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Final Report of the Reactor Criticality Analysis Program

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This work performed under the auspices of the United States Atomic Energy Commission for the Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, N. M.

NUCLEAR SAFETY OF AN AIRBORNE FAST REACTOR

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ABSTRACT

Neutronic calculations were performed for an airborne fast reactor concept in order to evaluate safety aspects of compactions and coolant voiding. The reactor will remain subcritical under severe compactions provided that (1) all the control elements are inserted prior to compaction, (2) the control material uses ^{10}B rather than natural boron, and (3) the excess reactivity at the beginning-of-life is less than 6.8%. Voiding of the metal coolant produces only a small reactivity effect.

I. INTRODUCTION AND SUMMARY

The Air Force Weapons Laboratory (AFWL) is evaluating various aspects of the safety of mobile nuclear reactors, particularly airborne reactors. It is sponsoring tests to assist in the development of containment vessels that will survive impact deformations without rupturing or leaking, to determine the deformation of the reactor cores due to impact, and to evaluate engineered safety features under impact. The Reactor Theory Group of the Los Alamos Scientific Laboratory (LASL) has supported this work by assessing the nuclear criticality and other reactor parameters for both normal and deformed core configurations.

This final report covers investigations of the effects of compaction and of coolant voiding of the AFWL fast reactor concept. Investigations of the AFWL thermal reactor concept were reported previously in Refs. 1 and 2.

A two-dimensional (R-Z) model, derived from descriptions given in Ref. 3, was used in 7-group diffusion theory calculations of the fast reactor. One-dimensional (cylinder), 16-group, transport (S_4) calculations were used to obtain the 7-group cross sections used in the two-dimensional calculations. The one-dimensional calculations, using an effective buckling height appropriate for the reference configuration, were also used to determine the enrichment of the fuel and as a crosscheck on the two-dimensional results.

Radial and axial compactions that do not distort the cylindrical geometry were studied. In both the radial and axial compaction cases, complete compaction was specified. That is, all the void and coolant spaces were eliminated in the compacted configurations. In addition, compaction was assumed to occur at the beginning-of-life (BOL) when the excess reactivity is at its maximum.

The reactor will remain subcritical under these compactions provided that (1) all of the control elements are inserted prior to compaction, (2) the control material (B_4C) uses ^{10}B rather than natural boron, and (3) the excess reactivity at the BOL is less than 6.8%.

Voiding of the liquid-metal coolant produces a small reactivity effect that is generally positive only in the innermost regions of the system and negative elsewhere. The net reactivity effect of voiding the coolant from all regions of the two-dimensional model was found to be -55¢.

II. CALCULATIONAL MODEL AND METHODS

The calculations were performed with the system of linked reactor physics codes described in Ref. 4. A two-dimensional (R-Z) model was defined

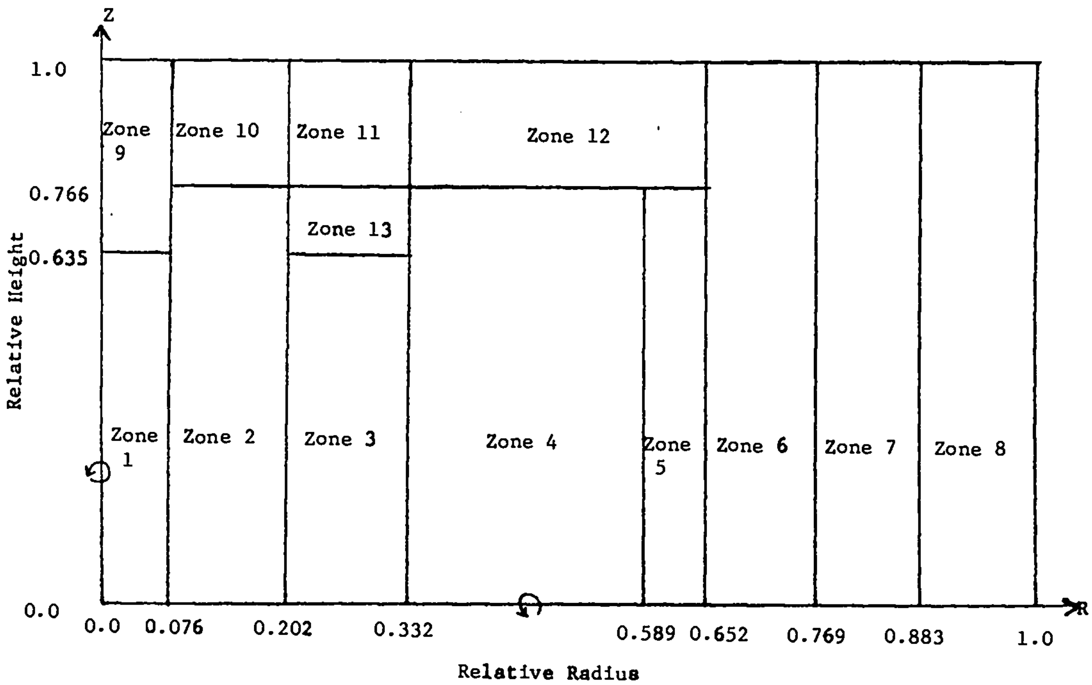

Fig. 1. Two-dimensional (R-Z) model.

for the reactor as shown in Fig. 1. The relative dimensions shown in the figure are for the normal (uncompacted) configuration. Note that the model assumes symmetry about the midheight of the core. Twenty-five radial and 16 axial mesh intervals and 13 zones were used to specify the geometry. A description of the 13 zones in the model is given in Table I.

Based on a radial trace at H = 0.0, one-dimensional, 16-group, transport (S_4) calculations were performed in cylindrical geometry with axial buckling. These calculations were performed with 25 mesh intervals. The primary purpose of the one-dimensional calculations was to collapse the 16-group cross sections to fewer groups for use in the two-dimensional diffusion calculations. The one-dimensional calculations were also used to determine the fuel enrichment and to provide a cross-check on the two-dimensional results.

With the exception of ^{10}B and tungsten, the 16-group cross sections were taken from the Hansen-Roach library.[5,6] These cross sections have been tested extensively on many fast reactor assemblies. Cross sections for ^{10}B and tungsten were generated from the Evaluated Nuclear Data File (ENDF) with the ETOG code.[7]

The one-dimensional calculations indicated that there is very little flux below 17 keV, the boundary between groups 6 and 7 of the 16-group structure. Consequently, the 16-group cross sections were reduced to seven groups by collapsing groups 7 through 16 into one group. Collapsed cross sections were obtained for both the control-out and control-in configurations. The one-dimensional calculations were then repeated with the collapsed cross sections in order to verify the collapsing procedure.

An effective buckling height equal to the actual core height plus a total reflector savings of 16.4 cm was used in all the one-dimensional calculations. The effective buckling height was obtained by requiring that the multiplication factor from the one-dimensional calculation for the control-out configuration be the same as that obtained from the corresponding two-dimensional calculation.

After the effective buckling height had been determined, a concentration search calculation was performed in one dimension to determine the

TABLE I

DESCRIPTION OF ZONES IN TWO-DIMENSIONAL MODEL

Zone	Description
1	With central shim rod assembly inserted, this zone contains poison, moderator, coolant, and structural material. With the shim rod withdrawn, this zone contains coolant and structural material only.
2	Contains fuel, cladding, coolant, and structural material.
3	With off-center shim rods inserted, this zone contains poison, moderator, fuel, cladding, coolant, and structural material. With the shim rods withdrawn, this zone contains fuel, cladding, coolant, and structural material.
4	Same as Zone 2.
5	Contains reflector, coolant, and structural material.
6	With control drums inserted (rotated to their most effective position), this zone contains poison, reflector, coolant, and structural material. With control drums withdrawn (rotated to their least effective position), this zone contains reflector, coolant, and structural material.
7	Contains reflector, coolant, and structural material.
8	With control drums inserted, this zone contains reflector, coolant, and structural material. With control drums withdrawn, this zone contains poison, reflector, coolant, and structural material.
9	Same as Zone 1, except that poison and moderator are present when the shim rod is withdrawn and absent when it is inserted.
10	Contains reflector, coolant, cladding, and structural material.
11	When the off-center shim rods are inserted, this zone contains the same materials as Zone 10. When the shim rods are withdrawn, this zone contains poison and moderator in addition to the materials in Zone 10.
12	Same as Zone 10.
13	Same as Zone 3, except that poison and moderator are present when the off-center shim rods are withdrawn and absent when they are inserted.

appropriate fuel enrichment. The enrichment was adjusted so that the effective multiplication factor for the control-out configuration is 1.05. Normalization to $k_{eff} = 1.05$ was based on an estimate of the excess reactivity required at the BOL to compensate for the average fuel burnup expected during the operating life of the reactor.

The reactivity worths of voiding the coolant were obtained from a two-dimensional perturbation calculation. Fluxes and currents (both regular and adjoint) from the two-dimensional diffusion calculations for the control-out configuration were used in the perturbation calculation.

III. RESULTS

Results of the one- and two-dimensional calculations related to the compaction studies are summarized in Table II. A description of each case included in the table is given below.

TABLE II

SUMMARY OF RESULTS RELATED TO COMPACTION STUDIES

Case	Effective Multiplication Factor: 7-Group Two-Dimensional Diffusion	Effective Multiplication Factor: 16-Group One-Dimensional Transport
I	1.048	1.050
II	---	1.050
III	0.898	0.899
IV	---	0.982
V	0.980	0.987
VI	0.970	---

Case I. This is the normal (uncompacted) configuration with all control elements withdrawn and ^{10}B used in the control material. The H/D ratio of the core for this configuration is 0.77.

Case II. Same as Case I, except that natural boron was used in the control material.

Case III. Normal configuration with all control elements inserted and ^{10}B used in the control material.

Case IV. Same as Case III, except that natural boron was used in the control material.

Case V. Complete radial compaction (holding axial dimensions fixed) with all control elements inserted and using ^{10}B in the control material. The H/D ratio of the core for this configuration is 0.89.

Case VI. Complete axial compaction (holding radial dimensions fixed) with all control elements inserted and using ^{10}B in the control material. The H/D ratio of the core for this configuration is 0.57.

Complete compaction in Cases V and VI means that the voids and the coolant were completely eliminated in the compaction. This amounted to volume reductions of approximately 26, 15, and 32%, respectively, in the core, radial reflector, and axial reflector.

From the results in Table II, it is concluded that the reactor will remain subcritical under the compactions considered provided that (1) all control elements are inserted prior to compaction, (2) ^{10}B is used in the control material, and (3) the excess reactivity at the BOL is less than 6.8%.

If natural boron is used in the control material, the results for Cases II and IV indicate that the worth of the control elements is only 45% of that for ^{10}B. Assuming that the excess reactivity at the BOL is less than 6.8%, natural boron would provide sufficient control under normal circumstances. However, the worth of the control elements would not be sufficient to hold down reactivity gains from major compactions, even at the end-of-life. Two-dimensional calculations for Cases II and IV were considered unnecessary because of the close agreement between the one- and two-dimensional results for Cases I and III.

The same effective buckling height was used for all the one-dimensional calculations. As mentioned previously, the effective buckling height used was that appropriate for the normal configuration with all control elements withdrawn. The close agreement between the one- and two-dimensional results for Case III indicates that the effective buckling height is not affected by insertion of all the control elements. However, the results for Case V indicate that the effective buckling height is affected somewhat by radial compaction. No attempt was made to calculate the axial compaction case (Case VI) in one-dimensional geometry because the effective buckling height is expected to change appreciably in this case.

Perturbation results for the reactivity worth of coolant voiding are summarized in Table III. These results were obtained using fluxes and currents (both regular and adjoint) for the two-dimensional model (Fig. 1) with all control elements withdrawn. In general, removal of the coolant causes an increase in reactivity only in the innermost regions of the reactor.

TABLE III

REACTIVITY WORTH OF COOLANT VOIDING

Zone	Worth (¢)
1	0.9
2	6.1
3	22.4
4	-49.3
5	-10.4
6	3.9
7	2.0
8	- 0.2
9	- 1.2
10	- 3.1
11	- 4.6
12	-16.2
13	- 4.9

At any mesh point in the system, the net reactivity effect is determined by the relative contribution of the absorption, moderation, and scattering effects. For coolant removal, the combined absorption and moderation effects are positive because the number of parasitic captures is reduced. Scattering events in the coolant tend to reduce the leakage and thus the scattering effect is negative for coolant removal. In the innermost regions of the reactor where the flux is high and the leakage is low, the absorption and moderation effects predominate. In the outer regions where the flux is low and the leakage is high, the scattering effect predominates.

Voiding of the coolant from all regions of the model results in an overall reactivity loss of 55¢. The effective delayed neutron fraction and prompt-neutron generation time obtained from the perturbation calculation were 0.0067 and 6.9×10^{-8} sec, respectively.

IV. SUGGESTIONS FOR FUTURE WORK

When results of impact tests become available for the fast reactor mockup, more realistic compaction calculations should be made. Reactivity gains from impact deformations will depend on the orientation of the core at time of impact, the amount of compaction, and the degree of distortion of the core. If deformed shapes are qualitatively similar to those previously observed[8] for other mockups, it is unlikely that the deformed core will be more compact than that for the radial compaction case (Case V) considered in this report.

Additional work is recommended in the area of meltdown studies. If the bottom boundary of the fuel remains fixed and the fuel cladding remains intact, meltdown of the fuel should have a small effect compared to complete compaction of the core. This is because voids comprise only about 4% of the fuel pin volume (or about 2% of the core volume), whereas complete compaction results in a volume reduction of about 26% in the core. In a meltdown situation in which the fuel cladding remains intact, it would be more realistic to assume that the fuel slumps into the fission gas chamber at the bottom end of the fuel pin. This, of course, assumes that the reactor is upright at the time of meltdown. In such a configuration, and with the shim rods inserted, about a third of the active core height will be below the bottom of the shim rods. This configuration, which requires a two-dimensional model in which the full height of the reactor is represented, should be calculated for both the normal and compacted cases.

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