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Study on Recriticality of
Fuel Debris During Hypothetical
Severe Accidents in the
Advanced Neutron Source Reactor

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DEPARTMENT OF ENERGY

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ENGINEERING TECHNOLOGY DIVISION

**STUDY ON RECRITICALITY OF FUEL DEBRIS
DURING HYPOTHETICAL SEVERE ACCIDENTS
IN THE ADVANCED NEUTRON SOURCE REACTOR**

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1. Introduction

Oak Ridge National Laboratory's (ORNL's) Advanced Neutron Source (ANS) reactor will be a new user facility [1,2] for a broad range of neutron research, centered around a research reactor of unprecedented ($\sim 10^{20} \text{ m}^{-2} \text{ s}^{-1}$) neutron flux available to the beam tubes. A defense-in-depth philosophy has been adopted. In response to this commitment, project management has initiated severe accident analysis and related technology development early in the design phase. This was done to aid in designing a sufficiently robust containment for retention and controlled release of radionuclides in the event of an accident. It also provides a means for satisfying on- and off-site regulatory requirements, accident-related dose exposures, containment response, and source-term analyses for the Levels-2 and -3 Probabilistic Risk Analyses (PRAs) that will be produced. Moreover, it will provide the best possible understanding of the ANS under severe accident conditions and consequently provide insights for development of strategies and design philosophies for accident mitigation, management, and emergency preparedness efforts.

Recriticality during severe accidents could lead to damaging steam explosion loads. Additional fission product generation and high-energy bursts of radiation are also undesirable byproducts. The scoping study of recriticality in ANS under hypothetical severe accidents was motivated by the need to gage the potential for such an occurrence and by the need to consider designed mitigative features early in the design process.

During hypothetical accidents in the ANS, fuel plate melting may occur either with or without a flowing medium next the melting plates. Hypothetical accident conditions such as core inlet flow blockages or large pipe loss-of-coolant accidents (LOCAs) may provide such conditions. Under such circumstances, and if a steam explosion does not occur, the core mass may slump and agglomerate downward into the primary coolant system piping regions. Again, experiments [3] with melting aluminum tubes in the presence of flowing media have shown that depending on the destabilizing surface forces caused by flowing media, debris dispersal and entrainment in the flowing medium may occur. Debris dispersal also may occur in the presence of steam explosions. Such dispersion mechanisms can cause fragmented core debris to be swept into the coolant outlet piping. Hence, for ANS severe accident analysis, lumped and dispersed configurations in the Reactor Coolant System (RCS) need to be analyzed for gauging recriticality potential. Also the recriticality potential for core debris in subpile room following downward-relocation of core debris, needs to be investigated. Figure 1 depicts various debris configurations studied for the current study.

As in the previous study [4], the well-known KENO V.A-SCALE neutronic code system [5] was the modeling framework of choice for evaluating the recriticality potential of ANS core debris, with 39 group ANSL-V cross-section libraries. Benchmarking and validation efforts of this code system and cross-section libraries were performed and reported in the previous study [4].

Work conducted for recriticality is presented in several chapters. Chapter 2 provides a brief summary of our previous work on recriticality following core debris transport into RCS for old two element core design (employing 93 w/o enriched uranium). Chapter 3 presents a discussion of numerical simulation of recriticality potential under the same situation for the new three element core design employing 50 w/o enriched uranium fuel. As may be expected, core debris may also relocate downward into the reactor subpile room following melt-through of the reactor vessel bottom structures. Therefore, possible recriticality in the subpile room was studied and described in Chapter 4. Thereafter, Chapter 5 presents a summary and conclusion of the work presented in this report.

2. Recriticality Potential in RCS for Two Element Core Design

A scoping study was performed in the past to investigate the recriticality potential in RCS during core plate melting accidents [4]. The previous study also includes benchmarking and validation of the KENO-SCALE neutronic code system for evaluation of system recriticality, wherein lumped and dispersed core-debris configurations may arise during hypothetical severe accidents in the ANS. Benchmarking and validation were performed against data from a series of criticality experiments and between various codes. These comparisons demonstrated the suitability of using the KENO-SCALE code system in conjunction with the 39-group cross-section library.

A detailed matrix of calculations was developed for evaluating the potential of recriticality in the ANS RCS during severe accidents. The evaluations indicated that lumped configurations in the RCS would not pose a recriticality threat. However, significant potential exists for recriticality from dispersed debris configurations of the type shown in Figure 2. Strong dependencies were noted on key thermal-hydraulic parameters such as mixture void fraction, H₂O contamination, aluminum content in debris, and dispersion length. A relatively weak dependence was noted on the mixture temperature. Mixture void fraction was evaluated to be the single most important parameter affecting recriticality.

3. Recriticality Potential in RCS for Three Element Core Design

Medium enriched uranium (MEU) fuel in the Advanced Neutron Source (ANS) reactor system is being proposed for a three element core design to achieve a desired level of reactor performance. Table 1 lists fuel mass inventory at the beginning of cycle of the three element core [6]. Criticality of this reactor system is to be well controlled while the reactor core is intact. During a hypothetical severe accident involving core melting or disruption, highly enriched fuel particles or melt globules may be dispersed into the reactor coolant system or relocate downwards to challenge the reactor structural integrity. Even in these abnormal situations, it is absolutely necessary to maintain the reactor system to be controllable by suppressing the nuclear chain reaction. Our previous study showed that finely dispersed fuel in a limited region of the primary coolant system might be possible to achieve recriticality [4]. For the current study, therefore, only the dispersed configuration has been considered. As in the previous study, a test matrix was developed and listed in Table 2 along with summarized results of obtained the k-effective values. Variables considered for the study include degree of light water contamination in heavy water piping, void fraction in fuel debris-water mixture, fuel debris dispersion length, aluminum content in fuel debris-water mixture, fuel debris temperature, and degree of B-10 depletion in fuel debris-water mixture. For the dispersed configuration shown in Figure 2, KENO-SCALE system was executed for individual cases listed in

Table 2. Results are summarized in Table 2, and also shown in Figures 3 through 8. Also in the same figures, data obtained for the three element core are compared with those for the two element core.

Figure 3 shows KENO-evaluated k_{eff} values for various degrees of light water contamination in heavy water coolant piping. As seen in the figure, neutronic characteristics change with light water contamination because of enhanced moderation with H_2O injection into the fuel mixing region compensated by increased absorption. Also seen in the same figure, with the three element core design (50% enrichment), a much lower k_{eff} is predicted as expected. Figure 4 shows that void formation in the fuel debris mixture provides substantial negative reactivity. Figure 5 shows variation of k_{eff} on fuel debris dispersion length. As fuel debris dispersion length becomes shorter (which becomes closer to the lumped configuration), the system becomes substantially subcritical. The same figure also shows that the k_{eff} becomes maximum at ~1.5 m of dispersion length. Variation of k_{eff} on amount of aluminum mass mixed in fuel debris mixture is shown in Figure 6. It also shows linear dependency of k_{eff} on aluminum mass. As seen in Figure 7, resonance absorption increases with increasing temperature, and thus k_{eff} decreases. However, the effect does not seem to be large. Figure 8 shows k_{eff} values as a function of B-10 mass in the fuel debris mixture. It shows that even a small depletion of B-10 seems to affect k_{eff} substantially.

In summary, recriticality potential is substantially reduced for the three element core design with 50% enrichment. As observed in the previous study [4], strong dependence was also observed of k_{eff} on key thermal hydraulic parameters. Light water contamination is shown to provide significant potential for positive reactivity insertion, and finally void formation due to boiling of mixed water can provide enough negative reactivity to bring the system down to subcritical.

4. Recriticality Potential in Subpile Room for Three Element Core Design

This study examined the recriticality potential if fuel were to relocate into the subpile room. Not having strong coolant inertia, the disrupted (or melted) core will relocate downwards to interact thermally and chemically with the bounding structure. Upon failure of the bounding structure, core debris moves to relocate into the subpile room located beneath the reactor vessel, where it could undergo possibly intensive chemical interactions with the concrete floor. To minimize the magnitude of such reactions (e.g., core concrete interaction - CCI), a decision has been made by the project management to employ alumina cement concrete lined on the floor, coupled with a strategic flooding to provide enough heat sink to lower the debris temperature. Whether or not intentional flooding is provided, it is highly probable, since upon the reactor bounding structure failure, a significant amount of water (D_2O from coolant system and/or H_2O from reactor vessel) may flow along with the debris into the subpile room. Depending on the debris configuration, it may be possible to have a recriticality situation. The pulsating mode of recriticality is of primary concern. If this should occur, the recriticality in the debris is repeated in a cyclic fashion, resulting in a continuous steaming source to challenge containment integrity. If pulsating recriticality is not possible, prompt recriticality may also conceivably force the debris particles to disperse further making it less probable to have successive recriticality. Therefore, the purpose of this study is to evaluate debris configurations for which it is possible to have recriticality potential, and to see if recriticality is ensured, whether it would occur in a cyclic fashion.

4.1 Description of Fuel Dispersion in Pool

Molten core debris relocates into the subpile room upon the failure of a reactor bounding structure. At the beginning of the reactor cycle, the fuel does not contain enough fission products to produce sufficient decay energy to penetrate the reactor structural wall, unless the recriticality occurs in an accumulated fuel debris above the bounding structure. However, the previous study for the in-vessel recriticality showed that the recriticality potential becomes negligible for the lumped fuel. Therefore, the molten fuel debris can penetrate the reactor structure to relocate into the subpile room only when it contains enough heat generating fission products. Therefore, this limited scoping study was performed mainly for fuel debris at the end of cycle.

The core debris can jet into the subpile room, or relocate along the control rod guide tube wall. It is possible that water can flow along with the debris. The subpile room will be flooded upon the debris relocation in it intentionally as a measure to mitigate CCI by providing a heat sink. Figure 9 depicts a possible mode of core debris relocation in the subpile room pool and the associated recriticality potential.

Progression of debris relocation in the subpile room will be primarily determined by whether the debris breakup occurs or not. If the debris relocates as melt jet stream (as may be possible if the reactor pressure is high enough), its interaction with water will be limited. Thus it is probable that the molten debris spreading over the concrete floor will form a pancake type geometry. According to the study performed on CCI [7], it is estimated that the debris will spread to be about 1 m radius. Then the debris surface area for interfacing with the pool water will be 3.14 m^2 . Assuming that only 3 % decay heat of total reactor power remains in the debris, the required heat flux to cool the debris will be $(300 \text{ MW} \times 0.03) / 3.14 \text{ m}^2 = 2.87 \text{ MW/m}^2$. This required heat flux is much higher than the critical heat flux (e.g., $\sim 1.0 \text{ MW/m}^2$). Therefore, unless significant mixing occurs to increase the heat transfer area, the debris will remain in a molten state. Noncondensable gases and steam generated from CCI will push the debris bed above the concrete floor. Since the debris will remain in a molten state, it is improbable for the debris bed to be levitated. Instead, the gases and steam will bubble out of the debris bed. Also it is possible that the debris bed is dispersed if the gas/vapor generation is intensive. If recriticality occurs in the lumped pancake type debris bed, power bursts may disperse the molten debris into several bodies or particles depending on the magnitude of the power. It is also possible the debris bed will remain as one lumped mass while its temperature increases further. However, if this configuration does not lead to recriticality, debris coolability will be eventually established. Considering uncertainties, the recriticality needs to be examined for various debris spreading radii and proportions of heavy and light water in the overlying water pool.

Molten debris might be broken up into small particles during its relocation into the subpile room. Depending on particle size and degree of dispersion, it may be possible to reach criticality. If criticality is ensured, the debris particles/water mixture will expand rapidly, resulting in further dispersion of the mixture. If the new dispersed configuration is again ensured for the recriticality, this process will be repeated until the debris particles settle down on the floor. The particles may spread widely over the entire subpile room floor.

Even though the recriticality does not occur during the debris relocation, the particles will settle down over the concrete floor. The particles may be in a solid or a molten state. Even though the heat transfer is not enough to solidify the particles, their surface will be oxidized during the relocation. If a stable oxide film forms on the surface, even though

the debris is molten particles, it will settle down as fragments. As the debris particles settle down to form a particle bed, water will enter to fill the gaps between the particles. For the 9 MW of decay heat per 100 kg debris mass, any particles of radius is smaller than 6.6 mm, will be quenched (based on 0.5 MW/m^2 of critical heat flux). Therefore, the particle bed is believed to have substantial voids in it. The criticality potential needs to be examined for this debris particle and water mixture. If the mixture becomes critical, its volume will expand due to the sudden power burst. The volume will expand until enough voids are generated to provide enough negative feedback to bring down the mixture to be subcritical. As the voids collapse in the subcooled water pool, the mixture volume may contract to form a configuration leading to successive recriticality. During the volume expansion, mostly the volume expands upward. However, the radius of the debris bed could keep increasing to reach a certain value at which no criticality becomes possible due to increased neutron absorption by water. Therefore, if the recriticality occurs in this mixture configuration, it may occur in a cyclic fashion until the particles are dispersed far enough not to be critical again. However, this dispersal process is very difficult to quantify mechanistically. During pulsating modes of recriticality, the subpile room water will heat up, and eventually get to saturation, to provide a steaming source into the containment. For this configuration of the debris and water mixture, probably the most important parameters affecting the recriticality might be degree of dispersion. Debris particle size may not be as an important parameter as a dispersion if it remains smaller than the neutron mean free path in heavy or light water (e.g., the mean free path is about 20 mm in heavy water, and about 3 mm in light water). Therefore, a parametric study is performed with various degrees of debris mixing for a homogeneous debris mixture.

4.2 Calculation Matrix Formulation

For the lumped pancake geometry, the recriticality potential is examined for various radii either in heavy or light water pools. The test matrix is given in Table 3 (shown as cases with $f(\text{water}) = 0$). Figure 10 shows a schematic geometry for the recriticality study with a lumped configuration. Some of geometrical parameters vary depending on the specific cases. A thick concrete wall (24") is assumed to surround the entire region of control volume as a boundary condition. The 24" wall was selected since it represents the thickest concrete wall available in KENO albedo library as a boundary condition, instead of modeling the thick concrete wall as a part of the problem.

For the dispersed configuration cases (as depicted in Table 3), the debris is assumed to be homogeneously mixed with water. System geometry is assumed to be the same as that of the lumped geometry. Fuel-water mixture is placed above the concrete floor, and 24" thick concrete is assumed to surround the entire subpile room as a boundary condition.

To verify the assumption of quasi-homogeneity of the mixture, two cases are tested for multiple 1 mm thick-lumped debris layers sandwiched between heavy/light water layers (cases with "multilayers" in Table 3). Also the effect of void content on recriticality is tested for 10% void and 50% void volume in the debris mixture. The voids are assumed as vacuum instead of being filled with the appropriate amount of steam (water molecules).

For the calculations, the 3 core design is used with 50 % enriched uranium fuel. Specifically, 19.45 kg of U^{238} , 12.64 kg of U^{235} (based on 35 % burnup), 3.08 kg of Si, and 100 kg of Al constitute the debris mixture along with various amounts of water depending on the case. Also, 0.22857 kg of Pu^{239} is included in the debris.

To investigate the effect of fission product poisoning, a few significant fission products were also included.

4.3 Model Description

The CSAS25 module of the SCALE system has been used for investigating the recriticality. This module includes BONAMI and NITAWL for neutron cross section processing, and KENO-V for the nuclear criticality calculations. The ANSL-V 39 group neutron cross section library was used as a master library. Then, AJAX, one of SCALE utility programs, was used to generate the library specific to our problem. This process involves extracting cross section data of the elements that are relevant to the problem under consideration. Any other elements not used in the current problem were discarded. During this process, there has been one assumption made. The cross section data for the element, Calcium (Ca), is not included in the master library. Therefore, it had to be assumed that Ca is a weak, absorbing material that is available in the master library (material identification number of a weakly absorbing element is 230112). This problem specific-cross section library was generated in unit 70, as the file, ft70f001. This library was used throughout the problem calculations unless we include additional elements into consideration.

Once the cross section library is ready, the SCALE system can be executed. To correct the cross section data for resonance shielding, BONAMI and NITAWL modules of SCALE were executed, followed by KENO-V execution for the criticality calculations.

4.4 Results and Discussion

Calculated values of k_{eff} cases are listed in Table 1, and shown in Figure 11. Heavy water is designated as hwx, where x denotes a sequential case number. Light water cases are designated as lwx, mixed water cases as mxx, and cases with various radii of debris mixing zone are designated as rdx.

For all the cases with lumped fuel configuration (e.g., cases with zero water fraction in debris - hw1, mx1, lw1, and all rdx cases), it is seen that the configuration becomes substantially subcritical. Also it is seen that k_{eff} becomes smaller as the debris spreads wider. From these results, we can conclude that these lumped configurations are very unlikely to reach criticality. Also the k_{eff} value is compared between debris mass at the beginning of cycle (BOC), and the end of cycle (EOC), even though it is very unlikely to have the BOC debris condition in the subpile room, as described above. The BOC debris is seen to yield substantially higher, but still very subcritical k_{eff} value (e.g., 0.700548 for EOC versus 0.79315 for BOC).

For the debris dispersed in the light water pool in the subpile room (cases lwx), the configurations are shown to remain subcritical. As the debris disperses to some degree as in the case lw3, the k_{eff} value goes up substantially because of increased moderation effects suppressing the effect of absorption of neutrons by H_2O . Also in the heavy water pool, the debris remains subcritical if its dispersion is limited. As the debris disperses further, the k_{eff} value seems to increase. That is the moderation becomes more effective as the debris disperses more. Neutron absorption by heavy water does not contribute much since its absorption is limited (e.g., σ_a of D_2O = 1 mb versus σ_a of H_2O = 664 mb). Leakage is not significant either, because the neutron mean free path in heavy water is about 20 mm, and there is enough heavy water surrounding the debris mixing region. For all these dispersion cases, 1 m depth of water (either heavy or light water depending on

the cases) exists above a dispersed debris mixing region. From these results, one can say that there exists a potential for the debris to reach the recriticality at a certain magnitude of dispersion (e.g., 90% volume fraction of heavy water in debris mixture in heavy water pool). Such a recriticality may lead to a sudden power burst, resulting in complete dispersion of the debris in the subpile room pool. Therefore, the case was repeated with complete dispersion of debris in the 3 m radius subpile room with 1 m depth of heavy water mixing. No water layer is assumed to exist above the debris mixing region. This case, hw7, yields k_{eff} value of 0.935157. The result indicates that no further recriticality is possible under the current conditions with a completely dispersed debris configuration. However, k_{eff} value of 0.935157 is still very close to the cutoff value based on benchmarking work of Ref. 4.

To confirm the quasi-homogeneous mixing of debris with water, the case, hw2, was repeated for the multiple lumped debris layers (1 mm thickness) separated by 1 mm thick-heavy water layers. A conservative value of k_{eff} was obtained to compare with that of the quasi-homogenized mixing case (e.g., 0.721396 versus 0.762185). A similar case (lw4) for the light water filled subpile room, was tested, too.

The effect of fission product poisoning was also examined for the case, hw4. With inclusion of major fission products (it excludes noble gases and halogens from consideration), the k_{eff} value comes down from 1.06365 to 1.0415. Also effects of void formation in the debris mixing region was examined with 10% and 50% voids. As seen in the table, the k_{eff} values do not come down substantially. This is because the majority of neutrons get moderated outside the debris mixing region for this specific geometry.

5. Summary and Conclusion

A study has been performed to measure the potential of recriticality during hypothetical severe accident in ANS. For the lumped debris configuration in RCS, as found in the previous study [4], recriticality potential may be very low. However, if fuel debris is dispersed and mixed with heavy water in RCS, recriticality potential has been predicted to be substantial depending on thermal-hydraulic conditions surrounding fuel debris mixture. The recriticality potential in RCS is substantially reduced for the three element core design with 50% enrichment. Also, as observed in the previous study [4], strong dependencies of k_{eff} on key thermal hydraulic parameters are shown. Light water contamination is shown to provide a positive reactivity, and void formation due to boiling of mixed water provides enough negative reactivity and to bring the system down to subcritical.

For criticality potential in the subpile room, the lumped debris configuration does not pose a concern. Dispersed configuration in light water pool of the subpile room is also unlikely to result in criticality. However, if the debris is dispersed in the pool that is mixed with heavy water, the results indicate that a substantial potential exists for the debris to reach the criticality. However, if prompt recriticality disperses the debris completely in the subpile room pool, subsequent recriticality may be prevented since neutron leakage effects become large enough.

6. References

1. C.D. West, "The Advanced Neutron Source: A New Reactor Based Facility for Neutron Research, " Transactions of the American Nuclear Society 61, 375 (June 1990)

2. Advanced Neutron Source Plant Design Requirements, ORNL/TM-11625, Oak Ridge National Laboratory (1991)
3. J.P. Morin, and M.L. Hyder, "The Reaction of Molten SRP Reactor Fuel with Water," ANS Workshop on the Safety of U-Al Fueled Reactors, Idaho Falls, Idaho (March 1990)
4. R.P. Taleyarkhan, et. al., "Modeling and Analysis of Core Debris Recriticality During Hypothetical Severe Accidents in the Advanced Neutron Source Reactor," ORNL/TM-12382, Oak Ridge National Laboratory (May 1993)
5. L.M. Petrie, and N.F. Landers, "KENO V.A-An Improved Monte Carlo Criticality Program with Supergrouping," Vol. 2, Sect. F11 from SCALE: A Licensing Evaluation, NUREG/CR-0200 Rev. 2, ORNL/NUREG/CSD-2/R2, Oak Ridge National Laboratory (December 1984)
6. Personal Communication with Jess Gehin
7. C.R. Hyman, and R.P. Taleyarkhan, "Characterization of Core Debris/Concrete Interaction for the Advanced Neutron Source," ORNL/TM-11761, Oak Ridge National Laboratory (February 1992)

Table 1 Fuel Mass Inventory at Beginning of Cycle for 3 Assembly Core with 50% Enrichment [6]

ORIGIN ID	SYMBOL	MASS (g)	X-S LIB ID
10020	H	9.4489E+03	1002/1402
50100	B	1.7000E+01	5010
50110	B	7.5300E+01	5011
60000	C	4.1000E+02	6012
80160	O	3.7520E+04	8016
120000	Mg	1.1194E+03	12000
130270	Al	1.6483E+05	13327
140000	Si	4.0125E+03	14000
220000	Ti	1.6790E+02	22000
240000	Cr	2.2390E+02	24000
250550	Mn	1.9650E+02	25055
260000	Fe	1.0702E+03	26000
290000	Cu	3.9320E+02	29000
300000	Zn	3.3720E+02	N/A
922340	U	2.0884E+02	92234
922350	U	1.9471E+04	92235
922360	U	8.9565E+01	92236
922380	U	1.9172E+04	92238

Table 2 Calculation Matrix for the Recriticality Study for Debris Dispersion Configuration in ANS RCS

CASE I.D.	H2O mole Frac.	Void Frac.	Dispersion Length (m)	Al (kg)	Temp (C)	B-10 (gr)	k-eff	std. deviation	Case Description
Base	0.002	0	1	80	50	17	0.94698	0.00322	base case
H2O-1	0.1	0	1	80	50	17	1.10027	0.00352	light water contamination
H2O-2	0.5	0	1	80	50	17	1.29148	0.00287	
H2O-3	1	0	1	80	50	17	1.30088	0.00274	
VF-1	0.002	0.2	1	80	660*	17	0.79763	0.00322	void fraction variation
VF-2	0.002	0.4	1	80	660*	17	0.68751	0.00280	
VF-3	0.002	0.6	1	80	660*	17	0.57658	0.00257	
DL-1	0.002	0	0.25	80	50	17	0.82531	0.00318	dispersion length variation
DL-2	0.002	0	0.5	80	50	17	0.92123	0.00281	
DL-3	0.002	0	1.5	80	50	17	0.95702	0.00329	
DL-4	0.002	0	2	80	50	17	0.94978	0.00344	
DL-5	0.002	0	3	80	50	17	0.92021	0.00338	
AL-1	0.002	0	1	0	50	17	1.00907	0.00338	aluminum mass variation
AL-2	0.002	0	1	60	50	17	0.96411	0.00323	
AL-3	0.002	0	1	120	50	17	0.91927	0.00300	
AL-4	0.002	0	1	164	50	17	0.87580	0.00314	
TM-1	0.002	0	1	80	72	17	0.93612	0.00311	mixture temp. variation
TM-2	0.002	0	1	80	100	17	0.93218	0.00370	
B10-1	0.002	0	1	80	50	0	1.04239	0.00315	B-10 mass variation
B10-2	0.002	0	1	80	50	6	1.00466	0.00353	
B10-3	0.002	0	1	80	50	12	0.96667	0.00368	

* This temperature is only for U3Si2, Al and B.

Table 3 Calculation Matrix for the Recriticality Study in ANS Subpile Room

case	debris mixing radius (m)	f(D2O)	f(water)	k-effective					
				BOC	EOC				
					w/o f.p.	w/ f.p.	multi-layers	10% void	50% void
hw1	1.0	1	0	0.793153	0.700548	1.04149	0.721396	1.03555	0.900841
hw2	1.0	1	0.5		0.762185				
hw3	1.0	1	0.8		0.898826				
hw4	1.0	1	0.9		1.06365				
hw5	1.0	1	0.95		1.27056				
hw6	1.0	1	0.99		1.69485				
hw7	3.0	1	0.99857		0.935157				
lw1	1.0	0	0		0.360941		0.907983		
lw2	1.0	0	0.5		0.533932				
lw3	1.0	0	0.85		0.880045				
lw4	1.0	0	0.9		0.951304				
lw5	1.0	0	0.92		0.96632				
lw6	1.0	0	0.95		0.926996				
lw7	1.0	0	0.99		0.397996				
mx1	1.0	0.5	0		0.420699				
mx2	1.0	0.5	0.5		0.56123				
mx3	1.0	0.5	0.8		0.795622				
mx4	1.0	0.5	0.9		0.986523				
mx5	1.0	0.5	0.95		1.07593				
mx6	1.0	0.5	0.99		0.624487				
rd1	0.5	1	0		0.791464				
rd2	0.5	0	0		0.495929				
rd3	1.5	1	0		0.509712				

Note : f(D2O) = mass fraction of D2O in water
f(water) = volume fraction of water in debris mixture
BOC = beginning of cycle
EOC = end of cycle
f.p. = fission products

Figure 1 Debris Configurations Considered in the Current Study

zone 1 = core debris-coolant mixture
 zone 2 = heavy water moderator
 zone 3 = pipe wall
 zone 4 = light water reactor pool

Figure 2 Schematic Configuration of Core Debris Dispersion in RCS

Figure 3 k-effective Versus H₂O Mole Fraction in D₂O Coolant

Figure 4 k-effective Versus Void Fraction in Fuel Mixing Zone

Figure 5 k-effective Versus Fuel Debris Dispersion Length

Figure 6 k-effective Versus Aluminum Mass in Fuel Mixture

Figure 7 k-effective Versus Fuel Mixture Temperature

Figure 8 k -effective Versus B-10 Mass in Fuel Mixture

Figure 9 Schematic Representation of Core Debris Relocation Process in Subpile Room

Figure 10 Assumed Geometry for Lumped Debris Configuration

Figure 11 Calculated values of k-effective as a function of debris dispersion

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