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Study on Core Debris Recriticality During Hypothetical Severe Accidents in Three Element Core Design of The Advanced Neutron Source Reactor

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Abstract

This study discusses special aspects of severe accident related recriticality modeling and analysis in the Advanced Neutron Source (ANS) reactor.[1, 2] The analytical comparison of three elements core to former two elements case is conducted including evaluation of suitable nuclear cross-section sets to account for the effects of system configulation, fuel and moderator mixture temperature, material dispersion and the other thermal-hydraulics. Three elements core ANS reactor is the alternative core design which was proposed as a modified core design, with three fuel elements instead of two, that would allow operation with only 50% enriched uranium (former uranium fuel is the baseline design value of 93%) A comprehensive test matrix of calculations to evaluate the threat of a criticality event in the ANS is described. Strong dependencies still on geometry, material constituents, and thermal-hydraulic conditions are verified. Therefore, the concepts of mitigative design features are qualified.

1. Introduction

Specifically, the ANS reactor will use about 15 kg of highly enriched ($\sim$ 93 m/o ^{235}U) uranium silicide fuel in an aluminum matrix with a plate-type geometry and a total core mass of 100 kg. About 13 g of B^{10} burnable poison is provided in the end caps of fuel plates to reduce excess reactivity at the beginning-of-cycle and to help shape the

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power distribution. Heavy water(D_2O) is used as moderator and coolant. The power density of the ANS will be about 50 to 100 times higher than that of a large LWR. The reactor core is furthermore enclosed within a core pressure boundary tube and enveloped in a reflector tank. Recriticality is the event that may cause a serious damage, if it occurs, to a reactor system in severe accidents at the ANS reactor. Loss of a heat balance between generation and removal in a reactor core may lead degeneration of fuel due to heat-up and melting. Depending on the geometry of dispersed debris and the degree of moderation, the fragmented fuel debris may become recritical. Why is recriticality issue important? Because it may lead to structural damaging steam explosion loads such as the containment failure, additional fission product generation and release to environment and high-energy bursts of radiation in the relation with shielding concerns.

2. Core Debris Recriticality Calculation

The study of recriticality represents an important phase of any hypothetical severe accident that has progressed to the point of core debris relocation outside of the control rod region. This section provides a synopsis of work conducted in this area. The KENO5-SCALE[3)] code system was adapted for the IBM RISC/6000 platform. Detailed benchmarking studies in the steady-state neutronics codes such as BONAMI-S and NITAWL-S were conducted. ANSL-V Cross-Section Library[4)] for 39 neutron group was also used. Thereafter, a matrix of several calculation was conducted for the phenomenological thermal-hydraulics. As documented in the previous progress report, lumped configurations would not lead to a prompt criticality in the ANS cooling circuit. Therefore, focus was placed on dispersed configurations. A detailed test matrix of calculations was set up to evaluate the effects of mixture temperature, aluminum content, void fraction, fuel burnup, boron depletion, dispersion length, and light water contamination. A summary of the test matrix and results of K_{eff} calculations are shown in Table 1, which indicates that light water contamination can significantly increase reactivity insertion. The thermal-hydraulic conditions prevalent in the mixture zone can also have a significant effect, as can be seen from the variation of

K_{eff} with mixture void fraction. These results would be adapted to provide insights for developing mitigative measures.

3. Analysis Results

Specific KENO-SCALE models for the various cases in Table 1 were set up and executed. The results of the K_{eff} calculations are summarized in the Table 1 and are shown graphically in Figs. 1 through 6. Fig. 1 indicates that H_2O contamination in the reactor coolant system(RCS) can significantly increase K_{eff} values. This is shown that neutronic characteristics are changed with H_2O contamination. However, the effect tapers off beyond 50% H_2O mole fraction and then starts to decrease because of enhanced moderation with H_2O injection into the fuel mixing region is compensated by increased neutron absorption. A linear decrease in K_{eff} is seen in Fig. 2 with increasing void fraction, in the debris zone. The variation with increased void fraction also tends to indicate that a strong mechanism exists for limiting a reactivity excursion event. The void formation in the fuel debris mixture provides substantial negative reactivity. A strong variation also is seen with dispersion length in Fig. 3. Reducing dispersion length causes a lumped mass-type geometry and decreases K_{eff}. As seen in Fig. 3, K_{eff} becomes maximum at 1.5m of dispersion length. Fig. 4 shows that the amount of aluminum accompanying the core debris also can have a significant effect on system criticality. The variation of K_{eff} with aluminum mass shows a linear dependency. It is not as strong as seen with variation with void fraction. Only a relatively mild variation with mixture temperature was noted. Fig. 5 shows that a K_{eff} decrease of about 7 ~ 8 cents/℃ is achieved. This result indicates that a resonance absorption caused by Doppler-broadening would provide enough negative feedback to compensate for positive reactivity insertion from increased thermal utilization by the fuel as the temperature increases. Finally, Fig. 6 demonstrates the importance of B^{10} in the fuel mixture. As can be seen, small depletion of B^{10} affects K_{eff} substantially. Obviously, this variation with burnup is predicated on the B^{10} accompanying the fuel debris at the beginning-of-cycle(BOC) conditions in the first place.

4. Summary and Conclusions

This study has pursued salient aspects of benchmarking and validation of the KENO-SCALE neutronic code system for evaluation of system criticality, wherein lumped and dispersed core-debris configurations may arise during hypothetical severe accidents in the ANS.

○ **Recriticality potential is substantially reduced for 3 elements core design with 50% enrichment**

○ **Strong dependencies on key thermal-hydraulic parameters are shown (i.e., void fraction, H_2O contamination, aluminum content, and dispersion length)**

○ **H_2O contamination provides a positive reactivity, in some instances, the system becomes supercritical.**

○ **Void formation (boiling of mixed water) provides enough negative reactivity to bring the system down to subcritical**

References

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Table 1. Test Matrix of Recriticality Calculations for ANS with Dispersed Configuration

CASE I.D.	H_2O mole Frac.	Void Frac.	Dispersion Length (m)	Al (kg)	Temp (℃)	B-10 (gram)	K-eff.	Case Description
Base	0.002	0.0	1.0	80	50	17	0.94698	base case
H_2O-1	0.1	0.0	1.0	80	50	17	1.10027	light water contamination
H_2O-2	0.5	0.0	1.0	80	50	17	1.29148	
H_2O-3	1.0	0.0	1.0	80	50	17	1.30088	
VF-1	0.002	0.2	1.0	80	660^*	17	0.79763	void fraction variation
VF-2	0.002	0.4	1.0	80	660^*	17	0.68751	
VF-3	0.002	0.6	1.0	80	660^*	17	0.57658	
DL-1	0.002	0.0	0.25	80	50	17	0.82531	dispersion length variation
DL-2	0.002	0.0	0.5	80	50	17	0.92123	
DL-3	0.002	0.0	1.5	80	50	17	0.95702	
DL-4	0.002	0.0	2.0	80	50	17	0.94978	
DL-5	0.002	0.0	3.0	80	50	17	0.92021	
AL-1	0.002	0.0	1.0	0	50	17	1.00907	aluminum mass variation
AL-2	0.002	0.0	1.0	60	50	17	0.96411	
AL-3	0.002	0.0	1.0	120	50	17	0.91927	
AL-4	0.002	0.0	1.0	164	50	17	0.87580	
TM-1	0.002	0.0	1.0	80	72	17	0.93612	mixture temperature variation
TM-2	0.002	0.0	1.0	80	100	17	0.93218	
B10-1	0.002	0.0	1.0	80	50	0	1.04239	B-10 mass variation
B10-2	0.002	0.0	1.0	80	50	6	1.00466	
B10-3	0.002	0.0	1.0	80	50	12	0.96667	

* This temperature is only for U_3Si_2, Al. and B-10

Fig. 1 H_2O Mole Fraction in Fuel Mixture

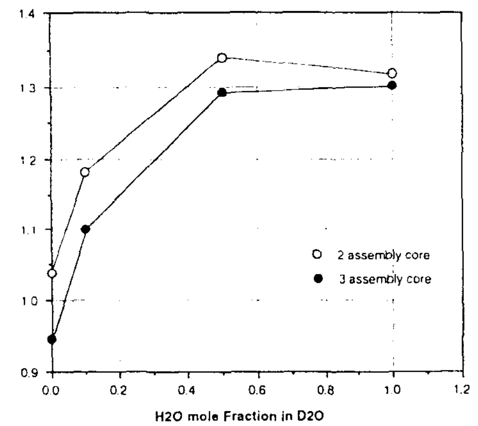

Fig. 2 Void Fraction in Fuel Mixing Region

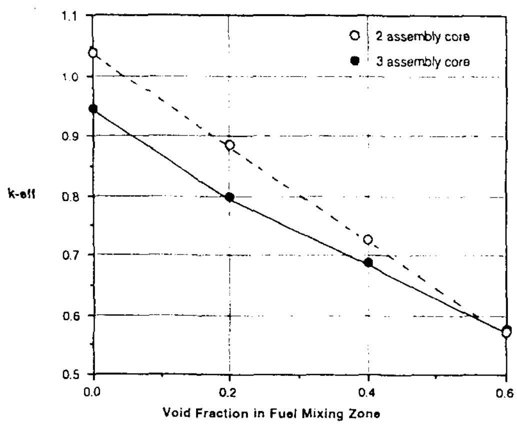

Fig. 3 Fuel Debris Dispersion Length

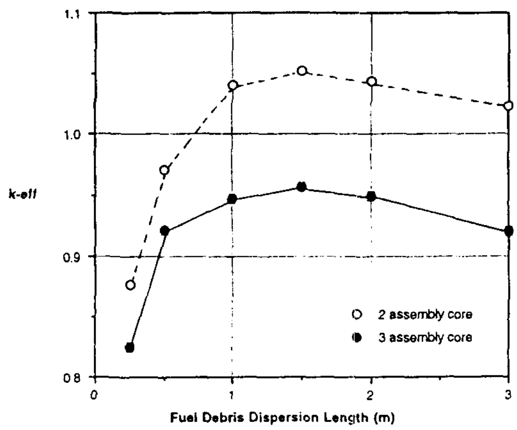

Fig. 4 Aluminum Mass in Fuel Mixture

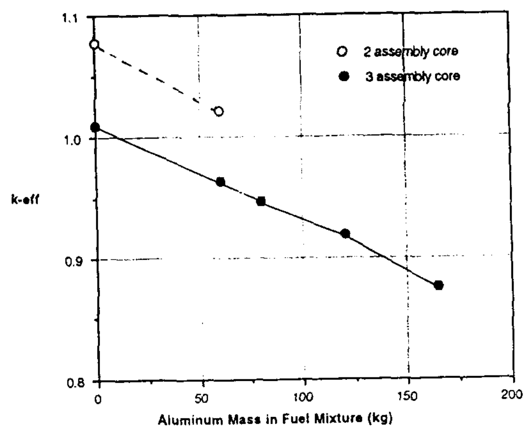

Fig. 5 Fuel Mixture Temp. Variation

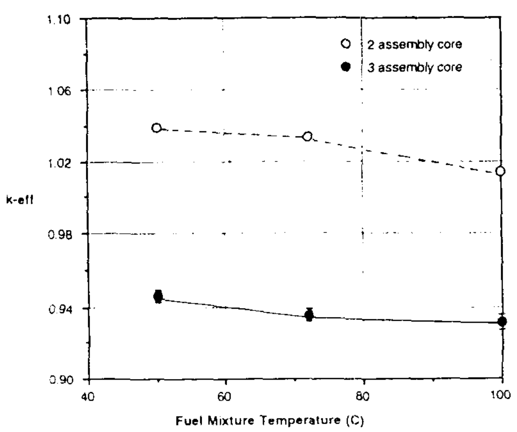

Fig. 6 B-10 Depletion