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Design Analysis Cover Sheet

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9. Lead Design Engineer	Peter Gottlieb	Peter Gottlieb	9/15/97
10. Department Manager	Hugh A. Benton	[signature] FOR H.A. BENTON	9/15/97

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Table of Contents

1. Purpose

The purpose of this analysis is to evaluate the transient behavior and consequences of a worst case criticality event involving intact pressurized water reactor (PWR) spent nuclear fuel (SNF) in a degraded basket configuration inside a 21 PWR assembly waste package (WP). The objective of this analysis is to demonstrate that the consequences of a worst case criticality event involving intact PWR SNF are insignificant in their effect on the overall radioisotopic inventory in a WP.

2. Quality Assurance

The Quality Assurance (QA) program applies to this analysis. The work reported in this document is part of the preliminary waste package (WP) design analysis that will eventually support the License Application Design phase. This activity, when appropriately confirmed, can impact the proper functioning of the Mined Geologic Disposal System (MGDS) waste package; the waste package has been identified as an MGDS Q-List item important to safety and waste isolation (Ref. 5.1, pp. 4, 15). The waste package is on the Q-List by direct inclusion by the Department of Energy (DOE), without conducting a QAP-2-3 *Classification of Permanent Items* evaluation. The responsible manager for the Waste Package Development Department has evaluated this activity in accordance with QAP-2-0, *Conduct of Activities*. The *Perform Criticality, Thermal, Structural, and Shielding Analyses* (Ref. 5.2) activity evaluation has determined that work associated with the commercial SNF waste package design task is subject to *Quality Assurance Requirements and Description* (QARD) (Ref. 5.3) requirements. As specified in NLP-3-18, *Documentation of QA Controls on Drawings, Specifications, Design Analyses, and Technical Documents*, this activity is subject to QA controls.

Design inputs which are identified in this document are for the preliminary stage of the WP design process; all of these design inputs will require subsequent confirmation (or superseding inputs) as the waste package design proceeds. Consequently, use of any data from this analysis for input into documents supporting construction, fabrication, or procurement is required to be controlled as "to be verified" (TBV) in accordance with the appropriate procedures.

3. Method

An internal WP criticality is modeled in a manner analogous to transient phenomena in a nuclear reactor core. The light water reactor (LWR) transient analysis code, RELAP5/MOD3 (Ref. 5.4), is used to calculate the time evolution of the power level and other characteristics of a criticality involving PWR SNF. Reactivity tables based on changes in k_{eff} from a baseline configuration must be included in the RELAP5 input. The Monte Carlo N-Particle computer program, MCNP4A (Ref. 5.5), is used to calculate a baseline k_{eff} for criticality safety evaluations and to determine the change in reactivity from one configuration to another. MCNP4A does not have an associated cross section library with sufficient temperature dependent data to calculate the reactivity changes associated with fuel and moderator temperature changes required for this analysis. The SAS2H sequence of SCALE4.3 (Ref. 5.10) does have the necessary cross sections. SAS2H employs a one-dimensional (1-D) assembly-cell discrete-ordinates technique (XSDRNPM) for calculation of the multiplication factor (k_{eff}) for a configuration. A correction for finite dimensions can be made through use of various buckling terms. Initially, infinite MCNP cases were run with which to compare the results from infinite SAS2H cases in order to develop the appropriate SAS2H model to match MCNP results. Corrections were then made to the SAS2H model to account for finite dimensions using the appropriate buckling terms for inclusion in the models based on the baseline MCNP finite case. The resulting SAS2H model incorporating the buckling terms is then used for calculating temperature and density reactivity effects. The reactivity changes calculated by MCNP4A and SAS2H are used as input to RELAP5 to track the transient behavior of a criticality. The ORIGEN-S program in the SCALE4.3 code package is used to calculate the changes to the radioisotopic inventory as a result of the analyzed criticality events.

4. Design Inputs

4.1 Design Parameters

4.1.1 Spent Fuel Assembly Parameters

The fuel assembly which this calculation is based upon is the B&W 15X15 fuel assembly. The mechanical parameters for this assembly type are shown in Table 4.1-1. Note that inches are converted to centimeters exactly (2.54 cm/in.); this is not an indication of tolerance (accuracy), but is done for consistency between calculations using English and metric units. The theoretical density of natural UO_2 is 10.96 g/cm^3 (Ref. 5.10, Table M8.2.1). This information represents B&W fuel assembly dimensions prior to irradiation and is considered qualified data.

Table 4.1-1. Mechanical Parameters of B&W 15X15 Fuel Assembly

Parameter	Value	Units	Metric	Units	Radius (cm)	Reference
Fuel Rods	208	/assbly	208	/assbly	-	5.7, p. 2.1.2.2-6
Fuel Rods on a Lattice Side	15	/side	15	/side	-	5.7, p. 2.1.2.2-6
Guide Tubes	16	/assbly	16	/assbly	-	5.7, p. 2.1.2.2-6
Instrumentation Tubes	1	/assbly	1	/assbly	-	5.7, p. 2.1.2.2-6
Total Guide + Instrument Tubes	17	/assbly	17	/assbly	-	-
Clad/Tube Material	Zirc-4		Zirc-4		-	5.7, p. 2.1.2.2-6
Fuel Pellet OD	0.3686	inches	0.936244	cm	0.468122	5.7, p. 2.1.2.2-6
Fuel Stack Height	141.8	inches	360.172	cm	-	5.7, p. 2.1.2.2-6
Fuel Assembly Height	165.625	inches	420.6875	cm	-	5.8, p. 2A-8
Mass of U	1023	lb	464	kg	-	5.8, p. 2A-8
Mass of UO_2	1160.64	lb	526.38	kg	-	5.7, p. 2.1.2.2-6

Table 4.1-1. Mechanical Parameters of B&W 15X15 Fuel Assembly

Parameter	Value	Units	Metric	Units	Radius (cm)	Reference
Percent of Theoretical Density	95	%	95	%	-	5.7, p. 2.1.2.2-6
Fuel Clad OD	0.430	inches	1.0922	cm	0.5461	5.7, p. 2.1.2.2-6
Clad Thickness	0.0265	inches	0.06731	cm	-	5.7, p. 2.1.2.2-6
Fuel Clad ID*	0.377	inches	0.95758	cm	0.47879	-
Fuel Rod Pitch	0.568	inches	1.44272	cm	-	5.7, p. 2.1.2.2-6
Guide Tube OD	0.530	inches	1.3462	cm	0.6731	5.7, p. 2.1.2.2-6
Guide Tube Thickness	0.016	inches	0.04064	cm	-	5.7, p. 2.1.2.2-6
Guide Tube ID*	0.498	inches	1.26492	cm	0.63246	-
Instrumentation Tube OD	0.493	inches	1.25222	cm	0.62611	5.7, p. 2.1.2.2-6
Fuel Assembly Envelope	8.536	inches	21.68144	cm	-	5.7, p. 2.1.2.2-6
Displaced Volume per Fuel Assembly	4927	$inches^3$	0.081	m^3	-	5.9, p. II-3.6-98

* The inner diameters (IDs) above are calculated by subtracting 2 × thickness from the outer diameter (OD).

4.1.2 Intact Waste Package Geometry Parameters

The intact waste package geometry parameters used for this analysis are listed in Table 4.1-2 below. These are considered unqualified TBV information, as other WPD QAP-3-9 analyses being performed in parallel may result in design changes not reflected in these parameter values. Minor dimensional revisions from the listed values, if incorporated in the computational models used in this analysis, will have an insignificant effect on results from this analysis.

Table 4.1-2. Intact WP Dimensions

Component	Dimension	Reference
Outer barrier length (skirt edge to skirt edge)	533.5 cm	5.11, p. I-18
Outer barrier skirt length (both ends)	22.5 cm	5.11, p. I-18
Outer barrier lid thickness	11.0 cm	5.11, p. I-18
Outer barrier inner radii	73.1 cm	5.12, p. 8
Outer barrier outer radii	83.1 cm	5.12, p. 8
Gap between inner and outer lids	3.0 cm	5.11, pp. I-18 & I-19
Inner barrier length (overall)	463.5 cm	5.11, p. I-19
Inner barrier lid thickness	2.5 cm	5.11, p. I-19
Inner barrier inner radii	71.095 cm	5.12, p. 8
Inner barrier outer radii	73.095 cm	5.12, p. 8
Fuel cell tube thickness	0.5 cm	5.11, p. I-21
Fuel cell tube height	457.5 cm	5.11, p. I-21
Fuel cell tube outside width	23.64 cm	5.11, p. I-21

Table 4.1-2. Intact WP Dimensions

Component	Dimension	Reference
Total displaced volume of single fuel cell tube	0.02117 m^3	5.11, p. VI-1
Criticality control plate thickness	0.7 cm	5.11, pp. I-29 to I-31
Criticality control plate height	113.38 cm	5.11, p. I-20
Total displaced volume of all criticality control plates	0.243 m^3	5.11, p. VI-1
Total displaced volume of guides and supports	0.259 m^3	5.11, p. VI-1

4.1.3 Material Properties

The atom densities for the SNF used are taken from a previous criticality analysis (Ref. 5.13, case r58h13f). Case r58h13f is the reference condition on which reactivity calculations are made and the RELAP5 cases are developed. The input for this case is included in Attachment I.

Table 4.1-3. Atom Densities for 4.9% Enriched B&W 15X15 SNF with 34 GWd/MTU and 25,000 Years Burnup (Ref. 5.13)

Isotope ID	Number Density
8016.50C	0.046947
42095.50C	4.794679E-05
44101.50C	4.354501E-05
43099.50C	4.284296E-05
45103.50C	2.608717E-05
47109.50C	3.714096E-06
60143.50C	3.74851E-05
60145.50C	2.799527E-05
62147.50C	1.138963E-05
62149.50C	1.455085E-07
62150.50C	1.043884E-05
62152.50C	4.59594E-06
63151.55C	8.136066E-07
63153.55C	3.93607E-06
64155.50C	1.686186E-07
92233.50C	3.326725E-07
92234.50C	1.018437E-05
92235.50C	5.531404E-04
92236.50C	1.774777E-04
92238.50C	2.174501E-02
93237.55C	4.392789E-05
94239.55C	7.906197E-05
94240.50C	3.440139E-06
94241.50C	2.761636E-12
94242.50C	7.012276E-06
95241.50C	8.639479E-11
95243.50C	1.386765E-07

4.2 Criteria

Requirements identified as TBD in the *Engineered Barrier Design Requirements Document* (EBDRD; Ref. 5.7) will not be carried to the conclusions of this analysis based on the rationale that the conclusions are for preliminary design, and will not be used as input in design documents supporting construction, fabrication, or procurement.

The criterion for this analysis is:

- The Engineered Barrier System shall be designed such that the probability and consequences of nuclear criticality provide reasonable assurances that the preformance objective of 10CFR60.112 is met [EBDRD 3.7.1.3.A, 3.3.1.G].

In addition, EBDRD 3.3.1.G indicates that "The Engineered Barrier Segment design shall meet all relevant requirements imposed by 10CFR60." The NRC has recently revised several parts of 10CFR60 which relate to the identification and analysis of design basis events (Ref. 5.9) including the criticality control requirement, which was moved to 60.131(h). These changes are not reflected in the current versions of the EBDRD or the CDA. The change to the criticality requirement simply replaces the phrase "criticality safety under normal and accident conditions" with "criticality safety assuming design basis events."

The criterion for this analysis, together with the wording in the current 10CFR60.131(h) can be summarized as: (1) Demonstration of the prevention of criticality, (2) Demonstration that the consequences of criticality (even if one did occur) are insignificant. This analysis is part of a continuing sequence which individually contribute to satisfying the second of these criteria in the following manner:

- The consequences of a criticality, particularly the increase in radionuclide inventory and transient overpressure and temperature, are shown to be insignificant under the range of conditions considered thus far.

- The severity of consequence (particularly increase in radionuclide inventory) will be used as input to the Total System Performance Assessment (TSPA) - Viability Assessment (VA) which, in turn, will demonstrate compliance with the performance objective of §60.112 (as specified in CDA Key assumption 60).

4.3 Assumptions

4.3.1 It is assumed that the nuclear reactor type model of a WP developed for RELAP5/MOD3 is an appropriate approximation to the criticality processes involving PWR SNF inside a waste package (TBV). The basis for this assumption is as follows:

RELAP5/MOD3 was developed for the U.S. Nuclear Regulatory Commission for simulations of transient phenomena in PWR systems such as loss of coolant (Ref. 5.4). The physical processes involving material behavior of PWR SNF within a waste package during a criticality event are similar to the situations for which RELAP5/MOD3 was developed to analyze. There is reasonable confidence in the capability of RELAP5/MOD3 to provide conservative results for the applications within this analysis.

Inherent in the assumption that RELAP5 provides an appropriate approximation for WP criticality events is also the assumption that the time dependent neutron population in the WP fuel assemblies can be represented by the point kinetics model. The basis for this assumption is the compact size of the fuel assembly array making the system tightly coupled neutronicly and preventing any spatially localized phase differences in the neutron amplitude.

This assumption is used in Sections 7.4 and 7.5.

4.3.2 It is assumed that the reactivity feedback mechanism for the point kinetics model can be represented by separable effects (TBV). The bases for this assumption are as follows:

(1) Doppler reactivity depends upon intrinsic fuel parameters with temperature being the only time dependent variable,

(2) moderator reactivity effects depend only upon the fluid density,

(3) no soluble poisons are modeled, and

(4) the settled iron oxide residue is not redistributed in the WP.

This assumption is used throughout Section 7.

4.3.3 The waste package is assumed to be filled with water at the start of the postulated reactivity driven scenarios. The basis for this assumption is that it is conservative and is developed as a scenario in previous probabilistic analyses (Ref. 5.18). This assumption is used in Sections 7.2, 7.3, and 7.4.

4.3.4 CDA assumption EBDRD 3.7.1.3.A has been used to replace TBVs in requirements applicable to this document. The bases for these assumptions are given in the CDA (Ref. 5.15). These assumptions are used in Section 4.2.

4.3.5 Water inflow to the degraded WP is assumed to be 20 m^3/year at ambient drift space conditions. The basis for this assumption is that this is the largest design basis flow rate for long term periods (300-20,000 years after emplacement) given by CDA Assumption TDSS

026. Climate models suggest that the long term infiltration rate could possibly increase by as much as a factor of 10. This assumption is used throughout Section 7.

4.3.6 The most reactive SNF disposed of in the absorber rod WPs have been excluded from consideration in this analysis since the absorber rod WP design will take credit for the long term presence of neutron absorber control rods (CDA Key 081).

4.4 Codes and Standards

Not Applicable. Neutronic design of the waste package is not controlled by codes and standards.

5. References

5.1 *Yucca Mountain Site Characterization Project Q-List*, YMP/90-55Q, REV 4, Yucca Mountain Site Characterization Project.

5.2 *QAP-2-0 Activity Evaluations*, ID No. WP-20, Perform Criticality, Thermal, Structural, and Shielding Analyses, Dated 8/3/97, Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O).

5.3 *Quality Assurance Requirements and Description*, DOE/RW-0333P REV 7, U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM).

5.4 *RELAP5/MOD3 Code Manual*, NUREG/CR-5535, INEL-95/0174, Prepared by Idaho National Engineering Laboratory for the U.S. Nuclear Regulatory Commission, August 1995.

5.5 *Software Qualification Report for MCNP4A*, CSCI: 30006 V4A, Document Identifier Number (DI#): 30006-2003 REV 02, CRWMS M&O.

5.6 *Software Qualification Report for The SCALE Modular Code System Version 4.3*, CSCI: 30011 V4.3, DI#: 30011-2002 REV 01, CRWMS M&O.

5.7 *Preliminary Waste Form Characteristics Report Version 1.0*, UCRL-ID-108314 Rev 1, Lawrence Livermore National Laboratory, December 1994.

5.8 *Characteristics of Potential Repository Wastes,* DOE/RW-0184-R1, Volume 1, US DOE OCRWM, July 1992.

5.9 *Final Design Package - Babcock & Wilcox BR-100 - 100 Ton Rail/Barge Spent Fuel Shipping Cask*, Document No. 51-1203400-01, B&W Fuel Company, November 1991.

5.10 *SCALE 4.3,* RSIC Computer Code Collection, CCC-545, Oak Ridge National Laboratory, October 1995.

5.11 *Waste Package Design Basis Events*, DI#: BBA000000-01717-0200-00037 REV 00, CRWMS M&O.

5.12 *Probabilistic Criticality Consequence Evaluation*, DI#: BBA000000-01717-0200-00021 REV 00, CRWMS M&O.

5.13 *Criticality Evaluation of Degraded Internal Configurations for the PWR AUCF WP Designs*, DI#: BBA000000-01717-0200-00056 REV 00, CRWMS M&O.

5.14 *Engineered Barrier Design Requirements Document*, YMP/CM-0024, REV 0, ICN 1, Yucca Mountain Site Characterization Project.

5.15 *Controlled Design Assumptions Document*, DI#: B00000000-01717-4600-00032 REV 04, ICN 02, CRWMS M&O.

5.16 *10 CFR Part 60; Disposal of High-Level Radioactive Wastes in Geologic repositories; Design Basis Events; Final Rule,* U.S. Nuclear Regulatory Commission, Federal Register, volume 61, Number 234, pp. 64257-64270, December 4, 1996.

5.17 Jensen, Peter J., et al, *Anticipated Transients Without Scram Analysis for the River Bend Station*, Proceedings: Fourth International RETRAN Conference, EPRI NP-4558-SR, p. 23-1, May 1986.

5.18 *Second Waste Package Probabilistic Criticality Analysis: Generation and Evaluation of Internal Criticality Configurations*, DI#: BBA000000-01717-0200-00005 REV 00, CRWMS M&O.

5.19 *Determination of WP Design Configurations*, DI#: BBAA00000-01717-0200-00017 REV 00, CRWMS M&O.

5.20 Duderstadt, James J., Hamilton, Louis J., *Nuclear Reactor Analysis*, John Wiley & Sons, New York, 1976.

5.21 *Third Waste Package Probabilistic Criticality Analysis: Methodology for Basket Degradation with Application to Commercial Spent Nuclear Fuel*, DI#: BBA000000-01717-0200-00049 REV 00, CRWMS M&O.

5.22 *Electronic Attachments for: BBA000000-01717-0200-00057 REV 00, Criticality Consequence Analysis Involving Intact PWR SNF in a Degraded 21 PWR Assembly Waste Package*, Colorado Backup Tape, RPC Batch Number MOY-970904-01, CRWMS M&O.

5.23 *Final Safety Analysis Report Three Mile Island Nuclear Station - Unit 1*, TMI-1/FSAR, April, 1996.

5.24 Idelchik, I. E, *Handbook of Hydraulic Resistance,* The State Scientific Research Institute for Industrial and Sanitary Gas Purification, Second Edition, Moscow, Russia.

6. Use of Computer Software

The calculation of nuclear reactivity of PWR SNF configurations was performed with the MCNP4A computer code, CSCI: 30006 V4A. MCNP4A calculates k_{eff} for a variety of geometric configurations with neutron cross sections for elements and isotopes described in the Evaluated Nuclear Data File version B-V (ENDF-B/V). MCNP4A is appropriate for the fuel geometries and materials required for these analyses. The calculations using the MCNP4A software were executed on Hewlett-Packard (HP) workstations. The software qualification of the MCNP4A software, including problems related to calculation of k_{eff} for fissile systems, is summarized in the Software Qualification Report for the Monte Carlo N-Particle code (Ref. 5.5). The MCNP4A evaluations performed for this design are fully within the range of the validation for the MCNP4A software used. Access to and use of the MCNP4A software for this analysis was granted by Software Configuration Management and performed in accordance with the QAP-SI series procedures. Inputs and outputs for the MCNP4A software are included as attachments (see Tables 9-1 and 9-2) as described in the following design analysis.

The calculation of nuclear reactivity of PWR SNF configurations was also performed with the SAS2H code sequence, which is a part of the SCALE 4.3 code system, CSCI: 30011 V4.3. SAS2H is designed for spent fuel depletion and reactivity calculations to determine spent fuel isotopic content. Thus, SAS2H and ORIGEN-S are appropriate for the fuel geometries and materials required for these analyses. The calculations using the SCALE4.3 software were executed on HP workstations. The software qualification of the SCALE4.3 software, including benchmark problems related to generation of isotope contents, is summarized in the Software Qualification Report for the SCALE Modular Code system (Ref. 5.6). The SAS2H evaluations performed for this design are fully within the range of the validation for the SAS2H software used. The associated 44GROUP cross section library was used for these calculations. Access to and use of the SAS2H software for this analysis was granted by Software Configuration Management and performed in accordance with the QAP-SI series procedures. Inputs and outputs for the SAS2H and ORIGEN-S are included as attachments (see Tables 9-1 and 9-2).

The transient simulation of criticality events is performed using RELAP5/MOD3. RELAP5/MOD3 has been installed on HP workstations and the 10 installation test cases (ans79.p, edhtrk.p, edhtrkd.p, edhtrkn.p, edrst.p, edstrip.p marpzd4.p pump2.p, typpwr.p, typpwrn.p) have been run successfully. These installation test cases are included on tape (Ref. 5.22). RELAP5/MOD3 has not been qualified according the QAP-SI-0. RELAP5/MOD3 was developed for the U.S. Nuclear Regulatory Commission for simulations of operational transients in PWR systems such as loss of coolant. The criticality events involving PWR SNF within a waste package are similar to the situations for which RELAP5/MOD3 was developed to analyze. There is reasonable confidence in the capability of RELAP5/MOD3 to provide conservative results for the applications within this analysis (TBV).

7. Design Analysis

7.1 Background

For postclosure, the low probability and consequences of a criticality must provide reasonable assurance that the performance objective of 10CFR60.112 is met. This analysis contributes to satisfying the above requirements for postclosure by determining the consequences of a criticality for PWR SNF within a waste package as measured by the effect on the repository and on the radioisotopic inventory. The probability of criticality events is addressed in a separate analysis.

In a probabilistic analysis (Ref. 5.21, Sections 4.1.2 and 4.1.3) it has been shown that the corrosion rate of the zircaloy cladding of the SNF is much slower than the corrosion rates of the two principal materials which make up the basket (carbon steel and borated stainless steel). Therefore, the basket materials will degrade while the SNF is still mostly intact. What is not known is the exact disposition of the basket material after it has degraded. The iron oxide is very insoluble and will tend to precipitate, but the distribution of the precipitate could range from: (1) collecting equally on all the available surfaces, to (2) settling into the configuration with the lowest gravitational energy, limited only by the maximum density of hydrated iron oxide. The parameters for these two alternatives, called the uniform and settled distributions, respectively, are described in some detail in a previous analysis (Ref. 5.13).

The uniform distribution means that the iron oxide is distributed throughout the waste package wherever there is water. The settled distribution has two different manifestations, depending on whether the basket is partially degraded or fully degraded. The settled distribution for the partial basket will fill the lower portion of each assembly cell with 1/21 of the total oxide formed thus far from the degradation of the carbon steel in the assembly tube basket structure and from the degradation of the borated stainless steel, but not from the carbon steel guides and supports. For the fully degraded basket, the settled distribution will fill the lower portion of the waste package with all of the iron oxide from the complete degradation of the basket, so that some of the assemblies are completely covered by iron oxide while others see no iron oxide at all. These two alternative configurations are described more fully in reference 5.13.

The design basis WP system configuration for 100% coverage of the projected PWR waste stream (Ref. 5.19, Table 8-1) includes five different types of PWR WPs. These types are identified as:

(1) 21 PWR no absorber WP,

(2) 21 PWR absorber plate WP,

(3) 21 PWR absorber rod WP,

(4) 12 PWR no absorber WP, and

(5) long 12 PWR absorber plate WP for South Texas fuel.

A previous analysis (Ref. 5.13) investigated the effects on k_{eff} of fuel burnup, enrichment, and decay time, as well as degradation of basket components. The most reactive fuel/WP configuration combination identified was in the 21 PWR absorber plate WP. The fuel designated for disposal in the no absorber plate WP is purposefully of very low reactivity and is subcritical in all configurations. The absorber rod WPs are precluded from criticality even with the otherwise very reactive fuel. The analysis of the absorber plate WP identified the most reactive SNF as ones having the following characteristics:

(1) an enrichment of 4.9%,

(2) a burnup of 34 GWd/MTU, and

(3) a flooded fuel-clad gap.

(Note that as a result of the analysis, the fuels designated for disposal with absorber rods could be adjusted to include all the fuel which can go critical in the absorber plate WP, thereby eliminating these critical configurations from consideration.) The most reactive configuration occurs with the basket fully degraded, the boron removed, the PWR assemblies are stacked together, and the iron oxide from the basket materials has accumulated at its highest reasonable density of 58% leaving one and a half rows of assemblies at the top of the stack in water alone free of oxidation products. This configuration is illustrated in Figure 7.1-1.

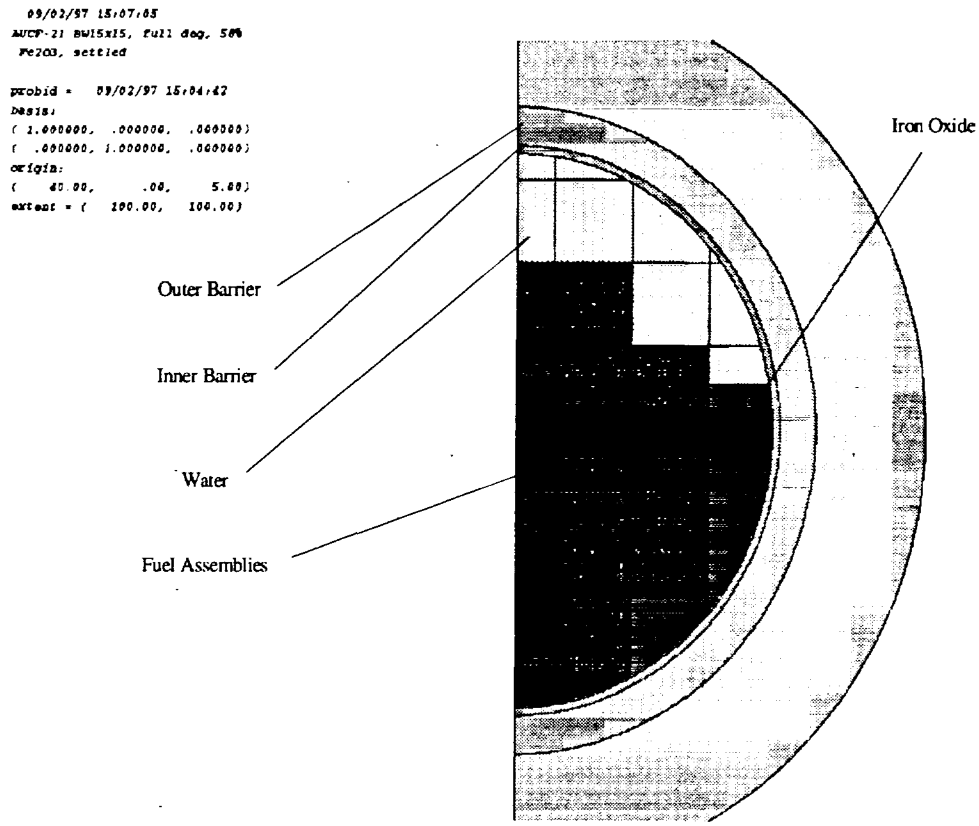

Figure 7.1-1. Base Configuration for Analysis of Stratified Degraded Waste Package

7.2 Neutronics Calculations and Reactivity Coefficients

The effects on reactivity due to changes in the system are shown to be separable into leakage effects and material effects in this section. Leakage effects are primarily dependant on boundary conditions such as water level in the waste package and must be calculated using finite waste package models. Material effects such as changes to fuel temperature, moderator temperature, or moderator density are primarily localized and can be approximated using infinite assembly models with a constant buckling (leakage) term.

Reactivity is defined as (Ref. 5.20, p. 222):

$$\rho = \frac{k_{eff} - 1.0}{k_{eff}}$$

and a change in reactivity ($\Delta\rho$) is defined as (Ref. 5.20, p. 222):

$$\Delta\rho = \rho_{Change} - \rho_{Base} = \frac{1}{k_{eff-Base}} - \frac{1}{k_{eff-Change}}$$

Thus, a positive reactivity change results when ρ_{Change} is greater than ρ_{Base}. In the RELAP5 input, ρ and $\Delta\rho$ are noted in terms of dollars ($) which is defined as (Ref. 5.20, p. 246):

$$\rho(\$) = \frac{\rho}{\beta_{eff}} \quad and \quad \Delta\rho(\$) = \frac{\Delta\rho}{\beta_{eff}}$$

where β_{eff} is the effective delayed neutron fraction. The value of the delayed neutron fraction for this analysis is given as (Ref. 5.23)

$$\beta_{eff} = 0.005$$

which is a conservative minimum value.

7.2.1 Reactivity Effect of Water Level in Waste Package

A separate analysis (Ref. 5.13, Table 7.4-10) investigated the effects of different configurations of iron oxide and water in the waste package. Results from that analysis are used here to provide the feedback due to changes in the water level within the waste package. The k_{eff} results for various water levels in the fifth (upper) row of assemblies for the 58% settled oxide case for fuel decayed for 25,000 years are listed in Table 7.2.1-1 below. For determination of feedback, only the nominal values are used (not adjusted by the standard deviation).

Table 7.2.1-1. Effects of Water Level on k_{eff}

Case ID	Water Height Relative to Top of Upper Row of Assemblies (cm)	k_{eff}
r58m13a1	+21.30	0.99656
r58m13a2	0.0	0.98569
r58m13aw	-12.98	0.92672
r58m13bw	-14.43	0.91801
r58m13cw	-15.87	0.91090
r58m13a3	-20.30	0.85541

In order to conservatively calculate the change in reactivity, the reference condition is taken at the water level even with the top of the assemblies (0.0 cm in Table 7.2.1-1). The negative effect of dropping to this level is neglected. The Δρs resulting from a drop in water level through the upper row of assemblies are listed in Table 7.2.1-2. The reactivity table for the RELAP5 model was extended on to -21.64 cm (lower edge of the assemblies) using the last reactivity value to define a zero level entry. Δρs for lower water levels are not required because the negative effect of dropping the water level to the bottom of the upper row is great enough to overwhelm the insertion postulated in this analysis.

Table 7.2.1-2. RELAP5 Reactivity Table for WP Water Level

Water Level Relative to Assembly Top (cm) - MCNP	Water Level Relative to Control Volume Bottom Elevation (ft) - RELAP5	$\$ = \Delta\rho/\beta_{eff}$
0	0.71	0.0
-12.98	0.28415	-12.911
-14.43	0.23657	-14.959
-15.87	0.18933	-16.660
-20.30	0.04399	-30.902
-21.64	0.0	-30.902

7.2.2 Reactivity Effect of Temperature and Density Changes

MCNP4A does not have an associated cross section library with sufficient temperature dependant data to calculate the reactivity changes required for this analysis. The SAS2H sequence of SCALE4.3 does have the necessary cross sections. SAS2H employs a one-dimensional (1-D) assembly-cell discrete-ordinates technique (XSDRNPM) for calculation of the multiplication factor (k_{eff}) for a configuration. A correction for finite dimensions can be made through use of buckling (leakage) correction terms. Initially, infinite MCNP cases were run with which to compare the results from infinite SAS2H cases in order to develop the appropriate SAS2H model to match MCNP results. Corrections were then made to the SAS2H model to account for finite dimensions using the appropriate buckling terms for inclusion in the SAS2H models based on the baseline MCNP finite case. The resulting SAS2H model incorporating the buckling terms is then used for calculating temperature and density reactivity effects.

7.2.2.1 SAS2H Setup and Model Development

The equation for the buckling (*B*) in the XSDRNPM-S computer software portion of the SAS2H code system is as follows (Ref. 5.10, Vol. 2, pp. F3.2.24-25):

$$B^2 = \left(\frac{\pi}{Axial\ length + f\,(0.710446)\,\lambda_m}\right)^2 + \left(\frac{\pi}{Radial\ length + f\,(0.710446)\,\lambda_m}\right)^2$$

This equation for the buckling of the three dimensional waste package models is based on the separability of the geometrical configuration into an axial coordinate and radial plane. The reflector effects are treated by the term:

$$\text{Reflector Effects} = f\,(0.710446)\,\lambda_m$$

where f is a factor greater or equal to 0.0, and λ_m is the effective neutron mean free path in the reflector region. The neutron mean free path is determined by the XSDRNPM internal calculations from the properties of the fuel region. The product of f and 0.710446 is a constant input to the SAS2H model to give the reflector effects indicated by the MCNP results. To determine the appropriate reflector effects constant ($f * 0.710446$), MCNP models of the waste package are evaluated. The k_{eff} values from MCNP and the k_∞ values from the SAS2H models are used to determine the SAS2H buckling values. The buckling values are then used to determine the constant, $f * 0.710446$. This process is performed in an iterative manner with the SAS2H model because the analytic solution of the equation involves multiple unknowns.

The separation of the independent neutron variables into an infinite assembly cell coupled with a buckling correction is assessed by first benchmarking the SAS2H infinite (∞) model (buckling = 0.0) with three MCNP k_∞ results. The MCNP k_∞ represents a fuel region with complete reflection on all finite surfaces. The complete reflection of the MCNP fuel model represents a buckling of 0.0, and a k_{eff} equal to k_∞.

The base finite MCNP model represents B&W 15X15 fuel assemblies, 4.9% U-235, 34,000 MWd/MTU burnup, and 25,000 years of isotopic decay. In the degraded state, within a waste package that has been breached by water, that has 58 percent iron oxide by volume settled in the bottom of the waste package, the MCNP k_{eff} is 1.0186 ± 0.0049 (Ref. 5.13, Table 7.4-7).

This MCNP model has two separate fuel regions: (1) the upper region of fuel in the waste package that has no iron oxide in the water, and (2) the lower region of fuel in the waste package that has 58% iron oxide in the water. The SAS2H infinite modeling must be able to produce the same k_∞ as the MCNP (within an insignificant deviation) for each independent fuel region. Note that the MCNP results are reported ±2σ (~ 95% confidence interval). Case output filenames which are included on tape (Ref. 5.22) are reported in parentheses beside or below the case results.

	MCNP-k_∞	SAS2H-k_∞	Δρ Difference
No Iron	1.20780 ± 0.00092 (INFH2O.O)	1.20693 (out.e49)	-0.00060
Iron	0.90595 ± 0.000186 (INFOX.O)	0.905533 (out.fe)	-0.00051

The above results show that the reactivity change between SAS2H and the MCNP reference k_∞ is between -5/10,000 and -6/10,000. This difference is quite insignificant and indicates that the separability of finite geometrical space and infinite cell - velocity space is generally valid using the SAS2H model with a buckling eigenvalue. A comparison of the SAS2H input with the MCNP input shows that the SAS2H pin cell and assembly cell has the same geometrical and material modeling as the MCNP pin and assembly lattice arrays.

The third SAS2H k_∞ model evaluation in comparison to MCNP was used to determine the SAS2H neutron flux and volume weighting of the upper fuel region with pure water and the lower fuel region with 58% iron oxide in water. The MCNP model used a square array of 16 fuel assemblies (4 by 4) with 12 containing 58% iron oxide in water and 4 containing pure water. This volume fraction of 0.25 pure water and 0.75 58% iron oxide in water is representative of the volume fraction of the 58 percent settled iron oxide in water model of the degraded waste package. The weighting of upper and lower regions was defined as follows:

$$k_\infty\text{ (MCNP)} - \Delta\rho\text{ bias} = (x)\, k_\infty\text{ (SAS2H pure water)} + (1 - x)\, k_\infty\text{ (SAS2H 58\% iron oxide in water)}$$

The x is the combined flux and volume weighting factor, and the $\Delta\rho$ bias is defined by the $\Delta\rho$ difference in the table of iron and no iron k_∞ values. The parameters for the above equation are:

k_∞ (MCNP) = 1.12754 ± 0.00094 (INFLUX2O)
$\Delta\rho$ bias = -0.00055
k_∞ (SAS2H pure water) = 1.20693 (out.e49)
k_∞ (SAS2H 58% iron oxide in water) = 0.905533 (out.fe)
x = 0.71855

The comparison of MCNP and SAS2H results are shown in the following table:

	MCNP - k_∞	SAS2H - k_∞	$\Delta\rho$ Difference
Inf. Waste Package	1.12754 ± 0.00094 (INFLUX2O)	1.12684 (out.wpi)	-0.00055

The degraded waste package MCNP model, with a k_{eff} of 1.01860, has a pure water volume fraction of 0.254 and a 58% iron oxide in water volume fraction of 0.746. These volume fractions will only slightly affect the importance of the pure water region and the 58% iron oxide water region in comparison to the MCNP model with 0.25 pure water and 0.75 with 58% iron oxide in water. An increase in the weighting factor of the pure water region to:

x = 0.751311

was judged to be appropriate. This value is used in the final calculation (wp.out) as a weighting factor for the fraction of water in the moderator and (1-x) is the weighting factor for the fraction of 58% iron oxide/water mix in the moderator.

Axial Leakage Correction

The SAS2H axial buckling equation for the degraded waste package modeling is as follows (Ref. 5.10, Vol. 2, pp. F3.2.24-25):

$$B_{Axial}\ (SAS2H) = \frac{\pi}{Axial\ length + f\ (0.710446)\ \lambda_m}$$

with the assumption that the axial coordinate and radial plane may be separated by a constant buckling eigenvalue. The infinite cell SAS2H k_∞ results for the pure water in the upper region of the degraded waste package and the k_∞ results for the 58% iron oxide in water in the lower region of the degraded waste package indicated that the SAS2H separability modeling is valid. The flux-volume weighting of the upper and lower regions indicated that the importance of the upper region relative to the lower region is a factor greater than 2 to 1. Therefore, the pure water upper region was used to establish the constants for the theoretical reflector effects.

The pure water axial model of the degraded waste package was computed with MCNP and SAS2H. The MCNP modeling used reflective radial boundary conditions on the radial surfaces of the fuel. Thus, the boundary conditions represented an infinite radial model. The MCNP axial modeling however represented the appropriate geometry and compositions in the degraded waste package with appropriate boundary conditions at the end of the waste package outer metal surfaces. The SAS2H modeling used a radial buckling of zero ($B_{Radial} = 0.0$) to represent an infinite radial model. The SAS2H axial modeling represented the axial fuel length as 360.172 cm.

The solution of the reflector effects constant, ($f * 0.710446$), was iterative. However, the theoretical solution of $f = 2$ gave a very good comparison between the MCNP and SAS2H $k_{eff-\infty}$ results as shown below:

$$\text{Reflector Effects Axial Constant} = f * 0.710446 = 1.420892$$

$$f = 2$$

	MCNP - $k_{eff-\infty}$	SAS2H - $k_{eff-\infty}$	$\Delta\rho$ Difference
Waste Package	1.20489 ± 0.00096 (INFH2OaO)	1.20430 (out.fin)	- 0.00041

The axial constant for the reflector effects on the buckling should be reduced somewhat to increase the axial leakage and reduce $k_{eff-\infty}$ such that the $\Delta\rho$ difference was closer to - 0.00058 (the weighted bias). However, since the reflection effects constant is a combined axial and radial value, the above results are sufficient. Therefore, no additional correction is needed for the axial buckling other than entering the fuel length (360.172 cm) in the SAS2H input.

Radial Leakage Correction

In the 1-D SAS2H model, the radial leakage from the SNF configuration may be represented by either a cylinder or a square. Both options are investigated to identify the best. There are three theoretical equations that are appropriate to evaluate the radial buckling (Ref. 5.10, pp. F3.2.24-F3.2.25, Ref. 5.20, pp. 205-214) given by:

$$B_{Cylinder} = \frac{J_0(0)\ Bessel\ Function}{Radius + f_C\ (0.710446)\ \lambda_m}$$

$$B_{Square} = \frac{\left(\pi/2\right)^2}{Radial\ length + f_S\ (0.710446)\ \lambda_m}$$

$$B_{\substack{Separable \\ Square}} = \frac{\sqrt{2}\ \pi}{(2)\ Radial\ length + f_{SS}\ (0.710446)\ \lambda_m}$$

In the radial buckling for a cylinder, the radial length for the waste package model is the radius of a cylinder which has a planar area equal to the area of the 21 fuel assemblies in the degraded waste package. The width of the fuel lattice in the MCNP baseline degraded case (Attachment I) is 21.3 cm (10.65 X 2). The radius is given by:

$$Radius = \left\{ \frac{(21.3\ cm)^2\ 21}{\pi} \right\}^{1/2} = 55.0699\ \text{cm}$$

In the radial buckling for a square, the radial length for the waste package model is either the above radius or one-half the length of a square which has a planar area equal to the area of the fuel assemblies in the degraded waste package. This radial length is given by:

$$Radial\ length = \frac{\left\{ (21.3\ cm)^2\ 21 \right\}^{1/2}}{2} = 48.8044\ \text{cm}$$

In the radial buckling for a separable square, the radial length for the waste package model is the above radial length.

Reflector Effects

The three radial buckling equations were evaluated in combination with the axial buckling equation to determine the appropriate constant for the reflector effects on the combined axial and radial leakage for the degraded waste package. The SAS2H radial equation was used to determine the effective radial length with the reflector effects constant set to zero. For example, the effective radial length in the SAS2H radial buckling equation to reproduce the radial buckling of the separable square equation was determined as follows:

$$\frac{\pi}{Effective\ Radial\ Length} = \frac{\pi}{\sqrt{2}\ \ Radial\ Length}$$

where:

Effective Radial Length = 69.01988844 cm.

Iterations with the radial buckling equations and reflector effects constant in the SAS2H model in comparison to MCNP k_{eff} results indicated that the separable square radial buckling equation gave the more consistent overall results. The effective radial length is that shown above. The combined (axial and radial) reflector effects constant is given by:

Reflector Effects Constant $= f * 0.710446 = 0.875108$.

The comparison of the MCNP and SAS2H k_{eff} values shown below indicates that the iterative solution of the reflector effects constant (0.875108) is appropriately converged.

	MCNP - k_{eff}	SAS2H - k_{eff}	$\Delta\rho$ Difference
Waste Package	1.14053 ± 0.00052	1.13991	- 0.00048
	(H2OH13FO)	(out.wpn)	

Based on the results of the axial buckling evaluation of the reflector effects constant, it would be expected that f would be between 1 and 2 for the combined axial and radial reflector effects with a probable value nearer to 1. The above analysis results in an f of 1.23, which is consistent with expectations.

SAS2H Effective Radial Length of Fuel Stack

The last step in the development of a SAS2H model for the waste package reactivity coefficients is to determine the effective radial length. Ideally, the effective radial length for the degraded waste package with pure water and with 58% dense iron oxide and water in separate regions would be the effective radial length for the pure water region. If this were the situation, it would mean that the effects of the spatial flux shape could adequately be defined by the importance weighting of the two water regions. There would be no additional leakage effects. Such a situation would help to theoretically validate the separability model. Unfortunately, the SAS2H k_{eff} results, with an effective radial length of 69.0199 cm and a reflector constant of 0.875108 did not agree with the MCNP k_{eff}

(1.01860 ± 0.00486). To obtain agreement between the MCNP and SAS2H k_{eff} values, the SAS2H effective radial length had to be significantly decreased. The revised value is given by:

$$\text{Effective Radial Length (MCNP } k_{eff}) = 50.7843927 \text{ cm}$$

The decrease in the effective radial length significantly increased the radial leakage and decreased the k_{eff}. The iteration to determine the effective radial length of 50.7843927 cm gave the following SAS2H k_{eff} in comparison to MCNP:

	MCNP - k_{eff}	SAS2H - k_{eff}	$\Delta\rho$ Difference
Waste Package	1.01860	1.01801	- 0.00057
	(Ref. 5.13)	(out.wp)	

This agreement reflects the appropriate bias in the SAS2H k_∞ results.

Summary

With the buckling corrections developed in this section and the SAS2H assembly model giving the same k_∞ and k_{eff} results as MCNP, the SAS2H model is appropriate to evaluate reactivity changes in the degraded waste package fuel region. Three values are required for the buckling correction to the SAS2H model: (1) axial length (dz) = 360.172 cm; (2) reflector effects constant (bkl) = 0.875108; and (3) effective radial length (dy) = 50.7843927 cm.

7.2.2.2 SAS2H Reactivity Calculations

The reactivity effects of changes in the fuel temperatures and water densities are calculated with SAS2H to evaluate the RELAP5 functional relations between the thermodynamic state points and the respective reactivity values. The input file for the base SAS2H case (in.wp) is included as Attachment II. The RELAP5 model of reactivity used in this evaluation is based on two reactivity variables: (1) fuel temperature, and (2) water temperature-density. These two reactivity variables are treated as separable entities and combined in the RELAP5 model to define a total reactivity for the waste package.

The development of the RELAP5 reactivity input data included the dependent relationship between the fuel temperature and water temperature-density variables. The dependent effects were modeled using the following constraints and approximations:

(1) the fuel temperature would lead in time the water temperature-density,

(2) the water temperature effect on reactivity is insignificant compared to the water density,

(3) the water pressure effect on reactivity is insignificant compared to the water density,

(4) the onset of vapor (steam void fraction) formation would occur in the temperature range around 373 K (212°F), and

(5) the fuel temperature does not exceed 813 K (1004°F).

Steam void fractions in the 10 percent range were assumed to be caused by fuel temperatures of 543 K (518°F). Greater void fractions were assumed to be caused by fuel temperatures of 813 K (1004°F). Table 7.2.2.2-1 provides a case listing of 20 SAS2H calculations which are the bases for the RELAP5 reactivity values.

Table 7.2.2.2-1. SAS2H Reactivity Input for RELAP5

Case	k_{eff}	Fuel Temperature (K)	Water Density Factor
1 (out.wp)	1.01801	300	1.000
2 (out~1.122)	1.01712	323	1.000
3 (out~2.122)	1.01391	323	0.988
4 (out~2.212)	1.01212	373	0.988
5 (out~1.212)	1.00792	373	0.973
6 (out~1.320)	1.00599	433	0.973
7 (out~5.518)	1.00265	543	0.973
8 (out~4.518)	0.998466	543	0.958
9 (out~3.518)	0.993319	543	0.940
10 (out~2.518)	0.987415	543	0.920
11 (out~1.518)	0.981273	543	0.900
12 (out~9.100)	0.974209	813	0.900
13 (out~8.100)	0.966130	813	0.875
14 (out~7.100)	0.957650	813	0.850
15 (out~6.100)	0.948748	813	0.825
16 (out~5.100)	0.939397	813	0.800
17 (out~4.100)	0.929578	813	0.775
18 (out~3.100)	0.919256	813	0.750

19 (out~2.100)	0.908416	813	0.725
20 (out~1.100)	0.897022	813	0.700

7.2.3 Reactivity Insertion Scenario

As previously stated, the base finite MCNP model represents B&W 15X15 fuel assemblies with 4.9% U-235, 34,000 MWd/MTU burnup, and 25,000 years of isotopic decay. In the degraded state where a waste package has been breached by water and where the iron oxide has settled to the bottom of the waste package occupying 58 percent of the space by volume, the MCNP k_{eff} is 1.0186 with a standard deviation of $\pm$ 0.0049 (Ref. 5.13, Table 7.4-7). This is the most reactive reasonable configuration possible in the absorber plate waste package. If the critical point is designated as a k_{eff} of 0.95, the maximum reactivity insertion possible is:

$$\frac{\Delta\rho}{\beta_{eff}} = \left[\frac{1}{0.95} - \frac{1}{1.0186}\right] \times \frac{1}{.005} = 14.18\$.$$

A change in reactivity value of this magnitude roughly corresponds to an insertion scenario involving the transition from a homogeneous distribution of iron oxide within the waste package to the stratified base configuration described above (Ref. 5.13, Table 7.4-9) or an increase in water level (Ref. 5.13, Table 7.4-10) for an SNF configuration not already completely submerged.

As will be demonstrated in the RELAP5 results, the magnitude of the insertion is not as important as the reactivity insertion rate. The negative reactivity effects of reduced water level in the package, increased fuel temperature and increased water temperature (decreased density) will eventually overwhelm any conceivable reactivity insertion mechanism. A significant transient criticality event can occur only when the balance of reactivity insertion and these negative counterbalancing effects exceed +1.0$ (prompt critical). If the insertion rate is sufficiently fast, the power level could be increasing by a factor of 2.7 (exponential period) on a time scale of a millisecond or less while the thermal changes are occurring on a time scale of a second or longer (Ref. 5.20, pp. 233-277). The greater the balance exceeds 1.0$ and the longer the duration, the greater will be the significance of the transient event in terms of the energy generated and its associated phenomena. This translates into a requirement for a relatively short insertion time (seconds) in order to achieve a prompt critical situation. The transition from a homogeneous to a stratified distribution of iron oxide within the waste package would, in general, be a slow process taking many days, months or years. Low probability events which conceivably could result in an insertion rate on a time scale of a second or minute would include:

(1) Increasing Ambient Episodic Focused Flow of water of 20 m^3 to 100 m^3 in one week (Ref. 5.15, CDA Assumption TDSS 026),

(2) Earthquake resulting in shaking of waste package and redistribution of iron oxide, and

(3) Rock fall resulting in shaking of waste package and redistribution of iron oxide.

The water level scenario (1) could insert reactivity on a minute time scale and the particle redistribution scenarios (2 and 3) could insert reactivity on a second or minute time scale depending on average particle size. Attachment III contains idealized terminal velocity (free fall, no impediment from other obstacles) calculations for particles sizes of 0.010 mm and 0.063 mm, which would take approximately 1 and 40 minutes, respectively, to fall to the bottom of the waste package. The typical crud particle size from metal oxidation is in the range of 0.0001 to 0.01 mm (Ref. 5.8, p. 2.6-6).

Based on these considerations, insertion times of 30 seconds and 3600 seconds were chosen for the RELAP5 calculations in order to demonstrate transient behavior for the criticality event.

7.3 RELAP5 Model Description

The purpose of this section is to describe the RELAP5 model used for the coupled neutronic-thermal-hydraulic analyses of a criticality event in a WP where the outer barrier has been compromised leading to a fully degraded basket assembly. The RELAP5 model of the WP, illustrated as a block diagram in Figure 7.3-1, consisted of 27 control volumes, 43 junctions, and 35 heat conductors. The spatial orientation of the WP is such that the cylindrical WP axis and long fuel assembly dimension are in the horizontal plane as shown in Figure 7.1-1. The model represents one-half of the WP cross-sectional cylinder since the system has left-right symmetry.

The RELAP5 code is designed to for use with fundamentally one-dimensional hydraulic systems but does include multi-dimensional flow representation under restricted conditions (Ref. 5.4). The RELAP5 model for the degraded WP contains flow connections in the two directions normal to the WP cylinder axis but not parallel to the axis. For this quasi-two dimensional model, the fuel bundles were modeled at one-fifth of the actual fueled length of 141.8 in. (Table 4.1-1) with appropriate adjustments to the model parameters. Fuel bundle and WP end fittings were excluded from the RELAP5 model. The principal elements of the model description include the geometric representation, flow connections, friction factors, and heat conductors. These elements are described in the following sections. Note that RELAP5 input quantities are specified in English units. A representative RELAP5 input file (r5wp2d.03c) is included in Attachment IV.

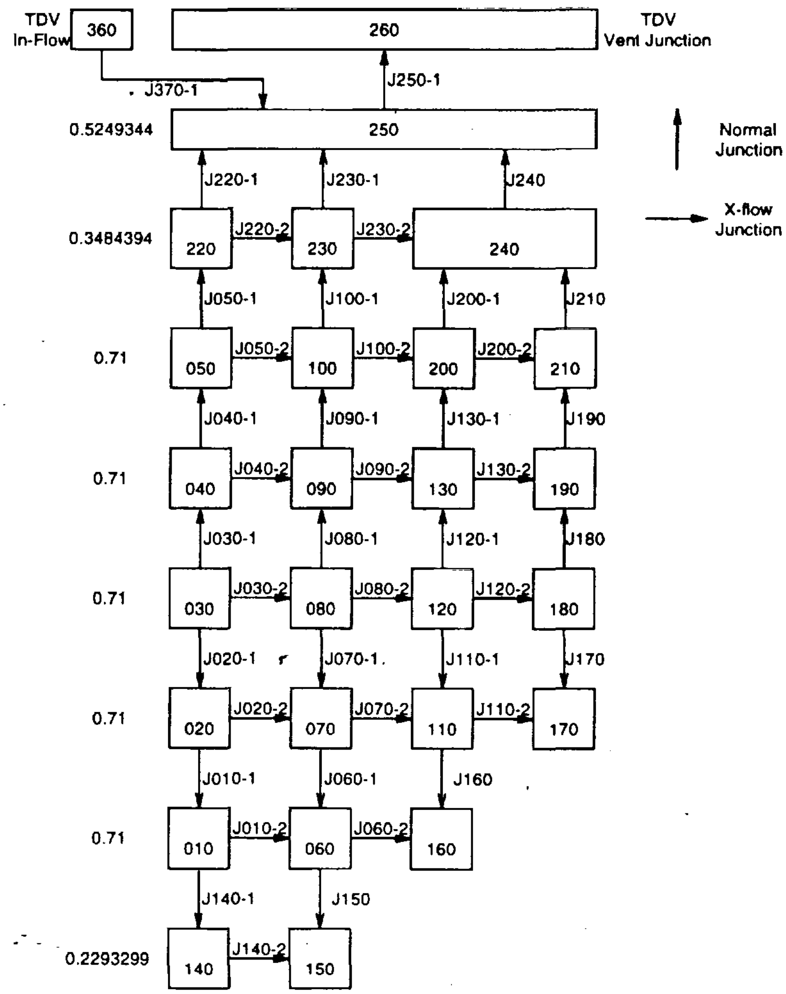

Figure 7.3-1. Block Diagram of RELAP5 Model

7.3.1 RELAP5 Model Geometry

The particular WP configuration modeled for the RELAP5 studies was the fully degraded basket condition with intact fuel assemblies. The iron oxide was assumed to have settled to the bottom of the WP covering the lower 3.5 rows of assemblies. The presence of oxide material was included in the development of the reactivity parameters but not specifically included in the hydrodynamic or thermodynamic modeling. The non-metal volume in each fuel assembly is represented by one RELAP5 control volume and the metal volume (fuel rods, guide tubes, and instrument tubes) modeled by heat conductors connected to the control volume. As stated previously, the WP is designed to hold fuel assemblies in a horizontal arrangement limiting the gravity contributions to volume pressures in the model to elevations of 21.6408 cm (0.568 in. pin cell pitch), the assembly width (Table 4.1-1). The control volume dimensions were assigned to produce the correct gravity pressure heads and fluid inventory. Dimensions of the water filled control vomunes around the WP periphery were derived by subtracting the area of the intersecting rectangular fueled cells from circular sector overlays with a radius of 71.32 cm (Drawing ID# BBAA00000-01717-2700-16004 Rev 00). The control volume dimensions for the model are listed in Table 7.3-1. The total volume contained in the control volumes is 16.051 ft^3 resulting in an initial inventory of 990.09 lb_m of water.

Control volumes representing SNF assemblies (heavily shaded rectangular areas in Figure 7.1-1) have IDs from 010010000 through 130010000 where control volumes 010010000-050010000 represent half assemblies. The remaining space in the WP interior (regions around the periphery and above the SNF assemblies in Figure 7.1-1) was described by the control volumes labeled 140010000-250010000. Two time-dependent control volumes (ID 260010000 and ID 360010000), representing the external boundary WP environment, complete the RELAP5 geometry setup. The block diagram of the RELAP5 model displayed in Figure 7.3-1, while not to scale, shows the relative control volume arrangement.

Initial conditions for the RELAP5 control volumes were specified as water filled at 122.0°F and 14.696 psia except for the time-dependent control volume (ID 260010000), representing the external environment, which was initialized as steam at 220.0°F and 14.696 psia to approximate a non-condensing gas environment.

Time-dependent volumes were included in the model to represent the drift space outside the WP where the out-flowing water inventory from the WP accumulates and to provide a low temperature flow path into the WP representing the drift flow leaking into the WP. Time dependent volumes are used as boundary conditions providing sinks and sources for the fluid inventory. Thermodynamic conditions in these control volumes are specified as functions of time and are not dependent upon the mass or enthalpy of connecting volumes.

Table 7.3-1. RELAP5 Control Volumes

Number ID*	Volume (ft^3)	Vertical Flow Area (ft^2)	Elevation (ft) (Center-line)	Pressure (psia)	Temperature (°F)
010010000	0.3516846	0.4953304	0.0	14.696	122.0
020010000	0.3516846	0.4953304	0.71	14.696	122.0
030010000	0.3516846	0.4953304	1.42	14.696	122.0
040010000	0.3516846	0.4953304	2.13	14.696	122.0
050010000	0.3516846	0.4953304	2.84	14.696	122.0
060010000	0.7033692	0.9906608	0.0	14.696	122.0
070010000	0.7033692	0.9906608	0.71	14.696	122.0

Table 7.3-1. RELAP5 Control Volumes

Number ID*	Volume (ft^3)	Vertical Flow Area (ft^2)	Elevation (ft) (Center-line)	Pressure (psia)	Temperature (°F)
080010000	0.7033692	0.9906608	1.42	14.696	122.0
090010000	0.7033692	0.9906608	2.13	14.696	122.0
100010000	0.7033692	0.9906608	2.84	14.696	122.0
110010000	0.7033692	0.9906608	0.71	14.696	122.0
120010000	0.7033692	0.9906608	1.42	14.696	122.0
130010000	0.7033692	0.9906608	2.13	14.696	122.0
140010000	0.2075716	0.9051223	-0.469665	14.696	122.0
150010000	0.2276341	0.9926054	-0.469665	14.696	122.0
160010000	0.7989270	1.125249	0.0	14.696	122.0
170010000	0.5438773	0.7660244	0.71	14.696	122.0
180010000	0.8980821	1.264904	1.42	14.696	122.0
190010000	0.8738187	1.230731	2.13	14.696	122.0
200010000	0.8633786	1.216026	2.84	14.696	122.0
210010000	0.7822260	1.101727	2.84	14.696	122.0
220010000	0.8633786	2.477844	3.36922	14.696	122.0
230010000	0.8633786	2.477844	3.36922	14.696	122.0
240010000	0.4918077	1.411458	3.36922	14.696	122.0
250010000	1.2517607	2.384604	3.80591	14.696	122.0
260010000	238.468	238.468	4.06837	14.696	220.0
360010000	238.468	238.468	3.54344	14.696	122.0

* First 3 digits correspond to the control volume labels in Figure 7.3-1.

7.3.2 RELAP5 Junction Description

The spatial orientation of the WP cylindrical axis is in the horizontal direction with the fuel assemblies stacked on their sides. The assemblies modeled for the MCNP analyses (Ref. 5.13) were B&W 15X15 assemblies with open pin arrays. This allows cross flow between assemblies since the internal WP structure is assumed to be fully degraded. The "normal" flow direction in the model (normal with respect to the one-dimensional hydraulic characteristic of the RELAP5 code) is vertical through the assemblies normal to the fuel rod long dimension. RELAP5 junctions define the cross sectional flow area between two control volumes which must intersect both volumes. These junctions are labeled as xxx010000 where xxx is the identifier of all junctions originating in a control volume. (Note that junction label prefixes "xxx" and control volume labels prefixes form independent sets.) A second flow direction was defined horizontally across the assemblies likewise normal to the fuel rod direction. The horizontal flow paths were modeled as junction "branch" components and labeled as xxx020000. Physical constraints on flow paths in the WP are incorporated into the junction flow areas and frictional loss coefficients.

In the development of the RELAP waste package model, form loss coefficients were included to treat the cross-flow between the flow channels. The fundamental expression for the cross-flow form loss coefficients is given by (Ref. 5.24):

$$\zeta = \psi A \, Re_{av}^{m}$$

where (ζ) is the loss coefficient,
(ψ) is a function of the angle of the flow (for 90° $\psi = 1$),
(A) is a function of the fuel rod pitch, and the hydraulic diameter,
(Re) is the average (av) Reynolds Number for the fluid conditions, and
(m) is a parameter to provide a best fit of the data.

Framatome has added two other terms, (1) a multiplier for the phase-flow characteristics, and (2) a multiplier for the number of cross-flow bundle-channels that are affected. The coefficient for highly voided regions that best matches data is 72. Sensitivity evaluations suggest that lower values would be appropriate at lower voids and flow velocities. However, for a range of Reynolds numbers (such as $3 \times 10^3 < Re < 10^5$ as noted by Idelchik), the value of 72 gives appropriate results.

All junction flow rates were initialized at zero (0) lb_m/sec except for junction 370000000 at 1.381×10^{-3} lb_m/sec at 122.0°F and 14.696 psia representing a drift inflow source of 20 m^3 per year. The junction parameters in the model are listed in Table 7.3-2.

Table 7.3-2. RELAP5 Junction Parameters

Junction ID*	Area (ft^2)	Orientation W.T. Horizontal (deg)	Connecting Volume IDs	Forward Loss Coefficient	Reverse Loss Coefficient	Choke Flag	Face Position (ft)
010010000	0.203838	90.0	01001000 02001000	72.0	72.0	no	0.355

Table 7.3-2. RELAP5 Junction Parameters

Junction ID*	Area (ft^2)	Orientation W.T. Horizontal (deg)	Connecting Volume IDs	Forward Loss Coefficient	Reverse Loss Coefficient	Choke Flag	Face Position (ft)
010020000	0.407675	0.0	010010000 060010000	72.0	72.0	no	0.355
020010000	0.203883	90.0	020010000 030010000	72.0	72.0	no	1.065
020020000	0.407675	0.0	020010000 070010000	72.0	72.0	no	1.065
030010000	0.203883	90.0	030010000 040010000	72.0	72.0	no	1.775
030020000	0.407675	0.0	030010000 080010000	72.0	72.0	no	1.065
040010000	0.203838	90.0	040010000 050010000	72.0	72.0	no	2.485
040020000	0.407675	0.0	040010000 090010000	72.0	72.0	no	1.775
050010000	0.203838	90.0	050010000 220010000	72.0	72.0	no	3.195
050020000	0.407675	0.0	050010000 100010000	72.0	72.0	no	2.485
060010000	0.407675	90.0	060010000 070010000	72.0	72.0	no	0.355
060020000	0.407675	0.0	060010000 160010000	72.0	72.0	no	0.355
070010000	0.407675	90.0	070010000 080010000	72.0	72.0	no	1.065
070020000	0.407675	0.0	070010000 110010000	72.0	72.0	no	1.065
080010000	0.407675	90.0	080010000 090010000	72.0	72.0	no	1.775
080020000	0.407675	0.0	080010000 120010000	72.0	72.0	no	1.065
090010000	0.407675	90.0	090010000 100010000	72.0	72.0	no	2.485

Table 7.3-2. RELAP5 Junction Parameters

Junction ID*	Area (ft^2)	Orientation W.T. Horizontal (deg)	Connecting Volume IDs	Forward Loss Coefficient	Reverse Loss Coefficient	Choke Flag	Face Position (ft)
090020000	0.407675	0.0	090010000 130010000	72.0	72.0	no	1.775
100010000	0.407675	90.0	100010000 230010000	72.0	72.0	no	3.195
100020000	0.407675	0.0	100010000 200010000	72.0	72.0	no	2.485
110010000	0.407675	90.0	110010000 120010000	72.0	72.0	no	1.065
110020000	0.407675	0.0	110010000 170010000	72.0	72.0	no	1.065
120010000	0.407675	90.0	120010000 130010000	72.0	72.0	no	1.775
120020000	0.407675	0.0	120010000 180010000	72.0	72.0	no	1.065
130010000	0.407675	90.0	130010000 200010000	72.0	72.0	no	2.485
130020000	0.407675	0.0	130010000 190010000	72.0	72.0	no	1.775
140010000	0.203838	90.0	140010000 010010000	72.0	72.0	no	-0.355
140020000	0.541983	0.0	140010000 150010000	0.0	0.0	no	-0.355
150010000	0.407675	90.0	150010000 060010000	72.0	72.0	no	-0.355
160010000	0.407675	90.0	160010000 110010000	72.0	72.0	no	0.355
170010000	1.10807	90.0	170010000 180010000	0.0	0.0	no	1.065
180010000	1.33394	90.0	180010000 190010000	0.0	0.0	no	1.775
190010000	1.03803	90.0	190010000 210010000	0.0	0.0	no	2.485

Table 7.3-2. RELAP5 Junction Parameters

Junction ID*	Area (ft^2)	Orientation W.T. Horizontal (deg)	Connecting Volume IDs	Forward Loss Coefficient	Reverse Loss Coefficient	Choke Flag	Face Position (ft)
200010000	0.754086	90.0	200010000 240010000	0.0	0.0	yes	3.195
200020000	1.79585	0.0	200010000 210010000	0.0	0.0	yes	2.485
210010000	1.03803	90.0	210010000 240010000	0.0	0.0	yes	3.195
220010000	0.203838	90.0	220010000 250010000	0.0	0.0	yes	3.54344
220020000	0.823478	0.0	220010000 230010000	0.0	0.0	yes	3.195
230010000	0.407675	90.0	230010000 250010000	0.0	0.0	yes	3.54344
230020000	0.823478	0.0	230010000 240010000	0.0	0.0	yes	3.195
240010000	0.973291	90.0	240010000 250010000	0.0	0.0	yes	3.54344
250010000	0.107639	90.0	250010000 260010000	0.0	0.0	yes	4.06837
370010000	1.0	0.0	360010000 250010000	0.0	0.0	no	3.54344

* Digits 1-3 and 5 correspond to the "J" IDs in Figure 7.3-1.

7.3.3 RELAP5 Heat Conductor Description

Energy sources in RELAP5 models must be modeled with powered heat conductors connected to control volumes. In addition, non-powered heat conductors may be used to transport energy between disjoint fluid paths and/or into heat sinks. In order to properly model the thermal characteristics of conductors, the geometry is normally representative of individual components such as fuel rods. The overall fuel assembly energy balance is modeled by assigning the proper heat transfer area to the conductor. For the RELAP5 model of the WP, two sets of conductors describing the fuel pins and guide tubes were defined, one powered set representing the UO_2 fuel pellets (IDs 3301001 through 3301013) and one passive set representing the fuel rod cladding and guide tubes (IDs 3481001 through 3481013).

The conductor series 3301 and 3481 were connected respectively to control volumes 01001000 through 130010000 where the SNF assemblies are located. The fuel rods were modeled with independent pellet and clad conductors to simulate breached conditions with no gas gap between the fuel pellets and cladding and water is in contact with the UO_2 pellets. In this model, the fuel rod cladding was dissociated from the fuel pellet-to-water heat conduction path placing the pellets directly in contact with the control volume water mass. The cladding and guide tubes were in turn heated from secondary contact with the control volume water mass.

The outer containment shell of the WP was modeled with a set of nine passive heat conductors (IDs 3121001 through 3121009) representing large carbon steel heat sinks connected to the peripheral water filled control volumes (IDs 140010000 through 220010000).

Initial conditions for all heat conductors were 122.0°F.

Global energy sources in the RELAP5 program are defined by the time-dependent solution of point kinetics equations for the fission contribution to the energy generation coupled with (optionally) fission product and actinide radioactive decay energy. The global energy sources are distributed locally to powered heat conductors (IDs 3301001 through 3301013) through power factors which consist of nodal weights within conductors and overall weight factors among the conductors. For the RELAP5 WP model, the time-dependent power history represented one fuel assembly and the power factors were specified accordingly; 0.2 for one-fifth length full area assemblies and 0.1 for one-fifth length half area assemblies. Nodal power factors within conductors were given equal weighing.

The heat conductor descriptions for the RELAP5 model are listed in Table 7.3-3.

Table 7.3-3. RELAP5 Heat Conductor Specifications

Conductor ID	Geometry	Composition	Coordinate (ft) Left Right	Volume Connection	Initial Temperature (°F)	Heat Transfer Area (ft^2)	Power Factor
3301001	Cylinder	UO_2	0.0 1.535833e-02	0 010010000	122.0	245.78667	0.1
3301002	Cylinder	UO_2	0.0 1.535833e-02	0 020010000	122.0	245.78667	0.1
3301003	Cylinder	UO_2	0.0 1.535833e-02	0 030010000	122.0	245.78667	0.1
3301004	Cylinder	UO_2	0.0 1.535833e-02	0 040010000	122.0	245.78667	0.1
3301005	Cylinder	UO_2	0.0 1.535833e-02	0 050010000	122.0	245.78667	0.1

Table 7.3-3. RELAP5 Heat Conductor Specifications

Conductor ID	Geometry	Composition	Coordinate (ft) Left Right	Volume Connection	Initial Temperature (°F)	Heat Transfer Area (ft^2)	Power Factor
3301006	Cylinder	UO_2	0.0 1.535833e-02	0 060010000	122.0	491.57333	0.2
3301007	Cylinder	UO_2	0.0 1.535833e-02	0 070010000	122.0	491.57333	0.2
3301008	Cylinder	UO_2	0.0 1.535833e-02	0 080010000	122.0	491.57333	0.2
3301009	Cylinder	UO_2	0.0 1.535833e-02	0 090010000	122.0	491.57333	0.2
3301010	Cylinder	UO_2	0.0 1.535833e-02	0 100010000	122.0	491.57333	0.2
3301011	Cylinder	UO_2	0.0 1.535833e-02	0 110010000	122.0	491.57333	0.2
3301012	Cylinder	UO_2	0.0 1.535833e-02	0 120010000	122.0	491.57333	0.2
3301013	Cylinder	UO_2	0.0 1.535833e-02	0 130010000	122.0	491.57333	0.2
3481001	Cylinder	Zr-4	1.570833e-02 1.791112e-02	010010000 010010000	122.0	265.875 531.750	0.0
3481002	Cylinder	Zr-4	1.570833e-02 1.791112e-02	020010000 020010000	122.0	265.875 531.750	0.0
3481003	Cylinder	Zr-4	1.570833e-02 1.791112e-02	030010000 030010000	122.0	265.875 531.750	0.0
3481004	Cylinder	Zr-4	1.570833e-02 1.791112e-02	040010000 040010000	122.0	265.875 531.750	0.0
3481005	Cylinder	Zr-4	1.570833e-02 1.791112e-02	050010000 050010000	122.0	265.875 531.750	0.0
3481006	Cylinder	Zr-4	1.570833e-02 1.791112e-02	060010000 060010000	122.0	265.875 531.750	0.0
3481007	Cylinder	Zr-4	1.570833e-02 1.791112e-02	070010000 070010000	122.0	265.875 531.750	0.0
3481008	Cylinder	Zr-4	1.570833e-02 1.791112e-02	080010000 080010000	122.0	265.875 531.750	0.0

Table 7.3-3. RELAP5 Heat Conductor Specifications

Conductor ID	Geometry	Composition	Coordinate (ft) Left Right	Volume Connection	Initial Temperature (°F)	Heat Transfer Area (ft^2)	Power Factor
3481009	Cylinder	Zr-4	1.570833e-02 1.791112e-02	090010000 090010000	122.0	265.875 531.750	0.0
3481010	Cylinder	Zr-4	1.570833e-02 1.791112e-02	100010000 100010000	122.0	265.875 531.750	0.0
3481011	Cylinder	Zr-4	1.570833e-02 1.791112e-02	110010000 110010000	122.0	265.875 531.750	0.0
3481012	Cylinder	Zr-4	1.570833e-02 1.791112e-02	120010000 120010000	122.0	265.875 531.750	0.0
3481013	Cylinder	Zr-4	1.570833e-02 1.791112e-02	130010000 130010000	122.0	265.875 531.750	0.0
3121001	Rectangular	Carbon Steel	0.0 190.0	140010000 0	122.0	1.73 0.0	0.0
3121002	Rectangular	Carbon Steel	0.0 190.0	150010000 0	122.0	1.73 0.0	0.0
3121003	Rectangular	Carbon Steel	0.0 190.0	160010000 0	122.0	1.73 0.0	0.0
3121004	Rectangular	Carbon Steel	0.0 190.0	170010000 0	122.0	1.73 0.0	0.0
3121005	Rectangular	Carbon Steel	0.0 190.0	180010000 0	122.0	1.73 0.0	0.0
3121006	Rectangular	Carbon Steel	0.0 190.0	190010000 0	122.0	1.73 0.0	0.0
3121007	Rectangular	Carbon Steel	0.0 190.0	200010000 0	122.0	1.73 0.0	0.0
3121008	Rectangular	Carbon Steel	0.0 190.0	210010000 0	122.0	1.73 0.0	0.0
3121009	Rectangular	Carbon Steel	0.0 190.0	220010000 0	122.0	1.73 0.0	0.0

7.3.4 RELAP5 Reactivity Tables

The feedback reactivity in the RELAP5 point kinetics model can be specified as direct time dependent tables (labeled as scram tables), weighted tables of fluid density vs reactivity, or through control system variables. The control system allows reactivity values to be more generally specified as functions of model variables.

The RELAP5 reactivity changes for fuel and moderator temperature effects are shown in Tables 7.3-4 and 7.3-5. The first parameter shown on Tables 7.3-4 and 7.3-5 is the 8 digit input line number beginning with the number 3 (30000000). The last 3 digits on these input lines identify the fuel temperature variables, 30000601 through 30000607, moderator density variables, 30000501 through 30000516, and the respective reactivities. The English units used here reflect the values used in the RELAP5 input.

The formulation of the reactivities for each input line is denoted as:

$$\rho\ (603) = \Delta\rho_{CB} + \rho\ (\text{sum})$$

where ρ (603) is the input line number (603 for example), ρ (sum) is the summation of reactivities from the initial state point (122 °F), and:

$$\Delta\rho_{CB} = \frac{1}{k_{eff\ -\ Base}} - \frac{1}{k_{eff\ -\ Change}}$$

where C represents the change case number from Table 7.2.2.2-1 and B represents the base case number from the same table. Note that the cases listed in Table 7.2.2.2-1 include a number of branch cases (fuel temperature varied at constant density and density varied at constant fuel temperature). The constant parameter is listed the last column in Table 7.3-4 and Table 7.3-5.

Table 7.3-4. Average Fuel Temperature Versus Reactivity

RELAP5 Input Line #	Fuel Temperature (°F)	Δρ($)	Density (lb_m/ft^3)
30000601	32.0	+0.1719079	62.4279606
30000602	80.33	+0.1719079	62.4279606
30000603	122.0	+0.0	61.6903146
30000604	212.0	-0.3488604	61.6903146
30000605	320.0	-0.7295469	60.7424057
30000606	518.0	-1.3918144	60.7424057
30000607	1004.0	-2.8696928	56.1851645

Table 7.3-5. Moderator Density Versus Reactivity

RELAP5 Input Line #	Density (lb_m/ft^3)	$\Delta\rho$($)	Fuel Temperature (°F)
30000501	43.6995724	- 22.8341124	1004
30000502	45.2602714	-20.0375898	1004
30000503	46.8209705	-17.4413905	1004
30000504	48.3816695	-15.0255317	1004
30000505	49.9423685	-12.7766726	1004
30000506	51.5030675	-10.6782739	1004
30000507	53.0637665	-8.7187079	1004
30000508	54.6244655	-6.8856192	1004
30000509	56.1851645	-5.1688975	518
30000510	57.4337238	-3.9010990	518
30000511	58.6822830	-3.9010990	518
30000512	59.8121897	-1.6592902	518
30000513	60.7424057	-0.8234196	212
30000514	61.6903146	0.00	122
30000515	62.4279606	+0.6225345	122
30000516	65.0000000	+0.6225345	80.33

The initial state point is represented by fuel temperatures of 122°F and a corresponding density of 61.6903146 lb/ft^3. There are interpolation control reactivity lines for ρ (601) and ρ (516). Temperatures less than 80.33°F {ρ (602)} cannot be attained. Therefore, 32°F is a dead-ended interpolation point:

$$\rho\,(601)_{32°F} = \rho\,(602)_{80.33°F.}$$

Likewise, water densities greater than 1.0 gm/cm^3 or 62.4 lb/ft^3 cannot be attained. Therefore, 65.0 lb/ft^3 is a dead-ended interpolation point:

$$\rho\,(516)_{65.0\,lb/ft^3} = \rho\,(515)_{62.4\,lb/ft**3}.$$

The reactivity summation, ρ (sum), begins with the base reactivity for the initial state points and proceeds in the direction of increasing positive values or decreasing negative ones.

The formulations for the fuel temperature reactivity values are shown below. These expressions are straightforward. For example, if a positive reactivity increase is considered to have resulted from a fuel temperature decrease from 122°F to 80.33°F, the base case in Table 7.2.2.2-1 is #2 and the change case is #1. Consequently, the change in reactivity is $\Delta\rho_{1,2}$. The sum of all previous reactivities is zero because this is the first change from the base reactivity, which is zero at 122°F.

$$\rho(601) = \rho(602)$$
$$\rho(602) = \Delta\rho_{1,2} + \rho(603)$$
$$\rho(603) = 0.0 = \Delta\rho = \rho(603)$$
$$\rho(604) = \Delta\rho_{4,3} + \rho(603)$$
$$\rho(605) = \Delta\rho_{6,5} + \rho(\text{sum})$$
$$\rho(\text{sum}) = \rho(604) + \rho(603)$$

$$\rho(606) = \Delta\rho_{7,6} + \rho(\text{sum})$$
$$\rho(\text{sum}) = \rho(605) + \ldots$$

$$\rho(607) = \Delta\rho_{12,11} + \rho(\text{sum})$$
$$\rho(\text{sum}) = \rho(606) + \ldots$$

The formulations for the moderator density reactivity values are shown below. The format and evaluation follow the same pattern as that for the fuel temperatures discussed above.

$$\rho(516) = \rho(515)$$
$$\rho(515) = \Delta\rho_{2,3} + \rho(514)$$
$$\rho(514) = 0 = \Delta\rho = \rho(\text{sum})$$
$$\rho(513) = \Delta\rho_{5,4} + \rho(514)$$
$$\rho(512) = \Delta\rho_{8,7} + \rho(\text{sum})$$
$$\rho(\text{sum}) = \rho(513) + \rho(514)$$

$$\rho(511) = \Delta\rho_{9,8} + \rho(\text{sum})$$
$$\rho(\text{sum}) = \rho(512) + \ldots$$

$$\rho(510) = \Delta\rho_{10,9} + \rho(\text{sum})$$
$$\rho(\text{sum}) = \rho(511) + \ldots$$

$$\rho(509) = \Delta\rho_{11,10} + \rho(\text{sum})$$
$$\rho(\text{sum}) = \rho(510) + \ldots$$

$$\rho(508) = \Delta\rho_{13,12} + \rho(\text{sum})$$

ρ (sum) = Sum of previous ρ values

ρ (507) = $\Delta\rho_{14,13}$ + ρ (sum)
ρ (506) = $\Delta\rho_{15,14}$ + ρ (sum)
ρ (505) = $\Delta\rho_{16,15}$ + ρ (sum)
ρ (504) = $\Delta\rho_{17,16}$ + ρ (sum)
ρ (503) = $\Delta\rho_{18,17}$ + ρ (sum)
ρ (502) = $\Delta\rho_{19,18}$ + ρ (sum)
ρ (501) = $\Delta\rho_{20,19}$ + ρ (sum)

During the development of the model, it was noted that the reactivity was remaining high during the transient when the water level was decreasing down through the upper row of assemblies. Based on the results in Section 7.2.1 that this was a very large negative effect, it was recognized that this effect needed to be included. The control system input option was used to incorporate the results in Table 7.2.1-2 into the RELAP5 model. A control block was added to the input file to compute an average liquid level in the top row of fueled assemblies and adjacent fluid volumes having the same elevation. Reactivity is calculated from the table at the current liquid level using linear interpolation procedures based on the results in Section 7.2.1. The MCNP analyses for the sequence of water levels in the WP were evaluated from the top of the fuel assembly to -20.30 cm as indicated in Section 7.2.1. The reactivity table for the RELAP5 model was extended to -21.64 cm (lower edges of the assemblies) using the last reactivity value to define a zero level entry. This is a conservative approach since the k_{eff} of the system is strongly correlated with the water level at these conditions.

The inclusion of the control block for water level necessitated that the moderator density table be overridden. Note that this is conservative since the drop in moderator density is shown in Table 7.3-5 to always result in a negative change in reactivity.

7.4 Results of RELAP5 Analysis

All results in this section from RELAP5 calculations are TBV because the RELAP5/MOD3 code has not been qualified according QAP-SI-0 as indicated in Section 6.

The consequences of a large reactivity insertion in the WP, one where the insertion rate was on the order of minutes and the second where the rate was on the order hours, were investigated with the RELAP5 model. In particular, the scenarios investigated were a positive reactivity insertion of 14.18$ at a constant rate over 30 seconds and over 3600 seconds. These cases are labeled as r5wp2d.sht for the 30 second scenario and r5wp2d.lng for the 3600 second scenario. The short term (initial power excursion) transient responses in both cases were qualitatively similar, being dominated by the positive ramp reactivity insertion and negative Doppler feedback reactivity which terminated the initial power rise in each case prior to the introduction of significant negative void reactivity. The transient response of the WP system following termination of the initial power rise was controlled by the rate of energy addition affecting the rate and magnitude of the void formation and thus the time evolution of the void reactivity component. Ultimately, sufficient fluid inventory was lost from the WP (> 225 kg in either case) to sustain a large negative void reactivity component, keeping the system in a subcritical condition.

Maximum pressures in the WP system remained below 2.55e+05 Pa and maximum center line fuel rod temperatures remained below 570 K. Sufficient fluid inventory remained in the WP at the problem termination to redistribute the energy in the system and reducing the fuel rod temperatures to less than 373 K. Values of several key parameters from the RELAP5 analyses are summarized in Table 7.4-1.

Table 7.4-1. Summary of 14.18$ Ramp Reactivity Insertion Cases

Variable	30 second reactivity insertion case r5wp2d.sht	3600 second reactivity insertion case r5wp2d.lng
Peak fission power/assembly	9.47e+07 watts	8.76e+05 watts
Time of peak fission power	2.52 seconds	176.0 seconds
Total fission and decay heat power per assembly at time of fission power maximum	9.48e+07 watts	9.00e + 05 watts
Total energy into WP/assembly at termination time	5.16e+07 joules	8.15e+07 joules
Maximum volume pressure	2.544e+05 Pa	2.258e+05 Pa
Control volume where maximum pressure monitored	150010000	150010000
Peak mean fuel rod temperature	497.5 K	438.4 K
Time of peak pin temperature	4.18 seconds	633 seconds
Water inventory - Initial	450.04 kg	450.04 kg
Water inventory - Final	209.02 kg	219.29 kg
Incremental Burnup	1.6e-03 MWd/MTU	1.8 MWd/MTU
Termination time	1200 seconds	1800 seconds

The consequences of each reactivity insertion scenario were directly related in severity to the reactivity insertion rate in the flooded WP which is typical of transient reactivity events analyzed in reactor systems such as during Anticipated Transients Without Scram (ATWS) (Ref. 5.17), supporting the assumption that the RELAP5 code can adequately model the WP system. The total energy generated may be larger for slower insertion rate events as shown in Table 7.4-1 but is distributed over longer time periods than the more rapid insertion rate events. Within an essentially closed system such as the WP being analyzed, the energy generation can be considered as an adiabatic process since the time scales are too short for significant amounts of energy to be transferred into the WP barriers as heat sinks. Thus, although the detailed histories differ markedly, preliminary analysis indicates that the final state of the system is, at most, only weakly dependent upon reactivity insertion rates since the fission reaction terminates as soon as the WP is sufficiently voided. In this state, sufficient fluid inventory has been converted to steam (or a two-phase fluid) and expelled from the WP to preclude any short term return to criticality.

The time evolution of key parameters from the 30 second scenario are shown in Figure 7.4-1 through Figure 7.4-10, respectively, for assembly power, reactivity components, control volume pressures, WP fluid inventory, junction flow rates, and average fuel temperature. Two ranges are shown for several of the parameters, one showing a panoramic view of the parameter value over the total time period, and the second providing a higher resolution study over a limited time scale. In this scenario, the energy generation rate was sufficiently rapid during the initial power excursion to raise fuel temperatures (Figure 7.4-10) well into the range where void formation occurs generating the sharp pressure rise (Figure 7.4-5) and inventory loss (Figure 7.4-7). As shown in Figure 7.4-3, the large negative void reactivity component prevented any possible return to criticality in the WP system and the fission power level (Figure 7.4-1) asymptotically approaches the characteristic 79 second decay period of the longest lived delayed neutron precursor group (standard 6-group model).

The total system reactivity and its three components (positive ramp insertion, negative Doppler and void feedback) are given in Figure 7.4-3. This figure shows the early Doppler feedback reactivity which terminated the initial power excursion followed by the larger negative void reactivity which ultimately terminates the event. All values of the reactivity components have reached their asymptotic values by 30 seconds.

Maximum pressures in the WP system reach approximately 2.5e+05 Pa during the initial phases of the event as shown in Figure 7.4-4 and Figure 7.4-5, then return to near initial values. The lower final values reflect the gravity head from the reduced final fluid inventory as shown in Figure 7.4-6 and Figure 7.4-7.

The flow rate in the exit junction, ID 250010000, and junction IDs 230010000 and 230020000 are shown in Figure 7.4-8 over the total event period and in Figure 7.4-9 for an initial phase. The flow rate in the exit junction, ID 250010000, is limited by the choking model which controls the rate of inventory loss and pressure relief. The direction of flow for the exit junction is predominately outward

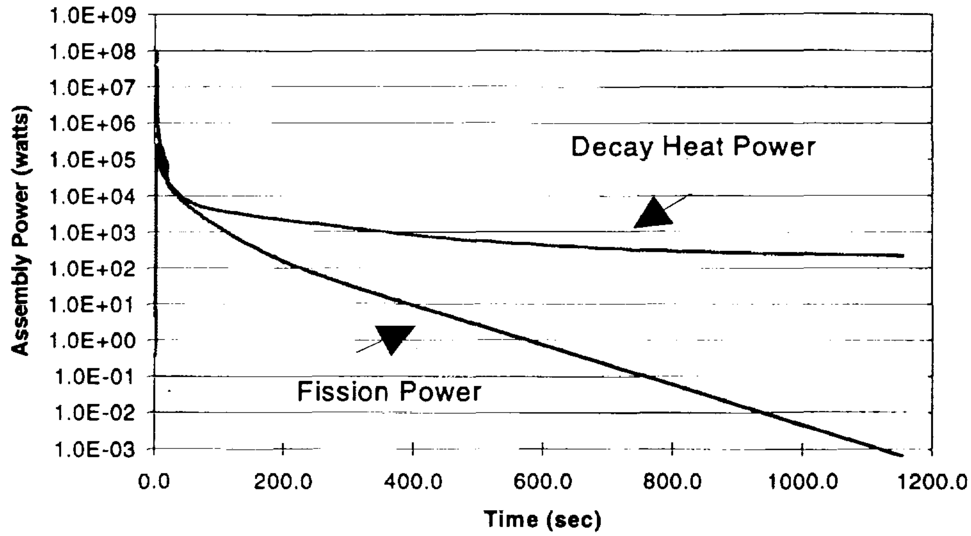

Figure 7.4-1. Assembly Power - 30 second Reactivity Insertion Scenario

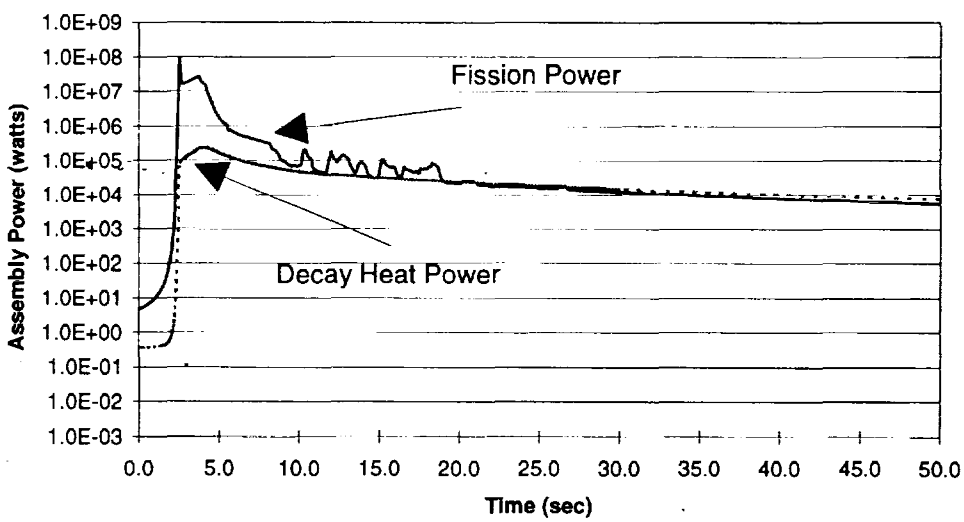

Figure 7.4-2. Assembly Power - 30 second Reactivity Insertion Scenario

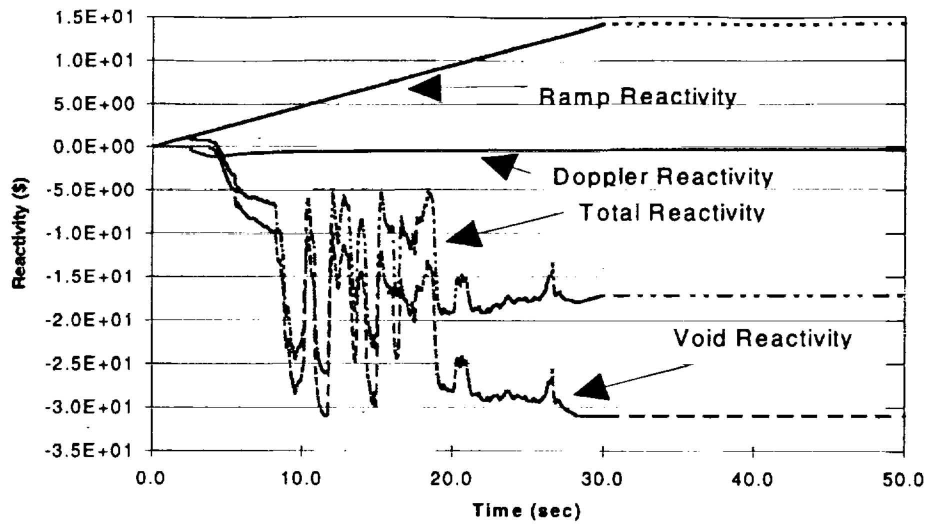

Figure 7.4-3. Reactivity Components - 30 second Reactivity Insertion Scenario

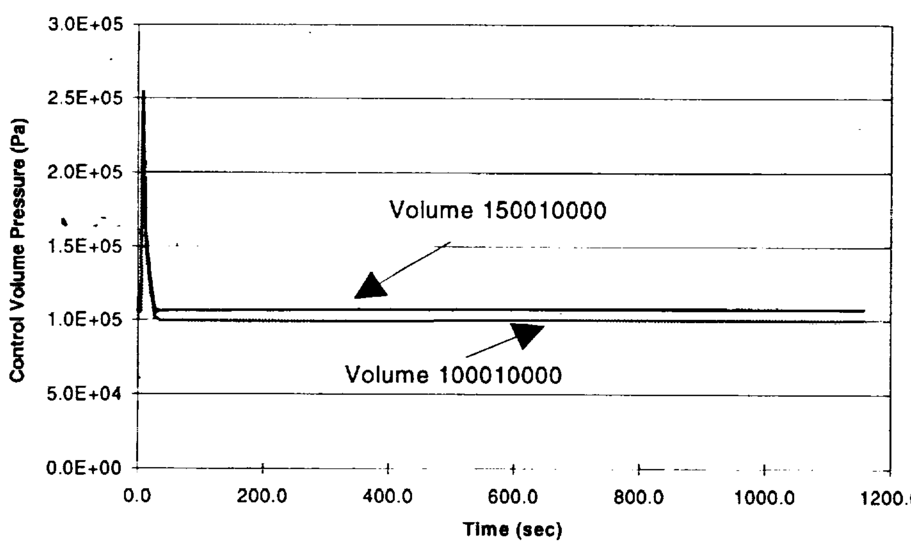

Figure 7.4-4. Volume Pressures - 30 second Reactivity Insertion Scenario

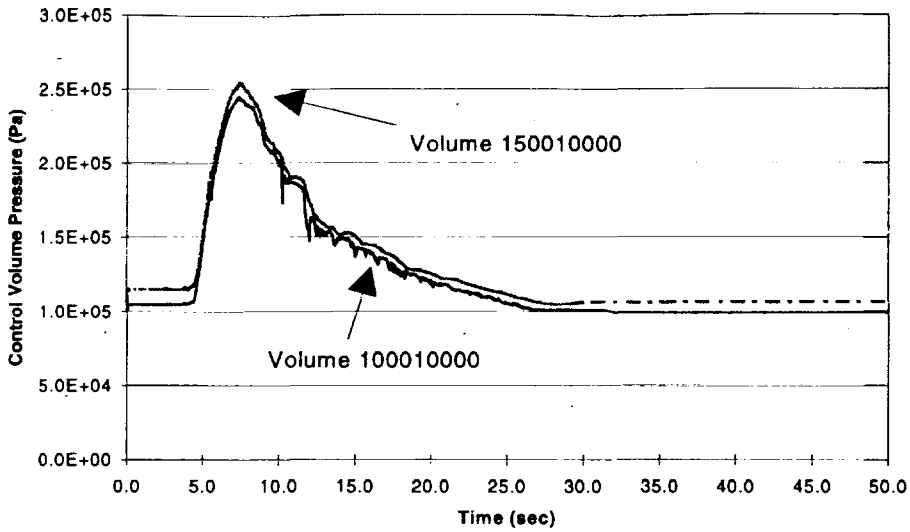

Figure 7.4-5. Volume Pressures - 30 second Reactivity Insertion Scenario

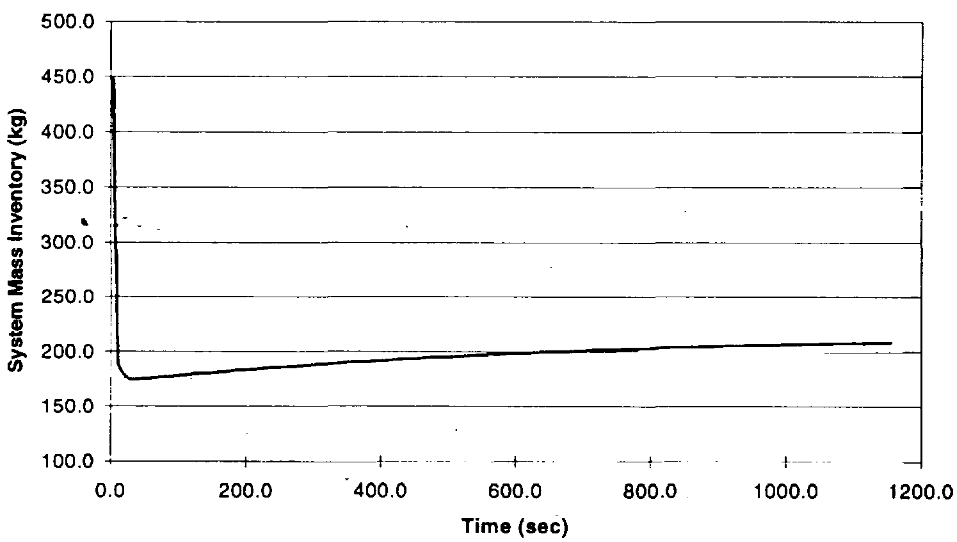

Figure 7.4-6. Waste Package Fluid Inventory - 30 second Reactivity Insertion Scenario

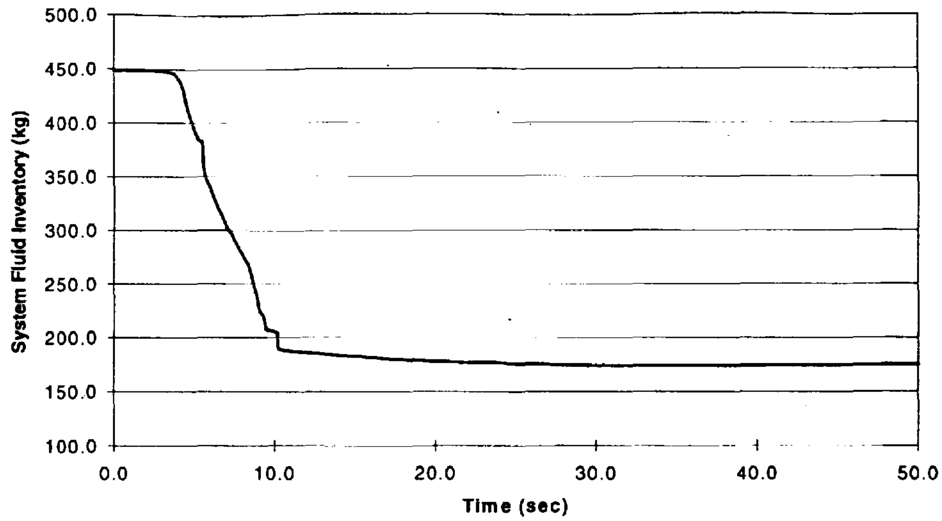

Figure 7.4-7. Waste Package Fluid Inventory - 30 second Reactivity Insertion Scenario

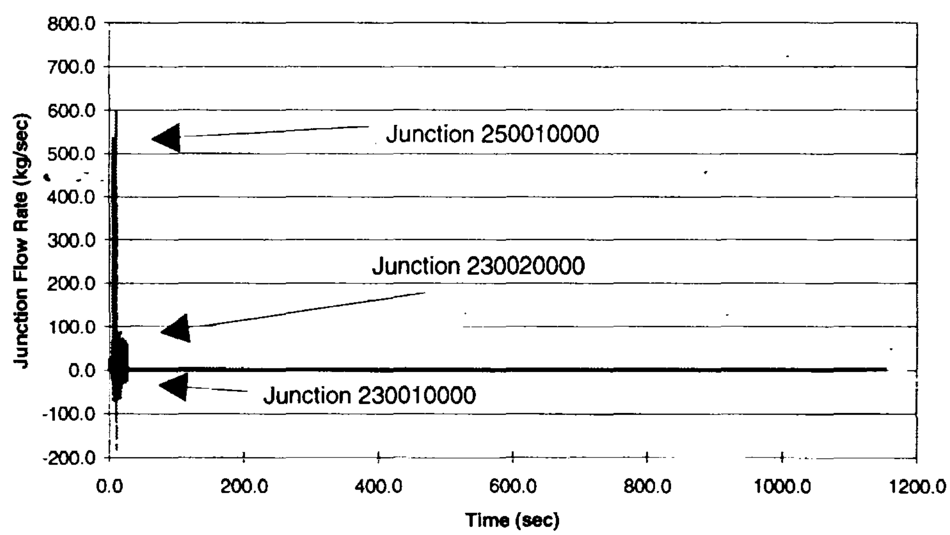

Figure 7.4-8. Junction Flow Rates - 30 second Reactivity Insertion Scenario

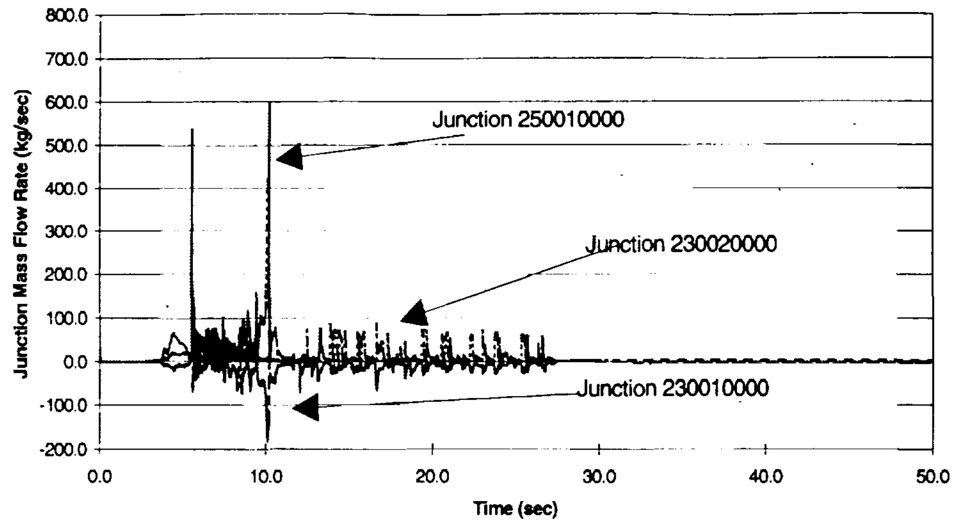

Figure 7.4-9. Junction Flow Rates - 30 second Reactivity Insertion Scenario

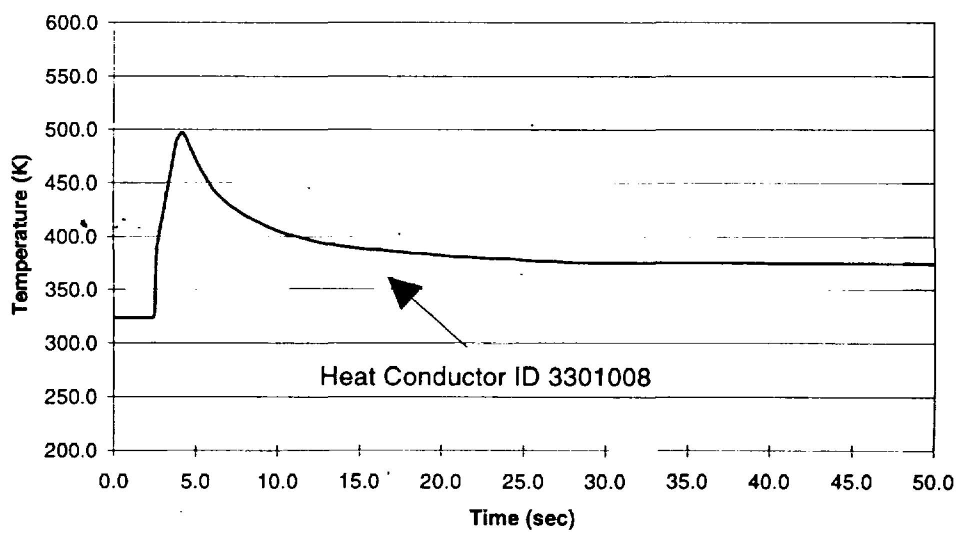

Figure 7.4-10. Average Metal Temperature - 30 second Reactivity Insertion Scenario

(inventory loss) with very low reverse mass flow rates since the external environment (Control Volume 260010000) was specified as water vapor. Interior junctions, as shown in these figures, may experience either positive or negative flow rates as the pressure distribution dictates. As stated previously, the system returns to a stable sub-critical configuration following the initial activity.

The much lower reactivity insertion rate in the 3600 second reactivity insertion scenario, and thus the energy generation rate, resulted in a less severe transient response than for the 30 second reactivity insertion scenario as listed in Table 7.4-1. The time evolution of key parameters from this scenario is shown in Figure 7.4-11 through Figure 7.4-20, respectively, for assembly power, reactivity components, control volume pressures, WP fluid inventory, junction flow rates, and average fuel temperature. Two ranges are shown, as above, for several of the parameters, one showing a panoramic view of the parameter value over the total time period, and the second providing a higher resolution study over a limited time scale. In the 3600 second reactivity insertion scenario, the power excursion is terminated by the negative Doppler reactivity (Figure 7.4-13) with fuel pin metal temperatures (Figure 7.4-20) at values where subcooled boiling can be initiated. The initial vapor generation was coincident with the initial WP inventory loss (Figure 7.4-15) but did not result in a prominent pressure surge as shown in Figure 7.4-16. During the 200-600 second time period in the scenario, negative reactivity from the void and Doppler effects was nearly equal to the positive ramp insertion reactivity, maintaining the power level (Figure 7.4-12). An increase in the vapor generation rate around 600 seconds into the scenario resulted in a pressure surge (Figure 7.4-16) and further inventory loss. As shown in Figure 7.4-13, the large negative void reactivity component prevents any possible return to criticality in the WP system and the fission power level (Figure 7.4-11) asymptotically approaches the characteristic 80 second decay profile. The inventory loss at this point is sufficient to prevent any possible return to critical conditions until the WP refills with water which has a time scale of years.

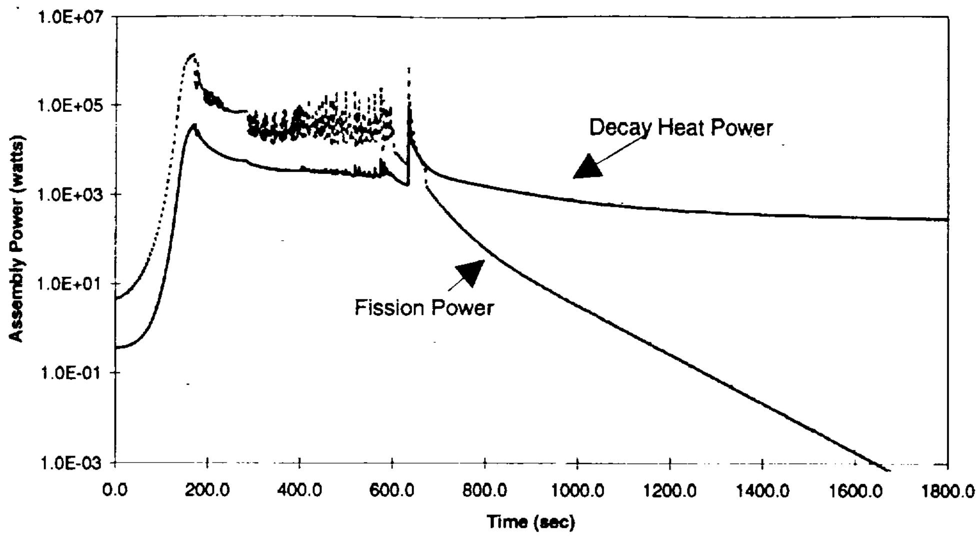

Figure 7.4-11. Assembly Power - 3600 second Reactivity Insertion Scenario

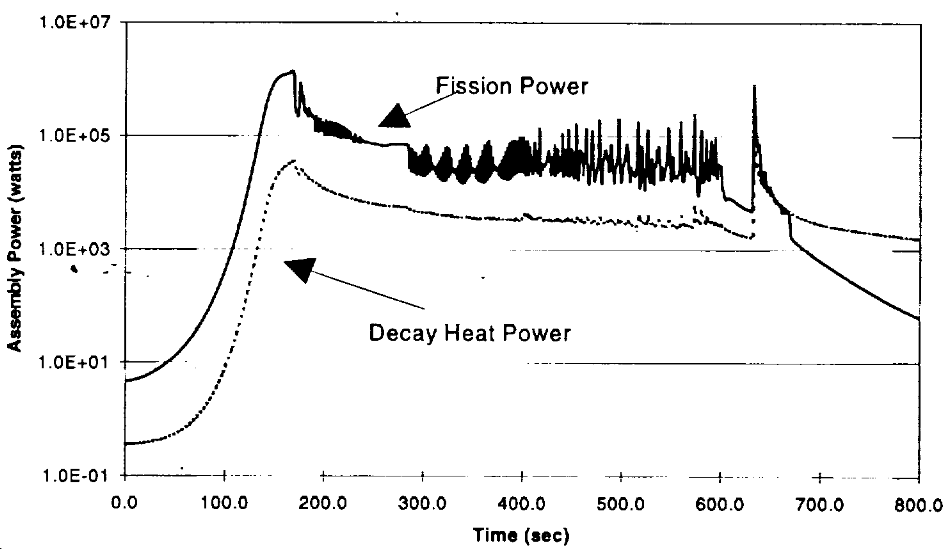

Figure 7.4-12. Assembly Power - 3600 second Reactivity Insertion Scenario

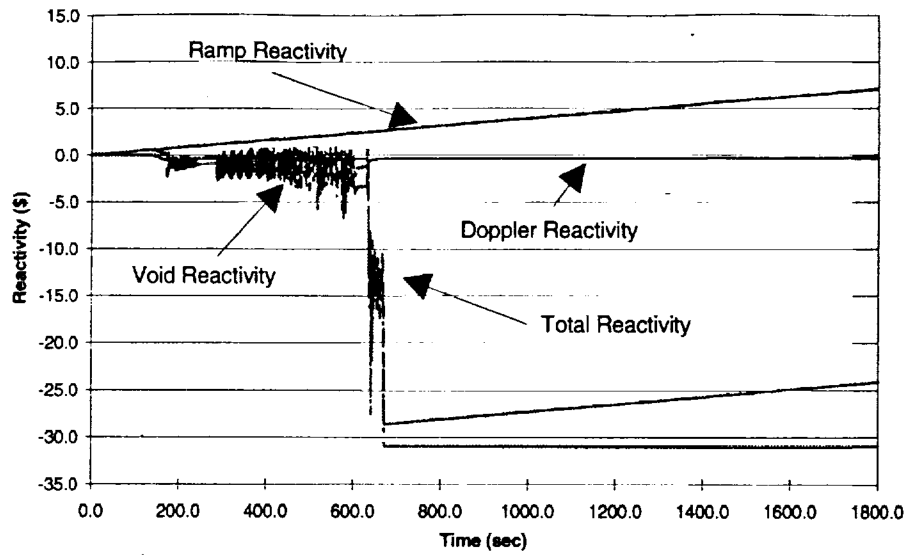

Figure 7.4-13. Component Reactivity - 3600 second Reactivity Insertion Scenario

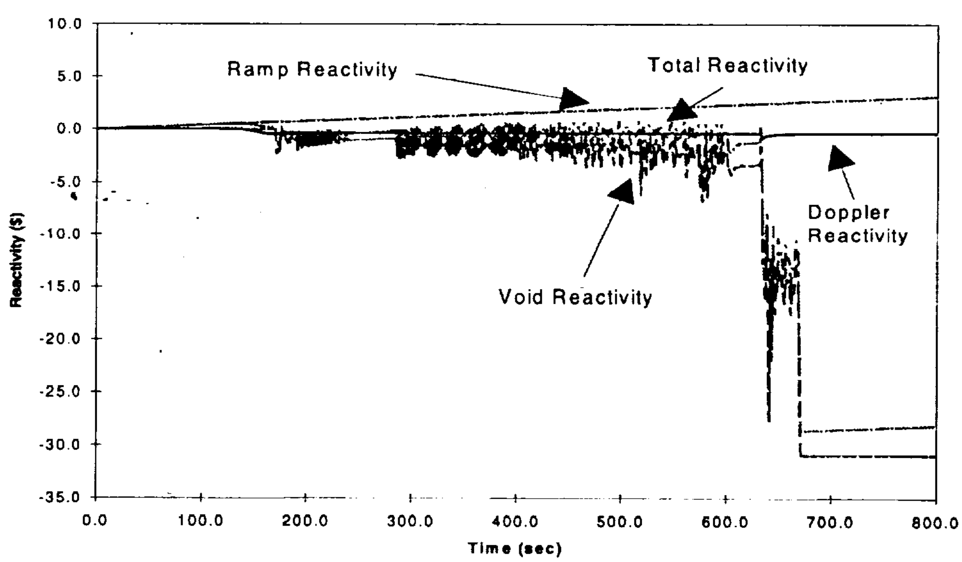

Figure 7.4-13. Component Reactivity - 3600 second Reactivity Insertion Scenario

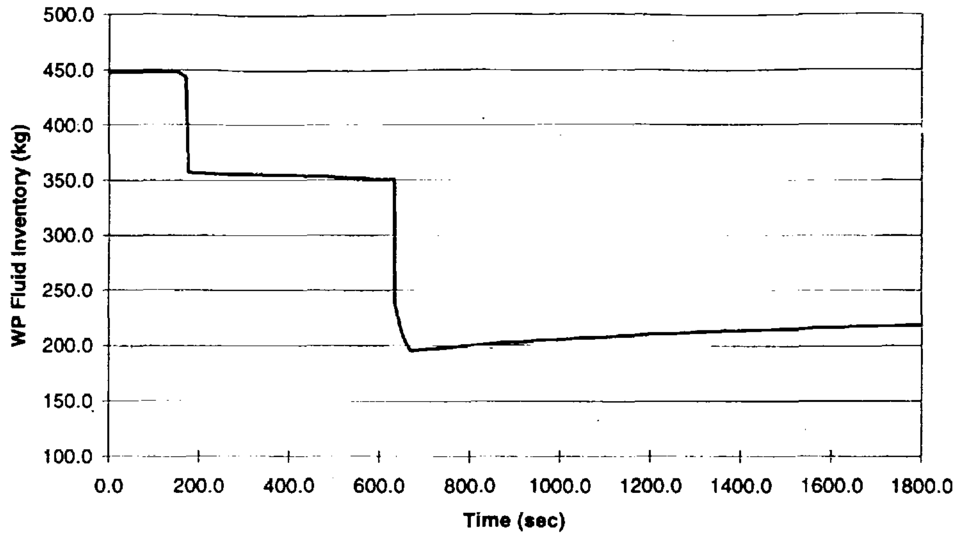

Figure 7.4-15. Waste Package Fluid Inventory - 3600 second Reactivity Insertion Scenario

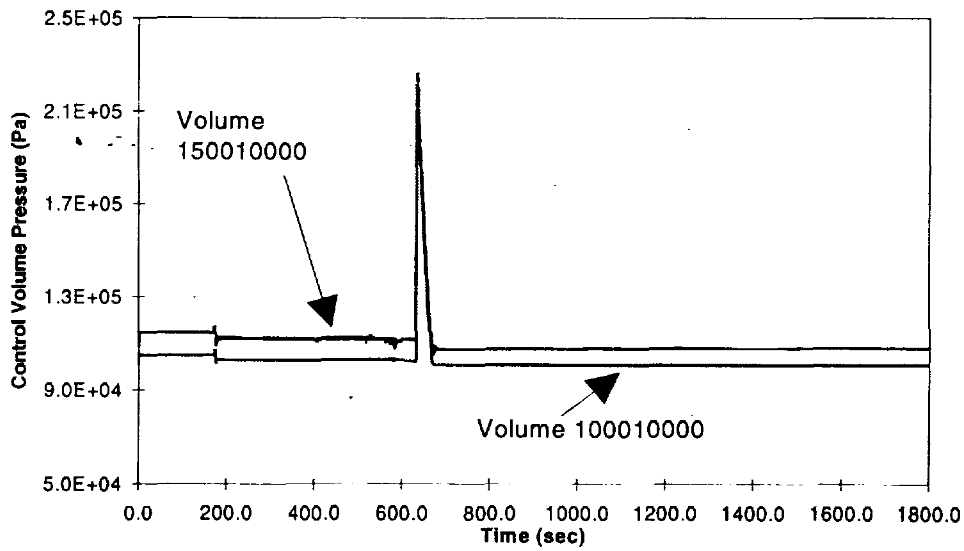

Figure 7.4-16. Volume Pressures - 3600 second Reactivity Insertion Scenario

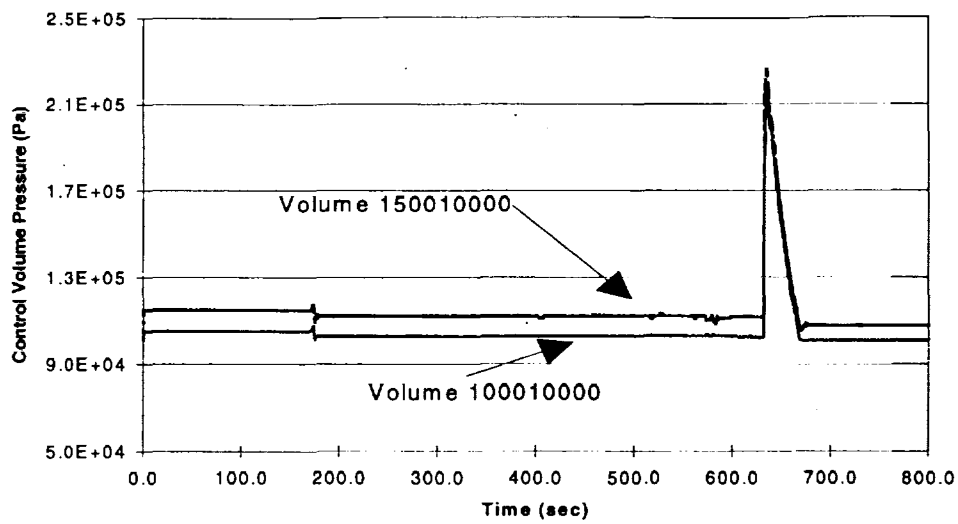

Figure 7.4-17. Volume Pressures - 3600 second Reactivity Insertion Scenario

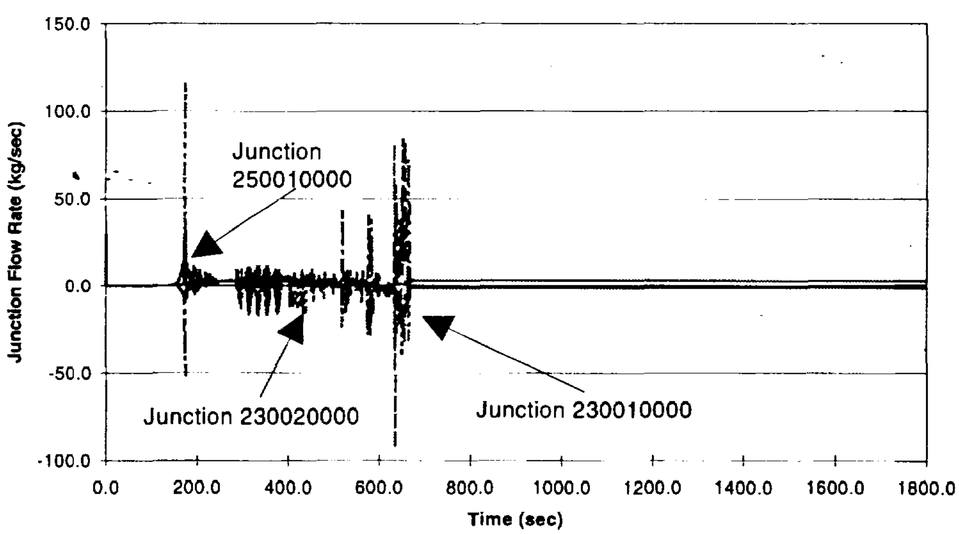

Figure 7.4-18. Junction Flow Rates - 3600 second Reactivity Insertion Scenario

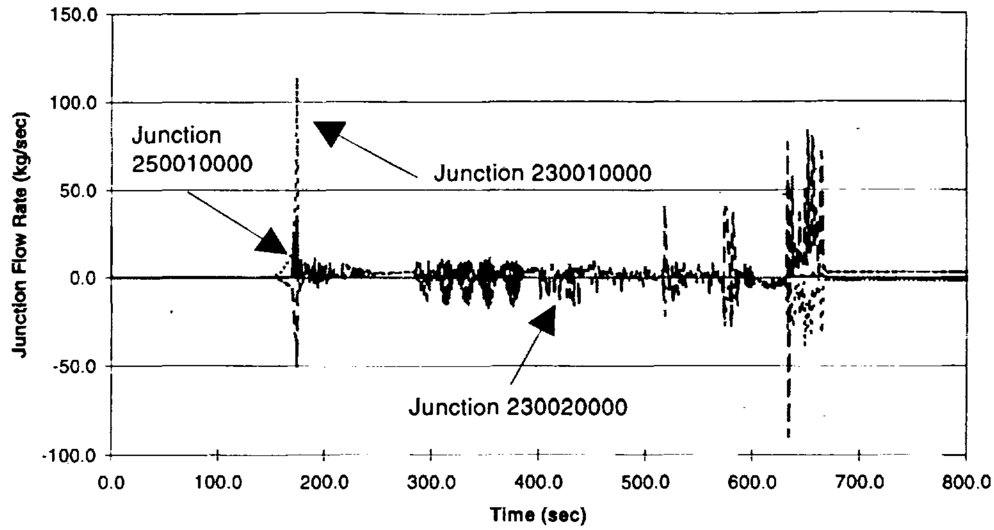

Figure 7.4-19. Junction Flow Rates - 3600 second Reactivity Insertion Scenario

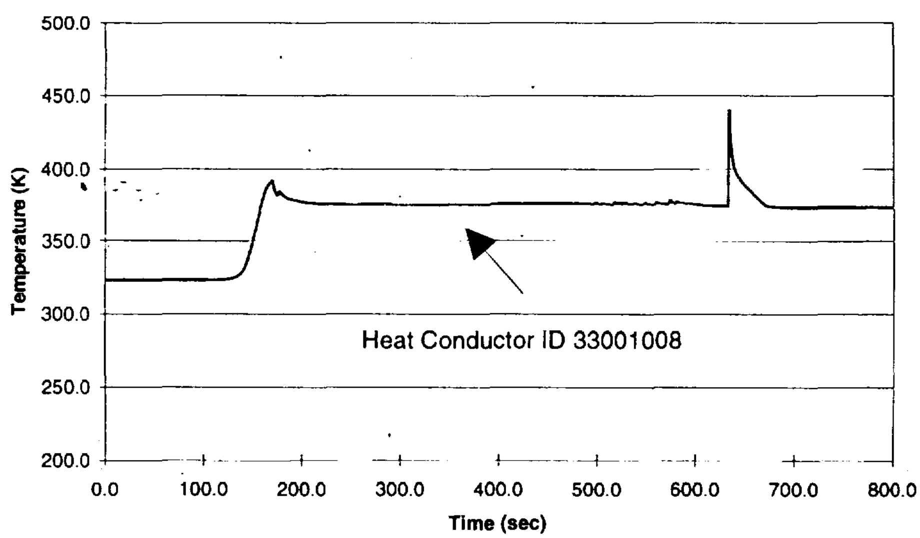

Figure 7.4-20. Average Metal Temperature - 3600 second Reactivity Insertion Scenario

7.5 Changes to the Radionuclide Inventory Due to Transient Criticality Event

To evaluate the effects of a criticality on the radionuclide inventory of a waste package, the code sequence SAS2H was run using the PWR criticality design basis fuel, power histories from the RELAP5 analyses, and a decay period of one year. The maximum decay period of one year was based on the short operating time of the criticality event which precludes formation of significant inventories of long lived isotopes. The transient fission power history and fuel temperature, listed in Table 7.5-1, for the SAS2H input files (short.inp, long.inp) were approximated by histograms derived from the graphical data shown in Section 7.4. Figure 7.4-1 and Figure 7.4-10 were the basis for the 30 second reactivity scenario histograms. Figure 7.4-11 and Figure 7.4-20 were the basis for the 3600 second reactivity insertion scenario histograms. The burnup calculated from these histograms (summation of time steps in days multiplied by power in MW and divided by 0.464 MTU) are only 1.6E-3 MWd/MTU and 1.8 MWd/MTU for the short and the long cases, respectively. The output of the SAS2H runs (short.out and long.out) list the radionuclide inventories in curies for the 30 second and 3600 second reactivity insertion scenarios, respectively. These values are compared in Table 7.5-2 to the initial radionuclide inventory for a 25,000 year decay period generated as part of a previous analysis (Ref. 5.13). The initial analysis contained 36 isotopes in the radionuclide inventory. For this analysis, only those isotopes whose inventories after one year decay differed from the original values by a minimum cutoff value ($\sim 10^{-20}$) are listed. As shown, small differences appear in the fission product activity but the principal radioactivity is due to the actinide decay which is not significantly altered by the criticality events.

Note that the input compositions for the short and long SAS2H runs are based on the MCNP criticality compositions which have been adjusted up to 96% of 10.96 g/cm^3 (theoretical density of natural UO_2). The 25,000 year decay case to which the results are compared has compositions based on a UO_2 density of 10.206. Therefore, the activities for the isotopes for which a composition was specified in the inputs for the long and short cases must be multiplied by 0.97 (10.206/10.5216) to be compared on the same basis.

Table 7.5-1. ORIGEN-S Input Parameters

Case	Power (MW)	Burn Time (days)	Fuel Temperature (K)
30 second Reactivity Scenario (short.out)			
	9.0	0.0000023	326.5
	50.0	0.0000023	383.2
	25.0	0.000015	469.3
	2.0	0.000023	455.4
	0.5	0.000069	422.1
	0.3	0.00046	388.8
3600 second Reactivity Scenario (long.out)	*	*	*
	0.5	0.00046	327.6
	1.0	0.00023	374.8
	0.5	0.00035	380.4
	0.07	0.0093	376.5
	0.03	0.0035	376.5
	0.01	0.001	373.2

Table 7.5-2. Radionuclide Inventory after One Year Decay Period

Isotope	Initial Activity (Ci) (Ref. 5.13)	30 second Reactivity Scenario (short.out) Increase (Ci)	3600 sec Reactivity Scenario (long.out) Increase (Ci)
Actinides	-	-	-
th229	3.71e-02	5.63e-06	5.63e-06
th230	2.60e-01	1.17e-05	1.17e-05
pa231	9.01e-03	5.20e-07	5.20e-07
u233	6.20e-02	-	-
u234	1.23e+00	-	-
u235	2.33e-02	-	-
u236	2.25e-01	-	-
u238	1.45e-01	-	-
np237	6.10e-01	-	-
pu238	0.00e+00	5.65e-04	6.27e-04
pu239	9.74e+01	-	-
pu240	1.56e+01	-	-
pu241	5.72e-03	-	-
pu242	5.57e-01	-	-
am241	5.95e-03	-	-
am243	5.59e-01	-	-
cm244	0.00e+00	1.22e-05	1.34e-05
Fission Products	-	-	-
tc99	6.02e+00	1.34e-02*	1.34e-02*
sm151	0.00e+00	1.22e-04	1.36e-04

* These values may be significantly overestimated as a result of roundoff to 3 digits in SAS2H.

8. Conclusions

All conclusions in this section from RELAP5 calculations are TBV because the RELAP5/MOD3 code has not been qualified according QAP-SI-0 as indicated in Section 6.

The criticality consequence analyses performed for the fully degraded internal structure of a 21 PWR WP loaded with 15X15 B&W SNF demonstrated that, based upon conservative assumptions, the system remains in a safe configuration following scenarios where 14.18$ of positive reactivity is added to the WP system over time scales of 30 to 3600 seconds. The 14.18$ reactivity value represents the maximum possible reactivity attainable in the WP designs as discussed in Section 7.2.3. The probability of these criticality scenarios will be addressed in separate analyses (TBD). The results of the preliminary analysis in Section 7.4 show that the PWR SNF WP system returns to a subcritical configuration with the fuel rod temperatures and WP internal pressures remaining well below levels which could melt fuel or generate more than minor effects on adjacent WP systems (e.g. humidity levels will temporarily increase in the drift environment). The results discussed in Section 7.4 also show that consequences of a reactivity insertion event decrease in severity as the insertion rate decreases. However, the final state of the system, where sufficient water is lost from the WP to maintain a subcritical state, depends primarily on the energy generated rather than the rate, since steam formation is the primary energy dissipation mechanism in the WP.

Consequently, criticality events in a WP will be restricted to localized incidents and not involve additional WPs or affect the overall integrity of the repository. The principal impact on the environment external to the WP experiencing a criticality event is the return of water in vapor form to the drift environment increasing the ambient humidity. This should not significantly impact the WP environment in an adverse manner since the presence of water in the environment is assumed initially. Although not considered in the RELAP5 model, condensation of the water vapor will prevent any significant over pressurization of adjacent WP modules since the drift environment is assumed to be 326.2 K. The criticality analysis of the WP (Ref. 5.13) showed that the system is subcritical unless the SNF in the WP is submerged in water. This criticality consequence analysis shows that sufficient water inventory is expelled from the WP to preclude any immediate return to a critical configuration. Flooding the WP to levels where criticality is again possible would require several years even at the most conservative flow rates forecast for the drift region.

Burnup from the transient reactivity scenarios was less than 2.0e-03 Mwd/MTU per scenario. The ORIGEN-S analysis of the scenarios showed that the radionuclide inventories in a WP had a negligible increase after a one year decay period which will have no significant effects on the WP or repository.

9. Attachments

The hardcopy attachments are listed in Table 9-1 below. Electronic attachments are provided on Colorado Trakker® tapes (Ref. 5.22) and are listed in Table 9-2 below for REV 00 Cases.

Table 9-1. Attachments of Supporting Documentation for Criticality Consequence Analysis Involving Intact PWR SNF in a Degraded 21 PWR Assembly Waste Package

Attachment Number	Description	Pages
I	Base MCNP Case (R58H13F)	4
II	Base SAS2H Case (IN.WP)	3
III	Terminal Velocity Calculation	1
IV	RELAP5 Input File (R5WP2D.03C)	17

Table 9-2. Attachments of Computer Outputs for Criticality Consequence Analysis

File Name	File Size (Bytes)	File Date	File Time of Day
ANS79.P	95,956	9/2/97	4:42p
EDHTRK.P	610,033	9/2/97	4:42p
EDHTRKD.P	605,830	9/2/97	4:42p
EDHTRKN.P	605,649	9/2/97	4:42p
EDRST.P	699,984	9/2/97	4:42p
EDSTRIP.P	7,743	9/2/97	4:42p
MARPZD4.P	693,794	9/2/97	4:42p
PUMP2.P	1,362,805	9/2/97	4:42p
TYPPWR.P	1,677,913	9/2/97	4:42p
TYPPWRN.P	1,679,245	9/2/97	4:43p
INFH2O.O	547,580	8/29/97	1:31p
INFOX.O	234,872	8/29/97	1:31p
OUT.E49	2,694,284	7/22/97	7:23p
OUT.FE	2,730,022	7/22/97	7:23p

Table 9-2. Attachments of Computer Outputs for Criticality Consequence Analysis

File Name	File Size (Bytes)	File Date	File Time of Day
INFLUX2O	556,209	8/29/97	1:31p
OUT.WP	2,738,210	8/29/97	1:23p
INFH2OaO	544,337	8/29/97	1:31p
OUT.FIN	2,694,880	8/19/97	7:46p
H2OH13FO	579,852	8/29/97	1:28p
OUT.WPN	2,694,372	7/22/97	7:59p
OUT.WP	2,738,210	8/29/97	1:23p
OUT~1.122	2,740,086	8/29/97	1:23p
OUT~2.122	2,740,107	8/29/97	1:23p
OUT~2.212	2,740,122	8/29/97	1:24p
OUT~1.212	2,740,122	8/29/97	1:23p
OUT~1.320	2,740,236	8/29/97	1:23p
OUT~5.518	2,740,464	8/29/97	1:24p
OUT~4.518	2,740,443	8/29/97	1:24p
OUT~3.518	2,738,807	8/29/97	1:24p
OUT~2.518	2,738,828	8/29/97	1:24p
OUT~1.518	2,738,828	8/29/97	1:23p
OUT~9.100	2,739,362	8/29/97	1:25p
OUT~8.100	2,739,341	8/29/97	1:25p
OUT~7.100	2,737,726	8/29/97	1:25p
OUT~6.100	2,737,684	8/29/97	1:25p
OUT~5.100	2,740,464	8/29/97	1:24p
OUT~4.100	2,737,726	8/29/97	1:24p
OUT~3.100	2,736,174	8/29/97	1:24p
OUT~2.100	2,736,153	8/29/97	1:23p
OUT~1.100	2,736,216	8/29/97	1:23p
R5WP2D.SHT	18,830,566	9/2/97	4:24p
R5WP2D.LNG	18,839,913	9/2/97	4:23p
SHORT.OUT	22,131,092	9/2/97	3:52p
LONG.OUT	22,136,053	9/2/97	3:46p

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c     ASSEMBLY LATTICE
5     1  -3.4592  -61  60 -63  62  IMP:N=1 LAT=1 U=1
      FILL=0:3 0:7 0:0  1 3R  56 56 1  1  56 56 56 1
                        56 56 56 1  59 59 59 60  57 57 58  58
                        58 3R   58 3R       $ 1/2 model
c     BARRIER CELLS
c     Basket Material-Lid Gap
76    8  -1.0000    1 -20  13  -14      IMP:N=1 $ 1/2 model
c     Inner Barrier
77    5  -8.4425    1   3  20 -21 -14  IMP:N=1 $ 1/2 model
c     Inner Lid
78    5  -8.4425    1  14 -15 -21      IMP:N=1 $ 1/2 model
c      Gap between Inner and Outer Barrier Lids
79    8  -1.0000    1  15 -16 -21      IMP:N=1 $ 1/2 model
c      Gap between Inner and Outer Barriers
80    8  -1.0000   21 -22   1   3 -16  IMP:N=1 $ 1/2 model
c     Outer Barrier
81    7  -7.8320   22 -24   1   3 -16  IMP:N=1 $ 1/2 model
c     Outer Barrier Lid
82    7  -7.8320    1 -24  16 -17      IMP:N=1 $ 1/2 model
c     12" of Water around Container
83    8  -1.0000   24 -25   1   3 -17  IMP:N=1 $ 1/2 model
c     12" of Water above Container
84    8  -1.0000   17 -19   1 -25      IMP:N=1 $ 1/2 model
c     OUTSIDE WORLD
85    0  -1:-3:19:25  IMP:N=0  $ 1/2 model
c     WET w/ Fe2O3 PIN LATTICE
86    1  -3.4592  -26 27 -28  29  IMP:N=1 LAT=1  U=56
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                          56 2 4R 4 2 2R 4 2 4R 56
                          56 2 14R 56  56 2 14R 56  56 16R
c     Water LATTICE
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                          57 3 2R 5 3 6R 5 3 2R 57  57 3 14R 57
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                          57 3 14R 57
                          57 3 6R 7 3 6R 57
                          57 3 14R 57
                          57 3 3 5 3 3 5 3 2R 5 3 3 5 3 3 57
                          57 3 14R 57  57 3 2R 5 3 6R 5 3 2R 57
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91    1  -3.4592    -30  11      IMP:N=1 U=2
92    8  -1.0000     30 -31 -11 IMP:N=1 U=2
93    1  -3.4592     30 -31  11 IMP:N=1 U=2
94    4  -6.5600     31 -32 -11 IMP:N=1 U=2
95    1  -3.4592     31 -32  11 IMP:N=1 U=2
96    1  -3.4592     32          IMP:N=1 U=2
c     Wet FUEL ROD
97    2    6.982783E-02 -30 -10      IMP:N=1 U=3
98    4  -6.5600    -30  10 -11 IMP:N=1 U=3
```

```
99     8  -1.0000   -30  11       IMP:N=1 U=3
100    8  -1.0000    30 -31 -11 IMP:N=1 U=3
101    8  -1.0000    30 -31  11 IMP:N=1 U=3
102    4  -6.5600    31 -32 -11 IMP:N=1 U=3
103    8  -1.0000    31 -32  11 IMP:N=1 U=3
104    8  -1.0000    32         IMP:N=1 U=3
C      WET w/ Fe2O3 CONTROL ROD/GUIDE TUBE
105    8  -1.0000  -33        IMP:N=1 U=4  $ No DCRA Rod
C      105   9  -7.8300  -33        IMP:N=1 U=4  $ DCRA Rod
106    1  -3.4592   33  -34  IMP:N=1 U=4
107    1  -3.4592   34  -35  IMP:N=1 U=4  $ No DCRA Cladding
C      107   4  -6.5600   34  -35  IMP:N=1 U=4  $ DCRA Cladding
108    1  -3.4592   35  -36  IMP:N=1 U=4
109    4  -6.5600   36  -37  IMP:N=1 U=4
110    1  -3.4592   37       IMP:N=1 U=4
C      Wet CONTROL ROD/GUIDE TUBE
111    8  -1.0000  -33        IMP:N=1 U=5  $ No DCRA Rod
C      111   9  -7.8300  -33        IMP:N=1 U=5  $ DCRA Rod
112    8  -1.0000   33  -34  IMP:N=1 U=5
113    8  -1.0000   34  -35  IMP:N=1 U=5  $ No DCRA Cladding
C      113   4  -6.5600   34  -35  IMP:N=1 U=5  $ DCRA Cladding
114    8  -1.0000   35  -36  IMP:N=1 U=5
115    4  -6.5600   36  -37  IMP:N=1 U=5
116    8  -1.0000   37       IMP:N=1 U=5
C      WET w/ Fe2O3 INSTRUMENTATION TUBE
117    8  -1.0000  -38          IMP:N=1 U=6
118    4  -6.5600   38 -39      IMP:N=1 U=6
119    1  -3.4592   39          IMP:N=1 U=6
C      Wet INSTRUMENTATION TUBE
120    8  -1.0000  -38          IMP:N=1 U=7
121    4  -6.5600   38 -39      IMP:N=1 U=7
122    8  -1.0000   39          IMP:N=1 U=7
C      WET w/ Partial Fe2O3 PIN LATTICE
123    1  -3.4592  -26 27 -28  29  IMP:N=1 LAT=1  U=59
       FILL -8:8 -8:8 0:0  59 16R  59 2 14R 59  59 2 14R 59
                           59 2 4R 4 2 2R 4 2 4R 59
                           59 2 2R 4 2 6R 4 2 2R 59  59 2 14R 59
                           59 2 2 4 2 2 4 2 2R 4 2 2 4 2 2 59
                           59 2 14R 59
                           59 2 6R 6 2 6R 59
                           59 3 14R 59
                           59 3 3 5 3 3 5 3 2R 5 3 3 5 3 3 59
                           59 3 14R 59  59 3 2R 5 3 6R 5 3 2R 59
                           59 3 4R 5 3 2R 5 3 4R 59
                           59 3 14R 59  59 3 14R 59  59 16R
C      Half Water/Half Fe2O3 LATTICE
124    8  -1.0000  -58 56 -59  66  IMP:N=1    U=60
125    1  -3.4592  -58 56 -66  57  IMP:N=1    U=60

C      SURFACE SPECIFICATIONS
1*    PX    0.0
3*    PZ    0.00
10    PZ  180.0860     $ TOP ACTIVE FUEL
11    PZ  201.2360     $ TOP FUEL HARDWARE
C     12   PZ  226.75      $ TOP TUBE - (Shielding Model)
13    PZ  228.75       $ TOP OF BASKET MATERIAL
14    PZ  229.25       $ TOP RING/WATER GAP
15    PZ  231.75       $ TOP INNER LID
16    PZ  234.75       $ TOP LID GAP
17    PZ  245.75       $ TOP OUTER LID
C     18   PZ  268.25      $ TOP SKIRT - (Shielding Model)
19    PZ  298.75       $ TOP REFLECTOR REGION
20    CZ   71.095      $ ID OF INNER BARRIER
21    CZ   73.095      $ OD OF INNER BARRIER
22    CZ   73.10       $ ID OF OUTER BARRIER
C     23   CZ   76.45      $ ID OF SKIRT LIP - (Shielding Model)
24    CZ   83.10       $ OD OF OUTER BARRIER
25    CZ  113.60       $ OD OF REFLECTOR REGION
C     PIN LATTICE BOUNDS
26    PX  0.72136
```

```
27   PX -0.72136
28   PY  0.72136
29   PY -0.72136
C     FUEL ROD
30   CZ  0.468122
31   CZ  0.478790
32   CZ  0.546100
C     CONTROL ROD/GUIDE TUBE
33   CZ  0.45340  $ 0.49022
34   CZ  0.46990  $ 0.50292
35   CZ  0.54610  $ 0.56007
36   CZ  0.62230  $ 0.63246
37   CZ  0.67310
C     INSTRUMENTATION TUBE
38   CZ  0.56007
39   CZ  0.62611
C    ASSEMBLY LATTICE BOUNDS Actual
56   PX  -11.95    $ UCF Intact Outside Tube ID
57   PY  -11.95
58   PX   11.95
59   PY   11.95
C    FUEL CELL LATTICE BOUNDS
60   PX  -10.65     $ ACTUAL 12.30
61   PX   10.65
62   PY  -10.65
63   PY   10.65
C    plane for half water/half oxide lattice cell
66   PY   0.72136

MODE  N
C     VOL   88J
KCODE   4000 1.01 10 400
C       MATERIAL SPECIFICATIONS
C          WATER AT 300 K d=3.4592 g/cc w/ 58% Fe2O3
M1    1001.50C  2.8089-2    8016.50C  4.8430-2  26000.55C 2.2924-2
MT1   LWTR.01T
C     e49b34.sum   25000  years decay
M2    8016.50C   .046947
     42095.50C   4.794679E-05
     44101.50C   4.354501E-05
     43099.50C   4.284296E-05
     45103.50C   2.608717E-05
     47109.50C   3.714096E-06
     60143.50C   3.74851E-05
     60145.50C   2.799527E-05
     62147.50C   1.138963E-05
     62149.50C   1.455085E-07
     62150.50C   1.043884E-05
     62152.50C   4.59594E-06
     63151.55C   8.136066E-07
     63153.55C   3.93607E-06
     64155.50C   1.686186E-07
     92233.50C   3.326725E-07
     92234.50C   1.018437E-05
     92235.50C   5.531404E-04
     92236.50C   1.774777E-04
     92238.50C   2.174501E-02
     93237.55C   4.392789E-05
     94239.55C   7.906197E-05
     94240.50C   3.440139E-06
     94241.50C   2.761636E-12
     94242.50C   7.012276E-06
     95241.50C   8.639479E-11
     95243.50C   1.386765E-07
C          Air d=0.001225 g/cc
M3    7014.50C  -0.80   8016.50C  -0.20
C          ZIRCALOY-4 d=6.56 g/cc
M4    8016.50C -0.0012  24000.50C -0.0010  26000.55C -0.0020
     40000.50C -0.9818  50000.35C -0.0140
C         ALLOY 625 d=8.4425 g/cc
```

```
M5    6000.50C -0.1000  13027.50C -0.4000  14000.50C -0.5000
     16032.50C -0.0150  22000.50C -0.4000  24000.50C -21.500
     25055.50C -0.5000  26000.55C -5.0000  28000.50C -58.000
     41093.50C -1.8200  42000.50C -9.0000  73181.50C -1.8200
     15031.50C -0.0150  27059.50C -0.9300
C        A516 CARBON STEEL d=7.832 g/cc
M7    6000.50C -0.00220  14000.50C -0.002750  15031.50C -0.00035
     16032.50C -0.00035  25055.50C -0.0090
     26000.55C -0.98535
C         WATER AT 300 K d=1.0000 g/cc
M8    1001.50C  2.    8016.50C  1.
MT8   LWTR.01T
C    TALLIES
PRINT
```

```
1          primary module access and input record ( scale driver - 95/03/29 - 09:06:37 )
-    module sas2h     will be called
      SAS2H: 4.9wt%, 34GWD/MTU, 25000yr, Waste-Pack Buckling Model
      '
      ' Iron (Fe2O3) rust in the water around the fuel pins  58 vol. %
      '
      ' Blending from MCNP = 0.751311 water + .248689 rusty water
      '
      ' B & W  15x15 fuel assembly, high temp burnup
      '
      44group      latticecell
      '
      '  MCNP input mixtures for fuel-pin-cell, assembly-cell, and waste package
      '
       o          1 0 4.694700-02 300.00 end
       u-233      1 0 3.326725-07 300.00 end
       u-234      1 0 1.018437-05 300.00 end
       u-235      1 0 5.531404-04 300.00 end
       u-236      1 0 1.774777-04 300.00 end
       u-238      1 0 2.174501-02 300.00 end
      np-237      1 0 4.392789-05 300.00 end
      pu-239      1 0 7.906197-05 300.00 end
      pu-240      1 0 3.440139-06 300.00 end
      pu-241      1 0 2.761636-12 300.00 end
      pu-242      1 0 7.012276-06 300.00 end
      am-241      1 0 8.639479-11 300.00 end
      am-243      1 0 1.386765-07 300.00 end
      mo-95       1 0 4.794679-05 300.00 end
      tc-99       1 0 4.284296-05 300.00 end
      ru-101      1 0 4.354501-05 300.00 end
      rh-103      1 0 2.608717-05 300.00 end
      ag-109      1 0 3.714096-06 300.00 end
      nd-143      1 0 3.748510-05 300.00 end
      nd-145      1 0 2.799527-05 300.00 end
      sm-147      1 0 1.138963-05 300.00 end
      sm-149      1 0 1.455085-07 300.00 end
      sm-150      1 0 1.043884-05 300.00 end
      sm-152      1 0 4.595940-06 300.00 end
      eu-151      1 0 8.136066-07 300.00 end
      eu-153      1 0 3.936070-06 300.00 end
      gd-155      1 0 1.686186-07 300.00 end
      kr-83       1 0 1-20        300.00 end
      kr-85       1 0 1-20        300.00 end
       y-89       1 0 1-20        300.00 end
      sr-90       1 0 1-20        300.00 end
      zr-93       1 0 1-20        300.00 end
      zr-94       1 0 1-20        300.00 end
      zr-95       1 0 1-20        300.00 end
      nb-94       1 0 1-20        300.00 end
      ru-106      1 0 1-20        300.00 end
      rh-105      1 0 1-20        300.00 end
      pd-105      1 0 1-20        300.00 end
      pd-108      1 0 1-20        300.00 end
      sb-124      1 0 1-20        300.00 end
      xe-131      1 0 1-20        300.00 end
      xe-132      1 0 1-20        300.00 end
      xe-135      1 0 1-20        300.00 end
      xe-136      1 0 1-20        300.00 end
      cs-134      1 0 1-20        300.00 end
      cs-135      1 0 1-20        300.00 end
      cs-137      1 0 1-20        300.00 end
      ba-136      1 0 1-20        300.00 end
      la-139      1 0 1-20        300.00 end
      pr-141      1 0 1-20        300.00 end
      pr-143      1 0 1-20        300.00 end
      nd-147      1 0 1-20        300.00 end
      ce-144      1 0 1-20        300.00 end
      pm-147      1 0 1-20        300.00 end
      pm-148      1 0 1-20        300.00 end
      eu-154      1 0 1-20        300.00 end
```

```
eu-155      1 0 1-20        300.00 end
'---------------------------------------
'
'  Homogenized zirc-4 clad and water gap
'
' water - o  2 0 4.27077-03  300.00 end
' zirc4 - o  2 0 2.602667-04  300.00 end
'
 h          2 0 8.54154-03  300.00 end
 o          2 0 4.52929-03  300.00 end
cr          2 0 6.62716-05  300.00 end
fe          2 0 1.23407-04  300.00 end
zr          2 0 3.70866-02  300.00 end
arbm-sn  5.7221016 1  0  0  0  50000  100.0
            2 0.013999775   300.00 end
'
'  sn          2 0 4.06386-04  300.00 end
'-------------------------------------------
'
'  Moderator around fuel pins and guide tubes
'
'     Assembly with iron
'
'   h          3  0  2.8089-02  300.00  end
'   o          3  0  4.8430-02  300.00  end
'   fe         3  0  2.2924-02  300.00  end
'
'     MCNP K-inf blended iron assembly
'
'  Contains (1-x) 58 vol% Fe2O3 water and x pure water
'  with x=0.734106 from blending equation
'
h           3  0  5.72276-02  300.00  end
o           3  0  3.71651-02  300.00  end
fe          3  0  5.70095-03  300.00  end
'
' 0 ppm boron
'-------------------------------------------
'
'  Zirc-4
'
 o          4 0 2.98378-04  300.00 end
cr          4 0 7.59759-05  300.00 end
fe          4 0 1.41478-04  300.00 end
zr          4 0 4.25173-02  300.00 end
arbm-sn     6.5600  1  0  0  0  50000  100.0
            4 0.013999775   300.00 end
'
'  sn          4 0 4.65894-04  300.00 end
'-------------------------------------------
'
'  Water region inside of the guide tubes
'
 o          5 0 3.34363-02  300.00 end
 h          5 0 6.68727-02  300.00 end
'
' 0 ppm boron
'-------------------------------------------
'
end comp
'--------------------------------------------
'
'  fuel - pin - cell geometry:
'
'  Water - Zirc-4  homogenized for water in gap
'
'  MCNP assembly pitch = 10.65 + 10.65 = 21.30
'
'  21.30/15(pin-cells) = 1.42 pin-cell pitch
'
```

```
squarepitch  1.42000  0.936244  1   3  1.0922  2 0.936245 0 end
'
'  Standard pin-cell pitch = 1.44272
'
'  squarepitch  1.44272  0.936244  1   3  1.0922  2 0.936245  0 end
'
'  Standard gap with gas and standard clad
'
'  squarepitch  1.44272  0.936244  1   3  1.0922  2 0.95758  0 end
'-----------------------------------------------------------------
'
'  Pin-cell buckling
'
more data   bkl=0.875108   dy=50.7843927
                           dz=360.172   end
'-----------------------------------------------------------------
'
'  assembly and cycle parameters
'
'  guide tube region is different
'
npin/assm=208 fuelngth=360.172 ncycles=1 nlib/cyc=1
printlevel=7 inplevel=3 numztotal=6   end
5  0.453400      2 0.453401      3 0.622300
4  0.6736472448  3 0.8011492  500 2.9146084
'
'  Assembly buckling
'
bon   end
nit   end
xsd
SAS2H: 4.9wt%, 34GWD/MTU, 25000yr, Inf-Assem, No iron
x5=  1.0-4  1.0-4  1.0  0.0  0.0  0.875108
      50.7843927   360.172   0.0   1.0   1.0-3   0.75
   end
power=7.25 burn=1.0-20 down=1.0-20
   end
```

Size of small spherical particle required to fall 1 meter in 1 minute in water

Density of water at 120°F $\rho f := 988.8 \cdot \frac{kg}{m^3}$

Viscosity of water at 120°F $\mu := 5.62 \cdot 10^{-4} \cdot \frac{kg}{m \cdot sec}$

Density of Fe_2O_3 $\rho s := 5240 \cdot \frac{kg}{m^3}$

Terminal velocity as a function of diameter for small sphere's using Stoke's law (Re<=1)

$$Fd = m \cdot g - Fb$$

$$3 \cdot \pi \cdot \mu \cdot v \cdot D = \rho s \cdot \frac{4}{3} \cdot \pi \cdot \left(\frac{D}{2}\right)^3 \cdot g - \rho f \cdot g \cdot \frac{4}{3} \cdot \pi \cdot \left(\frac{D}{2}\right)^3$$

From Fox, R.W., McDonald, A.T., *Introduction to Fluid Mechanics*, 3rd Edition, John Wiley & Sons, 1985. p. 461

Solving for v yields

$$v(D) := \frac{1}{18} \cdot D^2 \cdot g \cdot \frac{(\rho s - \rho f)}{\mu} \qquad Re(D) := \frac{v(D) \cdot D \cdot \rho f}{\mu}$$

$$\frac{1 \cdot m}{v(.063 \cdot mm)} = 1.019 \cdot min \qquad Re(.063 \cdot mm) = 1.813$$

However, a 0.063 mm diameter sphere at terminal velocity slightly outside of the range of Stoke's law (drag will be slightly higher and particle will fall slightly slower than indicated).

Note that typical crud particle sizes are in the range of 0.1 to 10 microns per *Characteristics of Repository Wastes*, DOE/RW-0184 vol. 1, p. 2.6-6

$$\frac{1 \cdot m}{v(.010 \cdot mm)} = 40.441 \cdot min \qquad Re(.010 \cdot mm) = 7.251 \cdot 10^{-3}$$

```
= relap5/mod2  waste package (b & w  15 by 15  21 fa)
*------------------------------------------------------
*
*
* { this is /kappa/jrw/lv/relap/r5wp2d.in
*
* the input is a transition from tmi-1 power uprate lbloca
* to waste package (near field) criticality excursion consequences
* with 4.90 wt.% u-235 , 34,000 mwd/mtu burnup and  25,000 year decay
*
*  b & w   heavy isotope actinide contribution }
*
*
*------------------ base model description ---------------------
*
*     fti  document 32-1244460-00
*     by: ks pacheco
*
* the base deck for the tmi-1 model was taken from 2772base1.in
* contained in 32-1234886-00.  /kappa/ksp/tmipug/base/tmibase.in
*
*  21fa, 208-pins/fa, 16-guide tubes/fa, 1-instrument tube/fa
*        one-fifth length model - Power into Assembly is 5 Watts
*        for Full Length assemblies
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*   deck obtained from tuck w. (lynchburg) 07/31/97
*   07/31/97 modifiation - jam (lv)
*     delete most of the $$$ cards from deck
*     convert to mod3 format
*     junction control flag - change from 3xxxx to 0xxxx
*                             no horizontal stratification
*     heat structure cards ...8xx and ...9xx - CHF Changes
*                             MOD2 - 5 wds, MOD3 - 9 wds
*     add Time-Dependent Vol and Time-Dependent Junction to input
*     InFlow Conditions
*     Add Minor Edits
*   Case 001 Using small time steps to make sure case runs ok
*   Case 002 Match Tuck Worsham's data (Fax memo - 08/04/97
*   Case 003 Use short time steps through power peak
*   Case 004 Add Doppler Weight Factors to activate Fuel Temp Feedback
*            B&W Relap5 has been modified to compute Doppler Weights
*            internally if none supplied.
*            Add Avg-Fuel Temp To Minor Edits
*            Add variable Void Weight Factors porportional to Control
*            Volume relative size
*   Case 005 Rerun Case C003 with Doppler Weights
*   Case 006 Add Reactivity Control Blocks to Edit Components to Case 004
*   Case 101 Switch to Implicit Numerics
*            Shorten time steps to avoid zero mass in control volumes
*            around 5.8 sec, turn on the choking model for junctions in
*            non-fuelled volumes.
*   Case 111 Similar to Case 101: reduce reactivity ramp by 50%;
*                                 increase refill rate by 50%;
*                                 change minor edits;
*                                 adjust minor edit frequencirs to 0.05 sec
*   Case 102 Try Case 101 with automatic T.S. control to cut down on
*            number of minor edit points
*            Redo case 102 to include fission and decay heat power,
*            add reactivity table vs mixture level
*   Case 102a review short T.S. case again
*        102b check for T.S. convergence (more stable than case 102a
*        102c check further for T.S. convergence
*        103a actually add mixture level calc - limit to top fuelled row
*             delete void reactivity table
*        103b 08/20/97 - revise case c103a and rerun
*             revise MCNP void reactivity table to use delta rho
*             and include all restart time steps, remove mixture level flgs
*        103c reinstate the mixture level model in vols 21001, 05001, 10001,
```

```
*             20001
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
100   new   transnt
101   run
* 101   inp-chk
102   british   british
105   150.  160.
*
* noncondensible gas
110   "nitrogen"
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
* time step control
*      end     min     max     time  minor  major  restart
*     time    delt    time     step  edit   edit    point
*     (sec)   (sec)   step     optn  freq   freq    freq
*
*  Case 103a time steps
  201   0.1       1.0-8   1.0-4    07   100     1000     1000
  202   1.5       1.0-8   1.0-3    07   100     100      100
  203   4.0       1.0-8   5.0-5    07   1000    10000    10000
  204  20.0       1.0-8   5.0-5    07   10000  20000    20000
*
*  Case c103a.rst01 time steps
  205  30.0       1.0-8   5.0-5    07   10000  20000    20000
*
*  Case c103a.rst02 time steps
  206  40.0       1.0-8   1.0-4    07   1000    10000    10000
*
*  Case c103a.rst03 time steps
  207  80.0       1.0-8   1.0-4    07   1000    10000    10000
*
*  Case c103a.rst04 time steps
  208  360.0      1.0-8   1.0-3    07   1000    10000    10000
*
*  Case c103a.rst05 time steps
  209  1800.0     1.0-8   1.0-2    07   200     1000     1000
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*
*        general tables
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*  reactivity insertion
*
20200100   reac-t
20200101   0.0  0.0  30.0  14.18  1.0+10  14.18
*  20200101  0.0  0.0  30.0   7.09  1.0+10   7.09
*
*
*   average fuel temperature vs. reactivity
*
20200200   reac-t
*
*          fuel temp. K      reactivity, dollars     density lb/ft**3
*
20200201    273.16              +0.1719079
20200202    300.01              +0.1719079
20200203    323.16               0.0
20200204    373.16              -0.3488604
20200205    433.16              -0.7295469
20200206    543.16              -1.3918144
```

```
20200207    813.16              -2.8696928
*
*  moderator density reactivity feedback
*
20200500  reac-t
*
*          density  kg/m**3    reactivity, dollars     fuel temp. f
*
20200501       701.470834          -22.8341124          *  1004
20200502       726.523364          -20.0375898          *  1004
20200503       751.575895          -17.4413905          *  1004
20200504       776.628425          -15.0255317          *  1004
20200505       801.680954          -12.7766726          *  1004
20200506       826.733484          -10.6782739          *  1004
20200507       851.786013          -08.7187079          *  1004
20200508       876.838543          -06.8856192          *  1004
20200509       901.891072          -05.1688975          *   518
20200510       921.933098          -03.9010990          *   518
20200511       941.975121          -02.6972060          *   518
20200512       960.112521          -01.6592902          *   518
20200513       975.044461          -00.8234196          *   212
20200514       990.260409           00.00               *   122
20200515      1002.101192          +00.6225345          *   122
20200516      1043.387881          +00.6225345          *    80.33
*
*
*     MCNP mixture level reactivity table (beta = 0.005)
*     Row 5 of fueled assemblies
*     Ref: W.D. reactor physics book + J. Massari Doc
*
*        Mixture level (ft)    Reactivity ($)
*
20201000  reac-t
*
20201001    0.0                 -30.902
20201002    0.04399             -30.902
20201003    0.18933             -16.660
20201004    0.23657             -14.959
20201005    0.28415             -12.911
20201006    0.71                  0.0
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*
*     minor edits
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*
*     pressure
*
301    "p"          150010000            * Vol Pressure
302    "p"          060010000            * Vol Pressure
303    "p"          070010000            * Vol Pressure
304    "p"          080010000            * Vol Pressure
305    "p"          090010000            * Vol Pressure
306    "p"          100010000            * Vol Pressure
307    "p"          250010000            * Vol Pressure
*
*     enthalpy
*
315    "hvmix"      090010000           * Vol Enthalpy
317    "hvmix"      250010000           * Vol Enthalpy
*
*
*     volume vapor generation/unit vol
*
321    "vapgen"     150010000           * Vol vapor gen rate
322    "vapgen"     060010000           * Vol vapor gen rate
```

```
323    "vapgen"     070010000            * Vol vapor gen rate
324    "vapgen"     080010000            * Vol vapor gen rate
325    "vapgen"     090010000            * Vol vapor gen rate
326    "vapgen"     100010000            * Vol vapor gen rate
*
*
*      Volume Mass
*
329    "tmass"      0                    * Fluid Inventory
330    "tmassv"     260010000            * Vol Mass
331    "tmassv"     150010000            * Vol Mass
332    "tmassv"     060010000            * Vol Mass
333    "tmassv"     070010000            * Vol Mass
334    "tmassv"     080010000            * Vol Mass
335    "tmassv"     090010000            * Vol Mass
336    "tmassv"     100010000            * Vol Mass
337    "tmassv"     220010000            * Vol Mass
338    "tmassv"     230010000            * Vol Mass
339    "tmassv"     240010000            * Vol Mass
340    "tmassv"     250010000            * Vol Mass
*
*      mass flow
*
341    "mflowj"     080010000            * Jun Flow
342    "mflowj"     080020000            * Jun Flow
343    "mflowj"     070010000            * Jun Flow
344    "mflowj"     070020000            * Jun Flow
345    "mflowj"     240010000            * Jun Flow
346    "mflowj"     230010000            * Jun Flow
347    "mflowj"     230020000            * Jun Flow
348    "mflowj"     250010000            * Jun Flow
349    "mflowj"     220010000            * Jun Flow
351    "mflowj"     220020000            * Jun Flow
352    "mflowj"     020010000            * Jun Flow
353    "mflowj"     020020000            * Jun Flow
*
*
*      average fuel temperature
*
361    "htvat"      3301008              * Avg Metal Temp
*
*    control variables
*
*    kinetics parameters
*
389    "rkfipow"    0           * "fission" "power"
390    "rkgapow"    0           * "decay heat" "power"
391    "rkreac"     0           * "total" "reactivi"
392    "cntrlvar"   081         * "MCNP void Reactivity
393    "cntrlvar"   014         * "doppler reac
394    "cntrlvar"   056         * "void reactivity
395    "cntrlvar"   060         * "ramp reactivity
396    "cntrlvar"   065         * "total calc reac
397    "cntrlvar"   070         * "assembly energy
398    "cntrlvar"   075         * "Sum (Heat slab vapor gen rate)
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*
*    waste package
*
*
* modeling begins with central planar region
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
* bottom of cylinder
*
```

```
1400000    "bot-watr"  "branch"
*          no. of jun  jun cntrl
1400001      2          0
*          aflow(norm)  len        vol      angle(az) inclin  elev change
1400101      0.00       .2293299  .2075716   0.0    -90.0    -.2293299
*          wall rough  hyd dia    cntrl
1400102    4.1667-5     1.0+10     00
*          vol cntrl   press       temp
1400200    003          14.696     122.00
*          from vol    to vol      ajun       k(f)    k(r)    jun cntrl
1401101    140000000 010010000  .2038375  72.0    72.0    01000
*          liq vel     vap vel     interface vel
1401201    0.0         0.0         0.0
*          from vol    to jun      ajun       k(f)    k(r)    jun cntrl
1402101    140000000 150000000  .5419829   0.0     0.0    01003
*          liq vel     vap vel     interface vel
1402201    0.0         0.0         0.0
*
* bottom side of cylinder
*
1500000    "bos-watr"  "branch"
1500001    1           0
1500101     0.00       .2293299  .2276341   0.0    -90.0    -.2293299
*                          cntrl (therm-off, mix-off, pack-on,
*                                vert strat-on,  interphase fric-pipe,
*                                wall-xdir, non-eq)
1500102    4.1667-5     1.0+10     0000000
1500200    003          14.696     122.00
1501101    150000000 060010000  .4076750  72.0    72.0    01000
1501201    0.0         0.0         0.0
*
* side of cylinder fuel level 1
*
1600000    "s1-watr"   "branch"
1600001    1           0
1600101     0.00       .71        .7989270   0.0    -90.0    -.71
1600102    4.1667-5     1.0+10     00
1600200    003          14.696     122.00
1601101    160000000 110010000  .4076750  72.0    72.0    01000
1601201    0.0         0.0         0.0
*
* side of cylinder fuel level 2
*
1700000    "s2-watr"   "branch"
1700001    1           0
1700101     0.00       .71          .5438773    0.0    -90.0    -.71
1700102    4.1667-5     1.0602200    00
1700200    003          14.696       122.00
1701101    170000000 180000000     1.1080708  0.0     0.0    01000
1701201    0.0         0.0           0.0
*
* side of cylinder fuel level 3
*
1800000    "s3-watr"   "branch"
1800001    1           0
1800101     0.00       .71          .8980821    0.0     90.0     .71
1800102    4.1667-5     2.1134025    00
1800200    003          14.696       122.00
1801101    180010000 190000000     1.3339422  0.0     0.0    01000
1801201    0.0         0.0           0.0
*
* side of cylinder fuel level 4
*
1900000    "s4-watr"   "branch"
1900001    1           0
1900101     0.00       .71          .8738187    0.0     90.0     .71
1900102    4.1667-5     2.0432176    00
1900200    003          14.696       122.00
1901101    190010000 210000000     1.0380308  0.0     0.0    01000
1901201    0.0         0.0           0.0
```

```
*
* side of cylinder - fuel level 5
*
2100000   "s5-watr"   "branch"
2100001   1          0
2100101    0.00      .71          .7822260    0.0    90.0    .71
2100102   4.1667-5   1.6252320    0100000
2100200   003         14.696      122.00
*  2101101    210010000 240000000     1.0380308  0.0    0.0    01000
   2101101    210010000 240000000     1.0380308  0.0    0.0    00000
2101201   0.0        0.0          0.0
*
* 21 fuel assemblies
*
* half symmetry gives 13 planar fuel areas
*
* modeling begins with central fuel length,
*
* center fuel column,  at the cylinder bottom
*
* hydraulic dia. based on flow around fuel-clad, guide tubes, inst. tube
*
*---**---**---**---**---**---**---**---**---**---**---**---*
*
* column  1
*
0100000   "fuel-010"  "branch"
0100001   2          0
0100101    0.00      .71          .3516846   0.0   -90.0   -.71
0100102   3.133-6    .04168514    00
0100200   003         14.696      122.00
0101101   010000000 020010000     .2038375   72.0    72.0   01000
0101201   0.0        0.0          0.0
0102101   010000000 060000000     .4076750   72.0    72.0   01003
0102201   0.0        0.0          0.0
*
0200000   "fuel-020"  "branch"
0200001   2          0
0200101    0.00      .71          .3516846   0.0   -90.0   -.71
0200102   3.133-6    .04168514    00
0200200   003         14.696      122.00
0201101   020000000 030000000     .2038375   72.0    72.0   01000
0201201   0.0        0.0          0.0
0202101   020000000 070000000     .4076750   72.0    72.0   01003
0202201   0.0        0.0          0.0
*
0300000   "fuel-030"  "branch"
0300001   2          0
0300101    0.00      .71          .3516846   0.0    90.0    .71
0300102   3.133-6    .04168514    00
0300200   003         14.696      122.00
0301101   030010000 040000000     .2038375   72.0    72.0   01000
0301201   0.0        0.0          0.0
0302101   030000000 080000000     .4076750   72.0    72.0   01003
0302201   0.0        0.0          0.0
*
0400000   "fuel-040"  "branch"
0400001   2          0
0400101    0.00      .71          .3516846   0.0    90.0    .71
0400102   3.133-6    .04168514    00
0400200   003         14.696      122.00
0401101   040010000 050000000     .2038375   72.0    72.0   01000
0401201   0.0        0.0          0.0
0402101   040000000 090000000     .4076750   72.0    72.0   01003
0402201   0.0        0.0          0.0
*
0500000   "fuel-050"  "branch"
0500001   2          0
0500101    0.00      .71          .3516846   0.0    90.0    .71
*                          cntrl (therm-off, mix-on, pack-on,
```

```
*                               vert strat-on,  interphase fric-pipe,
*                               wall-xdir, non-eq)
0500102   3.133-6   .04168514    0100000
0500200   003        14.696      122.00
0501101   050010000 220000000    .2038375  72.0    72.0    01000
0501201   0.0       0.0          0.0
0502101   050000000 100000000    .4076750  72.0    72.0    01003
0502201   0.0       0.0          0.0
*
*---**---**---**---**---**---**---**---**---**---**---**---*
*
* column  2
*
0600000   "fuel-060"  "branch"
0600001   2         0
0600101    0.00     .71         .7033692   0.0   -90.0   -.71
0600102   3.133-6   .04168514    00
0600200   003        14.696      122.00
0601101   060000000 070010000    .4076750  72.0    72.0    01000
0601201   0.0       0.0          0.0
0602101   060000000 160000000    .4076750  72.0    72.0    01003
0602201   0.0       0.0          0.0
*
0700000   "fuel-070"  "branch"
0700001   2         0
0700101    0.00     .71         .7033692   0.0   -90.0   -.71
0700102   3.133-6   .04168514    00
0700200   003        14.696      122.00
0701101   070000000 080000000    .4076750  72.0    72.0    01000
0701201   0.0       0.0          0.0
0702101   070000000 110000000    .4076750  72.0    72.0    01003
0702201   0.0       0.0          0.0
*
0800000   "fuel-080"  "branch"
0800001   2         0
0800101    0.00     .71         .7033692   0.0    90.0    .71
0800102   3.133-6   .04168514    00
0800200   003        14.696      122.00
0801101   080010000 090000000    .4076750  72.0    72.0    01000
0801201   0.0       0.0          0.0
0802101   080000000 120000000    .4076750  72.0    72.0    01003
0802201   0.0       0.0          0.0
*
0900000   "fuel-090"  "branch"
0900001   2         0
0900101    0.00     .71         .7033692   0.0    90.0    .71
0900102   3.133-6   .04168514    00
0900200   003        14.696      122.00
0901101   090010000 100000000    .4076750  72.0    72.0    01000
0901201   0.0       0.0          0.0
0902101   090000000 130000000    .4076750  72.0    72.0    01003
0902201   0.0       0.0          0.0
*
1000000   "fuel-100"  "branch"
1000001   2         0
1000101   0.00      .71         .7033692   0.0    90.0    .71
1000102   3.133-6   .04168514    0100000
1000200   003        14.696      122.00
1001101   100010000 230000000    .4076750  72.0    72.0    01000
1001201   0.0       0.0          0.0
1002101   100000000 200000000    .4076750  72.0    72.0    01003
1002201   0.0       0.0          0.0
*
*---**---**---**---**---**---**---**---**---**---**---**---*
*
* column  3
*
1100000   "fuel-110"  "branch"
1100001   2         0
1100101    0.00     .71         .7033692   0.0   -90.0   -.71
```

```
1100102   3.133-6    .04168514     00
1100200   003         14.696       122.00
1101101   110000000 120000000     .4076750  72.0    72.0    01000
1101201   0.0        0.0           0.0
1102101   110000000 170000000     .4076750  72.0    72.0    01003
1102201   0.0        0.0           0.0
*
1200000   "fuel-120"  "branch"
1200001   2          0
1200101    0.00      .71          .7033692   0.0    90.0    .71
1200102   3.133-6    .04168514     00
1200200   003         14.696       122.00
1201101   120010000 130000000     .4076750  72.0    72.0    01000
1201201   0.0        0.0           0.0
1202101   120000000 180000000     .4076750  72.0    72.0    01003
1202201   0.0        0.0           0.0
*
1300000   "fuel-130"  "branch"
1300001   2          0
1300101    0.00      .71          .7033692   0.0    90.0    .71
1300102   3.133-6    .04168514     00
1300200   003         14.696       122.00
1301101   130010000 200000000     .4076750  72.0    72.0    01000
1301201   0.0        0.0           0.0
1302101   130000000 190000000     .4076750  72.0    72.0    01003
1302201   0.0        0.0           0.0
*
* water - column  3
*
*---**---**---**---**---**---**---**---**---**---**---*
*
2000000   "ts-watr"   "branch"
2000001   2          0
2000101    0.00      .71          .8633786   0.0    90.0    .71
2000102   4.1667-5    1.0+10      0100000
2000200   003         14.696      122.00
*  2001101    200010000 240000000     .7540857    0.0     0.0    01000
   2001101    200010000 240000000     .7540857    0.0     0.0    00000
2001201   0.0        0.0          0.0
*  2002101    200000000 210000000    1.7958536    0.0     0.0    01003
   2002101    200000000 210000000    1.7958536    0.0     0.0    00003
2002201   0.0        0.0          0.0
*
* top of cylinder
*
*
* three water columns
*
*
2200000   "c1-watr"   "branch"
2200001   2          0
2200101    0.00      .3484394     .8633786   0.0    90.0    .3484394
2200102   4.1667-5    1.0+10      00
2200200   003         14.696      122.00
*  2201101    220010000 250000000     .2038375    0.0     0.0    01000
   2201101    220010000 250000000     .2038375    0.0     0.0    00000
2201201   0.0        0.0          0.0
*  2202101    220000000 230000000     .8234784    0.0     0.0    01003
   2202101    220000000 230000000     .8234784    0.0     0.0    00003
2202201   0.0        0.0          0.0
*
2300000   "c2-watr"   "branch"
2300001   2          0
2300101    0.00      .3484394     .8633786   0.0    90.0    .3484394
2300102   4.1667-5    1.0+10      00
2300200   003         14.696      122.00
*  2301101    230010000 250000000     .4076750    0.0     0.0    01000
   2301101    230010000 250000000     .4076750    0.0     0.0    00000
2301201   0.0        0.0          0.0
*  2302101    230000000 240000000     .8234784    0.0     0.0    01003
```

```
  2302101   230000000 240000000   .8234784   0.0    0.0   00003
2302201   0.0       0.0         0.0
*
2400000   "c3-watr"   "branch"
2400001   1         0
2400101    0.00      .3484394     .4918077   0.0    90.0    .3484394
2400102   4.1667-5  1.6908844    00
2400200   003        14.696      122.00
*  2401101   240010000 250000000   .9732914   0.0    0.0   01000
   2401101   240010000 250000000   .9732914   0.0    0.0   00000
2401201   0.0       0.0         0.0
*
* top plenum
*
2500000   "tp-watr"   "branch"
2500001   1         0
2500101    0.00      .5249344    1.2517607   0.0    90.0    .5249344
2500102   4.1667-5  1.3256083    00
2500200   003        14.696      122.00
* 2501101   250010000 260000000   .1076391   0.0    0.0   01000
  2501101   250010000 260000000   .1076391   0.0    0.0   00000
2501201   0.0       0.0         0.0
*
* outside of waste package,
*
* drift at 14.696 psia
*
2600000   "drift"    "tmdpvol"
2600101   238.46  1.0  0.0  0.0  90.0  1.0  1.0e-6  0.0  0010
2600200   003
2600201   0.0        14.696      220.00
*
* drift inflow volume
*
3600000    "gnd-watr"  "tmdpvol"
3600101    238.46  1.0  0.0  0.0  90.0  1.0  1.0e-6 0.0  0010
3600200    103
3600201    0.0    14.696     122.0
*
* Time-Dependent Junction for inflow
*
3700000    "in-flow"  "tmdpjun"
3700101    360010000   250000000    1.0
3700200    1           0
3700201    0.0         1.381e-3     0.0        0.0
*  3700201    0.0          2.762e-3     0.0        0.0
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
***
***
***                  heat structure input
***
***
***
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*    waste package wall
*
13121000   9   20   1   1   0.0
13121100   0   2
13121101   10.0     19
13121201   6   19
13121301   0.0 19
13121400   0
13121401   122. 20
13121501   140010000    10000000    1      1    1.73  9
13121601   0            0           0      1    1.73  9
13121701   0   0.0   0.0   0.0   9
* 13121801   0   0.0   0.0   0.0   9
* 13121901   0   0.0   0.0   0.0   9
```

```
  13121801   0.0   10.0   10.0   0.0   0.0  0.0   0.0  1.0  9
  13121901   0.0   10.0   10.0   0.0   0.0  0.0   0.0  1.0  9
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*    fuel assembly clad, guide tubes, & inst-tube in fuel region
*
13481000   13    3    2   1   0.01570833
13481100   0     1
13481101   2     0.01791112
13481201   5     2
13481301   0.0   2
13481400   0
13481401   122.  3
*                               225  *2.3633333 = 531.75  ft
*                               112.5*2.3633333 = 265.875 ft
13481501   010010000  10000000       1      1      265.8750   5
13481502   060010000  10000000       1      1      531.7500   13
13481601   010010000  10000000       1      1      265.8750   5
13481602   060010000  10000000       1      1      531.7500   13
13481701   0   0.0   0.0   0.0   13
* 13481801   0   0.0   0.0   0.0   13
* 13481901   0   0.0   0.0   0.0   13
  13481801   0.0   10.0   10.0   0.0   0.0  0.0   0.0  1.0  13
  13481901   0.0   10.0   10.0   0.0   0.0  0.0   0.0  1.0  13
*  13481801   0   0.05360754   0.05360754   0.0   13
*  13481901   0   0.04701465   0.04701465   0.0   13
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*    fuel assembly pellets - water in gap region
*
13301000   13     10    2    1     0.0
13301100   0      1
*  13301101   6     0.01535833   1     0.01570833  2   0.01791667
13301101   9      0.01535833
*  13301201   3     6    -4     7     -5     9
13301201   3      9
*  13301301   1.0   6     0.0   7     0.0    9
13301301   1.0    9
13301400   -1
13301401   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301402   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301403   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301404   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301405   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301406   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301407   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301408   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301409   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301410   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301411   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301412   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301413   122.  122.  122.  122. 122. 122. 122. 122. 122. 122.
13301501   0   0    0     0     0.0   13
*
* length of fuel pin = #pins/ass'y * 141.8/(5 * 12)
*                    = 208 * 2.363 = 491.57333
*
13301601   010010000  10000000       1      1      245.78667   5
13301602   060010000  10000000       1      1      491.57333   13
13301701   1000      0.1         0.0          0.0    5
13301702   1000      0.2         0.0          0.0    13
* 13301801   0         0.0          0.0          0.0    13
* 13301901   0         0.05492351 0.05492351 0.0    13
13301801   0.0   10.0      10.0     0.0     0.0     0.0     0.0     1.0     13
13301901   0.0   10.0      10.0     0.0     0.0     0.0     0.0     1.0     13
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
```

```
***
***
***   reactor vessel heat structures
***
***
*
*
*     lower plenum of reactor vessel
*
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*
* heat structure composition type
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
* fuel   ( uo2 )
*
20100300  "tbl/fctn"  1         1
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
* gap    (hot channel)
*
20100400  "tbl/fctn"  3         1
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
* clad   ( zr-4)
*
20100500  "tbl/fctn"  1         1
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
* base metal  ( carbon steel )
*
20100600  "tbl/fctn"  1         1
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
* cladding  ( stainless steel )
*
20100700  "tbl/fctn"  1         1
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*$$$ *$$$ *
*$$$ *$$$ * gap    (avg channel)
*$$$ *$$$ *
*$$$ *$$$ 20100900  "tbl/fctn"  3         1
*$$$ *
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*
*     heat structure thermal conductivities
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*    fuel     ( uo2 )
*
20100301    70.0     1.237e-3      200.0     1.237e-3
20100302   400.0     1.022e-3      800.0     0.745e-3
20100303  1200.0     0.592e-3     1600.0     0.492e-3
20100304  2000.0     0.430e-3     2400.0     0.395e-3
20100305  2800.0     0.383e-3     3200.0     0.367e-3
20100306  3600.0     0.370e-3     4000.0     0.380e-3
20100307  4400.0     0.405e-3     5000.0     0.470e-3
*
*    gap      ( bol )
*
20100401  "helium"     0.989748
```

```
20100402  "nitrogen"   0.008098
20100403  "oxygen"     0.002153
20100404  "krypton"    0.000000
20100405  "xenon"      0.000002
*
*    clad    (zr-4)
*
20100501     70.0   2.333e-3    200.0   2.333e-3    400.0   2.458e-3
20100502    800.0   2.805e-3   1200.0   3.278e-3   1600.0   3.805e-3
20100503   1800.0   4.112e-3   2000.0   4.445e-3   2100.0   4.667e-3
20100504   2200.0   4.945e-3   2800.0   7.000e-3
*
*    thermal conductivity     base metal   ( carbon steel )
*
20100601  0.0        .00728    2000.0    .00728
*
*    thermal conducitvity     cladding   ( stainless steel )
*
20100701  0.0        .00311    2000.0    .00311
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*
*     heat structure volumetric heat capacities
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
* volumetric heat capacity  fuel     ( uo2 )
*
20100351    77.0   33.8    200.0   40.62    400.0   43.87
20100352   600.0   45.82   800.0   47.12   1000.0   48.10
20100353  1200.0   48.88  1600.0   49.92   2000.0   50.37
20100354  2400.0   51.35  2800.0   53.62   3200.0   58.17
20100355  3600.0   66.30  4000.0   78.97   4400.0   90.80
20100356  4800.0   99.12  5100.0  101.40
*
* volumetric  heat  capacity   gap   (hot channel)
*
20100451  32.0   0.000075    5400.0    0.000075
*
* volumetric  heat  capacity   clad
*
20100551    32.0   28.346  1062.0    33.232   1140.0   35.432
20100552  1480.0   35.432  1510.0    49.440   1530.0   56.440
20100553  1560.0   58.916  1590.0    61.800   1610.0   66.332
20100554  1620.0   76.220  1650.0    80.340   1680.0   78.28
20100555  1700.0   74.16   1780.0    35.432   3000.0   35.432
*
* volumetric  heat  capacity   base metal   (carbon steel)
*
20100651  0.0        64.4      2000.0    64.4
*
* volumemetric heat capacity   cladding   (stainless steel)
*
20100751  0.0        64.4      2000.0    64.4
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*
*        general tables
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*  test power insertion
*
* 20200100  power
* 20200101  0.0  0.0  5.0  0.0  25.0  1.0-2
*
```

```
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*
*       control varialbes
*
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
* 20547400  "hcpwr"    "constant"  3.15e6
* 20547400  "hcpwr"    "function"  3.15e4  0.0  0
* 20547401  time  0  1
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
***
***
***                 reactor kinetics
***
***
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*  power in watts per assembly
*
30000000  "point"   "separabl"
30000001 "gamma-ac"  5.00000  .00000 .28637e+03   1.0  1.0
30000002  "ans73"   0.0   1.0
30000301  0.3230  0.000491  0.2910  0.00000341
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*  general table for waste package reactivity insertion  ttt = 1
*
30000011  1
30000012  10081
*
*---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*  moderator density reactivity feedback
*
*  beff = 0.005
*
*          density  lf/ft**3    reactivity, dollars     fuel temp. f
*
30000501     43.6995724          -22.8341124          *  1004
30000502     45.2602714          -20.0375898          *  1004
30000503     46.8209705          -17.4413905          *  1004
30000504     48.3816695          -15.0255317          *  1004
30000505     49.9423685          -12.7766726          *  1004
30000506     51.5030675          -10.6782739          *  1004
30000507     53.0637665          -08.7187079          *  1004
30000508     54.6244655          -06.8856192          *  1004
30000509     56.1851645          -05.1688975          *   518
30000510     57.4337238          -03.9010990          *   518
30000511     58.6822830          -02.6972060          *   518
30000512     59.8121897          -01.6592902          *   518
30000513     60.7424057          -00.8234196          *   212
30000514     61.6903146           00.00               *   122
30000515     62.4279606          +00.6225345          *   122
30000516     65.0000000          +00.6225345          *    80.33
*
*  control volume weighting  - modified from Original deck with uniform weights
*
30000701   010010000   0   .02191015   0.0
30000702   020010000   0   .02191015   0.0
30000703   030010000   0   .02191015   0.0
30000704   040010000   0   .02191015   0.0
30000705   050010000   0   .02191015   0.0
30000706   060010000   0   .04382030   0.0
30000707   070010000   0   .04382030   0.0
30000708   080010000   0   .04382030   0.0
30000709   090010000   0   .04382030   0.0
```

```
30000710   100010000   0   .04382030   0.0
30000711   110010000   0   .04382030   0.0
30000712   120010000   0   .04382030   0.0
30000713   130010000   0   .04382030   0.0
30000714   140010000   0   .01293183   0.0
30000715   150010000   0   .01418173   0.0
30000716   160010000   0   .04977361   0.0
30000717   170010000   0   .03388387   0.0
30000718   180010000   0   .05595103   0.0
30000719   190010000   0   .05443940   0.0
30000720   200010000   0   .05378898   0.0
30000721   210010000   0   .04873313   0.0
30000722   220010000   0   .05378898   0.0
30000723   230010000   0   .05378898   0.0
30000724   240010000   0   .03063990   0.0
30000725   250010000   0   .07798541   0.0
*
30000501
30000502
30000503
30000504
30000505
30000506
30000507
30000508
30000509
30000510
30000511
30000512
30000513
30000514
30000515
30000516
30000701
30000702
30000703
30000704
30000705
30000706
30000707
30000708
30000709
30000710
30000711
30000712
30000713
30000714
30000715
30000716
30000717
30000718
30000719
30000720
30000721
30000722
30000723
30000724
30000725
*---**---**---**---**---**---**---**---**---**---**---**---**---**---*
*
*   average fuel temperature vs. reactivity
*
*
*          fuel temp. f      reactivity, dollars     density lb/ft**3
*
30000601    32.0              +0.1719079         *  62.4279606
30000602    80.33             +0.1719079         *  62.4279606
30000603   122.0               0.0               *  61.6903146
30000604   212.0              -0.3488604         *  61.6903146
30000605   320.0              -0.7295469         *  60.7424057
```

```
30000606    518.0              -1.3918144          * 60.7424057
30000607   1004.0              -2.8696928          * 56.1851645
*
*
*
*  heat structure weighting - (added to deck - B&W code does weights
*                             internally)
*
30000801   3301001  0   .04762000   0.0
30000802   3301002  0   .04761900   0.0
30000803   3301003  0   .04761900   0.0
30000804   3301004  0   .04761900   0.0
30000805   3301005  0   .04761900   0.0
30000806   3301006  0   .09523800   0.0
30000807   3301007  0   .09523800   0.0
30000808   3301008  0   .09523800   0.0
30000809   3301009  0   .09523800   0.0
30000810   3301010  0   .09523800   0.0
30000811   3301011  0   .09523800   0.0
30000812   3301012  0   .09523800   0.0
30000813   3301013  0   .09523800   0.0
*
*   Control Blocks
*
20500000   999
20500100   cntrlvar   function  0.04762  0.0    0
20500101   htvat    3301001    002
20500200   cntrlvar   function  0.04761  0.0    0
20500201   htvat    3301002    002
20500300   cntrlvar   function  0.04761  0.0    0
20500301   htvat    3301003    002
20500400   cntrlvar   function  0.04761  0.0    0
20500401   htvat    3301004    002
20500500   cntrlvar   function  0.04761  0.0    0
20500501   htvat    3301005    002
20500600   cntrlvar   function  0.095238 0.0    0
20500601   htvat    3301006    002
20500700   cntrlvar   function  0.095238 0.0    0
20500701   htvat    3301007    002
20500800   cntrlvar   function  0.095238 0.0    0
20500801   htvat    3301008    002
20500900   cntrlvar   function  0.095238 0.0    0
20500901   htvat    3301009    002
20501000   cntrlvar  function  0.095238 0.0    0
20501001   htvat '  3301010    002
20501100   cntrlvar  function  0.095238 0.0    0
20501101   htvat    3301011    002
20501200   cntrlvar  function  0.095238 0.0    0
20501201   htvat    3301012    002
20501300   cntrlvar  function  0.095238 0.0    0
20501301   htvat    3301013    002
20501400   cntrlvar  sum       1.0      0.0    0
20501401  -6.63322e-5  1.0  cntrlvar 1 1.0  cntrlvar 2  1.0    cntrlvar 3
20501402         1.0  cntrlvar 4  1.0    cntrlvar 5    1.0    cntrlvar 6
20501403         1.0  cntrlvar 7  1.0    cntrlvar 8    1.0    cntrlvar 9
20501404         1.0  cntrlvar 10 1.0    cntrlvar 11   1.0    cntrlvar 12
20501405         1.0  cntrlvar 13
*
*
20502000   cntrlvar  function   0.02191015  0.0    0
20502001   "rho"     010010000  005
20502100   cntrlvar  function   0.02191015  0.0    0
20502101   "rho"     020010000  005
20502200   cntrlvar  function   0.02191015  0.0    0
20502201   rho     030010000  005
20502300   cntrlvar  function   0.02191015  0.0    0
20502301   rho     040010000  005
20502400   cntrlvar  function   0.02191015  0.0    0
20502401   rho     050010000  005
20502500   cntrlvar  function   0.0438203   0.0    0
```

```
20502501   rho        060010000  005
20502600   cntrlvar   function   0.0438203    0.0    0
20502601   rho        070010000  005
20502700   cntrlvar   function   0.0438203    0.0    0
20502701   rho        080010000  005
20502800   cntrlvar   function   0.0438203    0.0    0
20502801   rho        090010000  005
20502900   cntrlvar   function   0.0438203    0.0    0
20502901   rho        100010000  005
20503000   cntrlvar   function   0.0438203    0.0    0
20503001   rho        110010000  005
20503100   cntrlvar   function   0.0438203    0.0    0
20503101   rho        120010000  005
20503200   cntrlvar   function   0.0438203    0.0    0
20503201   rho        130010000  005
20503300   cntrlvar   function   0.01293183    0.0    0
20503301   rho        140010000  005
20503400   cntrlvar   function   0.01418173    0.0    0
20503401   rho        150010000  005
20503500   cntrlvar   function   0.04977361    0.0    0
20503501   rho        160010000  005
20503600   cntrlvar   function   0.03388387    0.0    0
20503601   rho        170010000  005
20503700   cntrlvar   function   0.05595103    0.0    0
20503701   rho        180010000  005
20503800   cntrlvar   function   0.05443940    0.0    0
20503801   rho        190010000  005
20503900   cntrlvar   function   0.05378898    0.0    0
20503901   rho        200010000  005
20504000   cntrlvar   function   0.04873313    0.0    0
20504001   rho        210010000  005
20504100   cntrlvar   function   0.05378898    0.0    0
20504101   rho        220010000  005
20504200   cntrlvar   function   0.05378898    0.0    0
20504201   rho        230010000  005
20504300   cntrlvar   function   0.03063990    0.0    0
20504301   rho        240010000  005
20504400   cntrlvar   function   0.07798541    0.0    0
20504401   rho        250010000  005
*
20505000   cntrlvar   sum        1.0      0.0   0
20505001   0.0  1.0   cntrlvar 20  1.0  cntrlvar 21  1.0   cntrlvar 22
20505002        1.0   cntrlvar 23  1.0  cntrlvar 24  1.0   cntrlvar 25
20505003        1.0   cntrlvar 26  1.0  cntrlvar 27  1.0   cntrlvar 28
20505004        1.0   cntrlvar 29  1.0  cntrlvar 30  1.0   cntrlvar 31
*
20505500   cntrlvar   sum        1.0      0.0   0
20505501   0.0  1.0   cntrlvar 32  1.0  cntrlvar 33  1.0   cntrlvar 34
20505502        1.0   cntrlvar 35  1.0  cntrlvar 36  1.0   cntrlvar 37
20505503        1.0   cntrlvar 38  1.0  cntrlvar 39  1.0   cntrlvar 40
20505504        1.0   cntrlvar 41  1.0  cntrlvar 42  1.0   cntrlvar 43
20505505        1.0   cntrlvar 44
*
20505600   cntrlvar   sum        1.0      0.0   0
20505601   0.1185681   1.0   cntrlvar 50  1.0   cntrlvar 55
*
20506000   cntrlvar   function   1.0    0.0   0
20506001   time       0          001
20506500   cntrlvar    sum        1.0     0.0  0
20506501   0.0  1.0   cntrlvar 14  1.0    cntrlvar 56  1.0  cntrlvar   60
*
20507000   cntrlvar   integral   1.0    0.0   0
20507001   rktpow     0
*
20507500   cntrlvar   sum    6.22971e-2    0.0   0
20507501   0.0     1.0  htgamw  312100100  1.0  htgamw  312100200
20507502           1.0  htgamw  312100300  1.0  htgamw  312100400
20507503           1.0  htgamw  312100500  1.0  htgamw  312100600
20507504           1.0  htgamw  312100700  1.0  htgamw  312100700
20507505           1.0  htgamw  312100900
```

```
*
*              scale factor = 1/area sum
20508000   cntrlvar  sum   0.26289886    0.0      0
20508001   0.0      0.3516846 voidf  050010000  0.7033692  voidf 100010000
20508002            0.8633786 voidf  200010000  0.7822260  voidf 210010000
*
20508100   cntrlvar  function  1.0    0.0    0
20508101   cntrlvar  80         010
. * end of data
```