfer to FRP	Vault storage of GCR fuels at Wylfa	Vault storage to be installed at vitrification plant at Sellafield

TABLE A-3. (contd)

Country	Fuel Type	Wet Storage of Spent Fuel	Spent fuel	HLW Glass
USA	LWR, HTR	AR pool storage pending transfer to FRP, repository, or MRS	Evaluation of metal storage casks	
U.S.S.R.	LGR, PWR	AR pool storage pending transfer to FRP or AFR; a 600 t (pool) technology widely used	Evaluating Castor cask	R&D/ engineered surface storage

TABLE A-4. Waste Disposal

Country	Wastes to Be Accepted By Repository	Minimum Cooling Time Before Emplacement	Repository Host Rock	Earliest Date for Repository Operation
Argentina	HLW, TRU	NA[(a)]	Cryst. rock	NA
Belgium	HLW, TRU	50 yr	Plastic clay	TBD[(a)]
Canada	Fuel or HLW, TRU	50 yr	Cryst. rock	2010
Denmark[(b)]		40 yr	Salt	2040
Finland	Fuel or HLW, TRU	40 yr	Cryst. rock	2020
France	HLW, TRU	TBD	TBD (clay, salt)	TBD
Germany (FRG)	HLW, TRU (& fuel?)	30 yr	Salt	2000
India	HLW, TRU	30 yr	Cryst. rock	NA
Italy	HLW, TRU	50 yr	TBD (clay, cryst. rock)	NA
Japan	HLW, TRU	30 yr	TBD (argil-lite, cryst. rock)	2020
Netherlands	HLW, TRU	TBD	Salt	TBD
Spain	Fuel	10 yr	TBD (salt, cryst. rock)	TBD
Sweden	HLW, TRU (& fuel?)	30 yr	Cryst. rock	2020
Switzerland	HLW, TRU (& fuel?)	35 yr	Cryst. rock	2020
United Kingdom	HLW, TRU	>50 yr	TBD (salt, cryst. rock)	2040
USA	HLW, TRU (& fuel?)		Salt, cryst. rock	1998
U.S.S.R.	HLW, TRU	NA	TBD (salt, cryst. rock)	NA

(a) NA - information not available; TBD - to be determined.
(b) The Danish utilities have produced a waste disposal plan in case they are allowed to build a nuclear power plant.

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