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Nuclear Safety of an Airborne Thermal Reactor

Status Report of the Reactor Criticality Analysis Program to October 1, 1971

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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 THERMAL REACTOR

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PREFACE

The Air Force Weapons Laboratory (AFWL) is evaluating various aspects of the safety of mobile nuclear reactors, particularly airborne reactors. AFWL is sponsoring tests to assist in the development of containment vessels which 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) is supporting this work by assessing the nuclear criticality and other reactor parameters for both normal and deformed core configurations.

This report covers initial investigations of possible shutdown mechanisms for meltdown of a proposed gas-cooled, light-water-moderated thermal reactor. AFWL is also considering a liquid-metal-cooled fast reactor that LASL will evaluate for nuclear safety when design specifications are available. The applicability of proposed shutdown mechanisms will be evaluated for the experimentally determined core and containment configurations when data are available from the AFWL impact tests.

I. SUMMARY

Neutronic calculations were performed to investigate the feasibility of using a diluent-poison to solve the criticality problem arising from core meltdown for the airborne thermal reactor concept. Survey calculations were performed in one-dimensional spherical geometry on both bare and reflected spheres containing diluent:UO_2 core volume ratios of 0.0, 0.5, 1.0, 2.0, and 3.0. Two-dimensional calculations were also performed for one particular diluent in order to obtain an indication of how the one-dimensional results relate to more realistic geometrical configurations.

The diluents studied were W, WB, WB_2, Ta, TaB_2, and Re. Both natural boron and ^{10}B were used in the survey calculations for the borides. With the exception of W, the calculations indicate that any of these diluents could be used to solve the criticality problem with diluent:UO_2 volume ratios of 1.7 or less. For W, a volume ratio of 3.0 is required.

On a volume basis, the order of decreasing effectiveness of the various diluents is: $Ta^{10}B_2$, $W^{10}B_2$, $W^{10}B$, TaB_2, Re, WB_2, Ta, WB, and W. On a mass basis, the order is the same, except that Re comes after WB.

II. INTRODUCTION

The airborne thermal reactor concept is a water-moderated and reflected, helium-cooled reactor fueled with enriched UO_2. Initial neutronic calculations of this concept were devoted to determining the feasibility of using a diluent-poison to solve the meltdown criticality problem. Meltdown of the core is assumed to occur solely as a result of the decay of fission products (afterheat) following a loss of coolant. The loss of coolant causes scramming of the control element and rapid removal of the moderator-reflector water from within the core pressure vessel. Heating from the decay of fission products then causes the core to melt and collect in a pool at the bottom of the pressure vessel which is protected by a tungsten liner and thermal insulation. Core structural materials are assumed to collect in one or more layers over the pool of molten UO_2.

The amount of enriched UO_2 in the core was assumed to be 868 kg (1914 lb) at density 10.8 g/cm^3 with uranium isotopic abundances as shown in Table I. This amount of enriched UO_2, if allowed to collect within the pressure vessel and if undiluted with a neutron poison, will become supercritical. For a bare sphere of enriched UO_2, the critical radius is 13.4 cm and the critical mass is 109 kg. If the sphere is reflected with an essentially infinite thickness of $^{238}UO_2$, the critical core radius is 9.1 cm, and the critical mass is 34 kg. Thus, in the most reactive configuration conceivable, only 4% of the original 868 kg of enriched UO_2 is required to form a critical mass.

TABLE I

URANIUM ISOTOPIC ABUNDANCES IN ENRICHED UO_2

Isotope	Abundance (at.%)
^{235}U	93.10
^{238}U	5.75
^{234}U	0.886

Any material that is to be used as a diluent must satisfy the following three requirements:

1. Density greater than that for UO_2,
2. Melting point appreciably higher than that for UO_2, and
3. Capture cross section sufficiently high so that the diluent and enriched UO_2 mixture is subcritical with a diluent:UO_2 volume ratio of 3 or less.

The first requirement is necessary to ensure that the diluent does not float on top of the molten UO_2. The second requirement is necessary to ensure that the diluent does not melt and form a layer at the bottom of the UO_2 pool. The third requirement arises from the method in which the diluent is introduced in case of a meltdown. It is contemplated that small spheres (say ≤1 in. diam) of the diluent material would be contained in an annulus surrounding the reflector regions of the reactor. The containment for the spheres would be such that, when the core melts, the spheres would fall to the bottom of the pressure vessel and dilute the molten UO_2. For spheres of uniform size, the largest packing fraction achievable is 0.74. This packing fraction, which is obtained with a face-centered cubic lattice, would allow a diluent:UO_2 volume ratio of 2.8. For a body-centered cubic lattice, the packing fraction is 0.68, which would allow a diluent:UO_2 volume ratio of 2.1. Under conditions other than close packing, a packing fraction of 0.60 is probably reasonable. This would allow a diluent:UO_2 volume ratio of 1.5.

Schematic diagrams of the normal and meltdown configurations using the "diluent-spheres" concept are shown in Figs. 1 and 2. Because stratification of the UO_2 and core structural materials presents the most severe criticality problem, the meltdown configuration of Fig. 2 is conservative.

Materials considered as possible diluents are given in Table II. As shown in the table, these materials satisfy the requirements on density and melting temperature. Note that the melting temperatures of WB_2 and TaB_2 are uncertain but potentially in the right neighborhood. Densities and melting

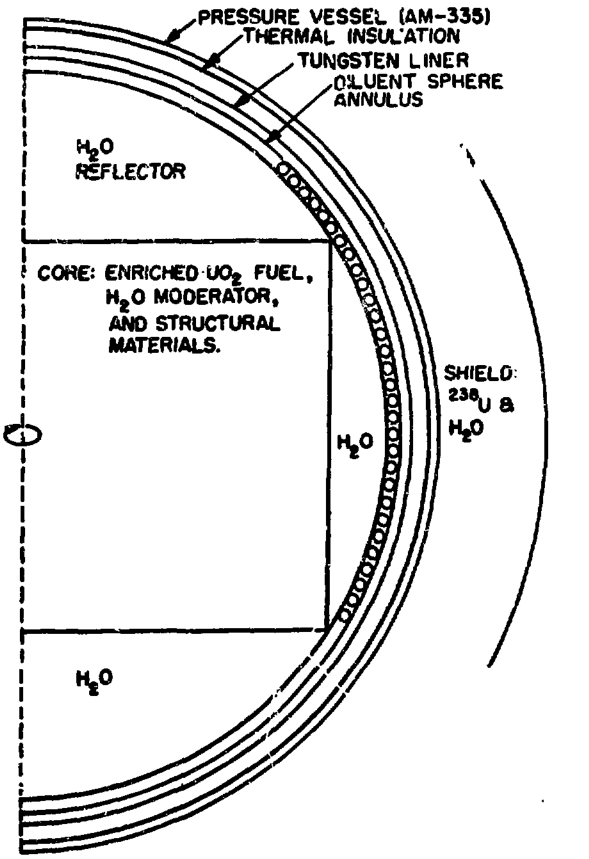


Fig. 1. Normal configuration.

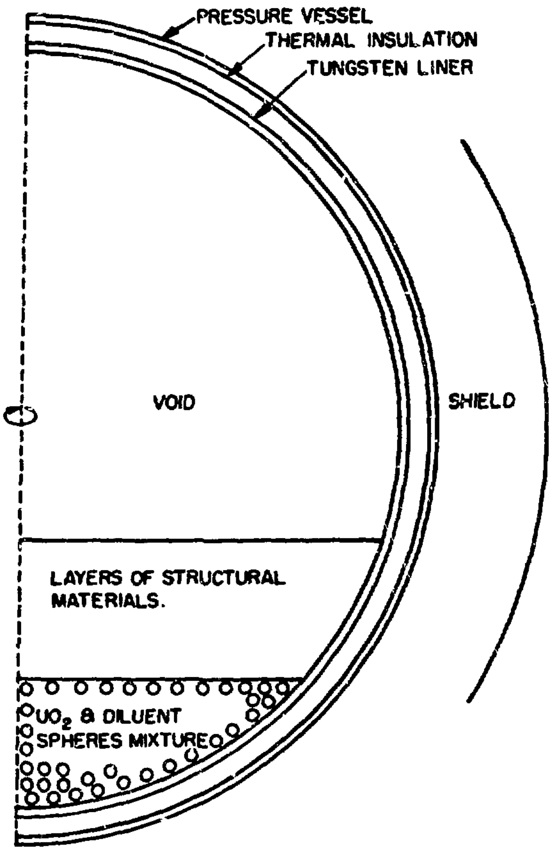


Fig. 2. Meltdown configuration

TABLE II

MATERIALS CONSIDERED AS POSSIBLE DILUENTS

Material	Density (g/cm^3)	Melting Temperature (°C)
W	19.3	3370
WB	15.7	2920
WB_2	12.75	2900 (?)
Ta	16.6	3000
TaB_2	12.4	3000 (?)
Re	20.5	3167

temperatures in Table II were obtained from Ref. 1. Survey calculations were performed in one-dimensional spherical geometry to establish the relative effectiveness of these materials in solving the meltdown criticality problem. The survey calculations are discussed in Sec. III. Two-dimensional calculations, discussed in Sec. IV, were performed to obtain an indication of how the one-dimensional results relate to more realistic geometries.

Because the moderator-reflector water is assumed to be removed from the pressure vessel prior to core meltdown, the meltdown configuration is a fast system, and detailed thermal cross sections are not required for the neutronic computations. For this reason, cross sections from the Hansen-Roach (H-R) 16-group library[2,3] were used in the one-dimensional analyses. These cross sections have been tested extensively on many fast and intermediate assemblies. The group boundaries and fission spectrum for the 16-group structure are given in Table III.

TABLE III

GROUP BOUNDARIES AND FISSION SPECTRUM FOR 16-GROUP STRUCTURE

Group	Energy Range				Fission Spectrum (^{235}U)
1	3	-	10	MeV	0.204
2	1.4	-	3	"	0.344
3	0.9	-	1.4	"	0.168
4	0.4	-	0.9	"	0.180
5	0.1	-	0.4	"	0.090
6	17	-	100	keV	0.014
7	3	-	17	"	0.0
8	0.55	-	3	"	↓
9	100	-	550	eV	↓
10	30	-	100	"	↓
11	10	-	30	"	↓
12	3	-	10	"	↓
13	1	-	3	"	↓
14	0.4	-	1	"	↓
15	0.1	-	0.4	"	↓
16	0.0	-	0.1	"	↓

Cross sections for nuclides not in the H-R library were computed with the ETOG code[4] from the Evaluated Nuclear Data File (ENDF/B). These nuclides included ^{10}B, ^{234}U, ^{182}W, ^{183}W, ^{184}W, ^{186}W, ^{185}Re, ^{187}Re, and Ti. Natural tungsten and rhenium cross sections were obtained from the isotopic cross sections using the natural abundances given in Table IV. The naturally occurring isotope ^{180}W (0.14% abundance) is not in the ENDF/B data file and was ignored in the calculations.

The one-dimensional calculations indicated that there is very little flux below Group 7 of the 16-group structure. Therefore, for the two-dimensional

TABLE IV

ABUNDANCES OF NATURALLY OCCURRING ISOTOPES OF TUNGSTEN AND RHENIUM

Isotope	Natural Abundance (at.%)
^{182}W	26.41
^{183}W	14.40
^{184}W	30.64
^{186}W	28.41
^{185}Re	37.07
^{187}Re	62.93

calculations, the 16-group structure was reduced to seven groups by collapsing Groups 7 through 16 into one group.

III. ONE-DIMENSIONAL SURVEY CALCULATIONS

Survey calculations were made in one-dimensional spherical geometry to establish the relative effectiveness of the materials in Table II as neutron poisons. The calculations were performed with the DTF-IV code,[5] a transport theory program in S_4 approximation using the 16-group energy structure of Table III. Spherical geometry was used because it is the most reactive configuration that can be assumed by the molten UO_2.

Both bare and reflected spheres were calculated for the various diluent-UO_2 mixtures. The core in each case was a homogeneous mixture of enriched UO_2 and diluent. Calculations were made for diluent:UO_2 volume ratios of 0.0, 0.5, 1.0, 2.0, and 3.0. The amount of UO_2 was held fixed at 868 kg (density 10.8 g/cm^3), which is the initial core loading. For the diluents containing boron, both natural boron and ^{10}B were used in the calculations.

Atom densities for the uranium isotopes and oxygen are given in Table V for the various diluent:UO_2 volume ratios. Also given in the table are the volume and spherical radius of the diluent-UO_2 mixture. Atom densities for the diluent materials and total diluent mass are given in Table VI for the various diluent:UO_2 volume ratios.

In the reflected calculations, 25 cm of $^{238}UO_2$ (density 10.8 g/cm^3) was used to simulate reflection from the heavy shield material outside the pressure vessel and from layers of core structural materials that may form over the pool of UO_2. The 25 cm of $^{238}UO_2$ was established by calculations to be effectively an infinite thickness as far as its effect on k_{eff} is concerned. This can be seen in Fig. 3, which shows k_{eff} as a function of $^{238}UO_2$ reflector thickness for a WB_2:UO_2 core volume ratio of 2.0. Atom densities used in the reflector were 0.02409 and 0.04817 (10^{24} atoms/cm^3) for ^{238}U and O, respectively.

Results of the one-dimensional survey calculations are summarized in Tables VII through XII. These results are plotted in Figs. 4 and 5 for easy comparison of the various diluents. In Fig. 4, the multiplication factor (k_{eff}) is shown as a function of diluent:UO_2 core volume ratio for the bare sphere case. Corresponding results for the reflected sphere are shown in Fig. 5.

TABLE V

ATOM DENSITIES OF URANIUM AND OXYGEN IN DILUENT-UO_2 MIXTURES

Diluent:UO_2 Volume Ratio	Mixture Volume (10^3 cm^3)	Core Radius (cm)	Atom Densities (10^{24} atoms/cm^3) ^{235}U	^{234}U	^{238}U	O
0.0	0.8037	26.77	0.02266	0.00022	0.00140	0.04868
0.5	1.2055	30.45	0.01511	0.00014	0.00093	0.03246
1.0	1.6074	33.73	0.01133	0.00011	0.00070	0.02434
2.0	2.4111	38.61	0.00755	0.00007	0.00047	0.01623
3.0	3.2148	42.50	0.00566	0.00005	0.00035	0.01217

TABLE VI

ATOM DENSITIES OF DILUENT MATERIALS IN DILUENT:UO_2 MIXTURES

Diluent Material	Diluent:UO_2 Volume Ratio	Diluent Mass (kg)	Atom Density of Diluent[a] (10^{24} atoms/cm^3) Component 1	Component 2
All	0.0	0.0	0.0	0.0
W	0.5	775	0.02107	—
	1.0	1551	0.03161	—
	2.0	3102	0.04215	—
	3.0	4653	0.04742	—
WB	0.5	631	0.01619	0.01619
	1.0	1262	0.02429	0.02429
	2.0	2524	0.03238	0.03238
	3.0	3785	0.03643	0.03643
WB_2	0.5	512	0.01246	0.02491
	1.0	1025	0.01869	0.03737
	2.0	2049	0.02491	0.04983
	3.0	3074	0.02803	0.05606
Ta	0.5	667	0.01842	—
	1.0	1334	0.02762	—
	2.0	2668	0.03683	—
	3.0	4002	0.04144	—
TaB_2	0.5	498	0.01229	0.02458
	1.0	996	0.01843	0.03687
	2.0	1993	0.02458	0.04915
	3.0	2990	0.02765	0.05530
Re	0.5	824	0.02210	—
	1.0	1648	0.03315	—
	2.0	3295	0.04420	—
	3.0	4943	0.04973	—

[a] In WB_2, for example, W is Component 1 and B is Component 2.

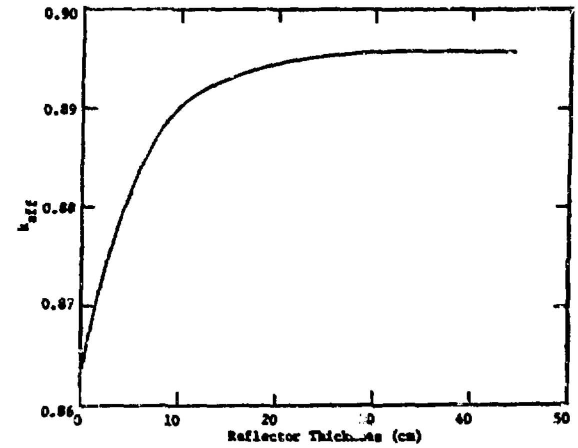


Fig. 5. Effect of reflector thickness on reactivity for $WB_2:UO_2$ core volume ratio of 2.0.

TABLE VII

SURVEY CALCULATIONS FOR $W-UO_2$ MIXTURES

$W:UO_2$ Volume Ratio	Multiplication Factor (k_{eff}) Bare	Reflected
0.0	1.609	1.772
0.5	1.469	1.589
1.0	1.344	1.438
2.0	1.146	1.210
3.0	0.998	1.045

TABLE VIII

SURVEY CALCULATIONS FOR $WB-UO_2$ MIXTURES

$WB:UO_2$ Volume Ratio	Multiplication Factor (k_{eff})			
	Bare		Reflected	
	Natural Boron	^{10}B	Natural Boron	^{10}B
0.0	1.609	1.609	1.772	1.772
0.5	1.386	1.086	1.483	1.146
1.0	1.198	0.823	1.264	0.855
2.0	0.934	0.555	0.971	0.571
3.0	0.762	0.420	0.787	0.430

TABLE IX

SURVEY CALCULATIONS FOR WB_2-UO_2 MIXTURES

$WB_2:UO_2$ Volume Ratio	Multiplication Factor (k_{eff})			
	Bare		Reflected	
	Natural Boron	^{10}B	Natural Boron	^{10}B
0.0	1.609	1.609	1.772	1.772
0.5	1.346	0.973	1.438	1.020
1.0	1.139	0.707	1.199	0.732
2.0	0.863	0.459	0.896	0.472
3.0	0.693	0.341	0.714	0.351

TABLE X

SURVEY CALCULATIONS FOR $Ta-UO_2$ MIXTURES

$Ta:UO_2$ Volume Ratio	Multiplication Factor (k_{eff}) Bare	Reflected
0.0	1.609	1.772
0.5	1.345	1.455
1.0	1.154	1.237
2.0	0.902	0.955
3.0	0.742	0.779

TABLE XI

SURVEY CALCULATIONS FOR TaB_2-UO_2 MIXTURES

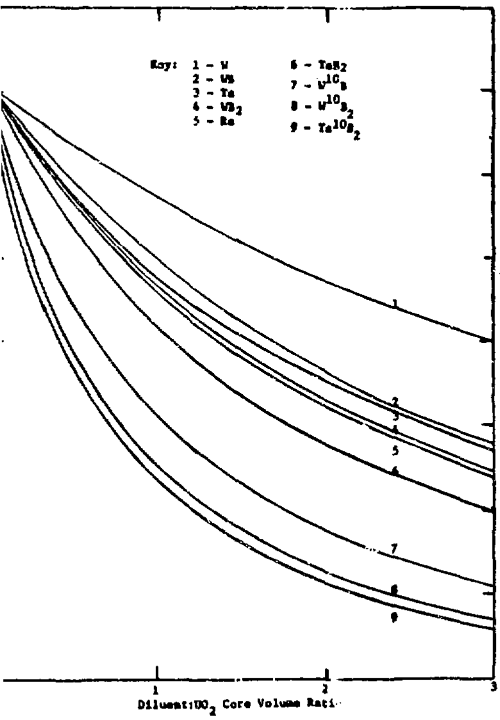
$TaB_2:UO_2$ Volume Ratio	Multiplication Factor (k_{eff})			
	Bare		Reflected	
	Natural Boron	^{10}B	Natural Boron	^{10}B
0.0	1.609	1.609	1.772	1.772
0.5	1.275	0.943	1.359	0.989
1.0	1.042	0.675	1.094	0.700
2.0	0.758	0.433	0.786	0.445
3.0	0.595	0.319	0.613	0.330

TABLE XII

SURVEY CALCULATIONS FOR $Re-UO_2$ MIXTURES

$Re:UO_2$ Volume Ratio	Multiplication Factor (k_{eff}) Bare	Reflected
0.0	1.609	1.772
0.5	1.330	1.424
1.0	1.120	1.183
2.0	0.847	0.882
3.0	0.680	0.704

Assuming a spherical pressure vessel, a two-dimensional calculation (Sec. IV) indicates that the multiplication factor for a more realistic geometry is about 3% smaller than that computed for the bare sphere. That is, the results obtained for the bare sphere can be used conservatively to estimate the reactivity in a more realistic geometry. The diluent:UO_2 volume ratio and diluent mass required to reduce k_{eff} to unity in the bare sphere case are summarized in Table XIII. In the table, the diluents are given in order of decreasing effectiveness on a volume basis. On a mass basis, the order is the same except for Re, which would fall between WB and W. Note that all of the diluents except W could potentially be used in the form of spheres (as discussed previously) to solve the criticality problem. Since the largest diluent:UO_2 volume



4. Bare sphere survey calculations.

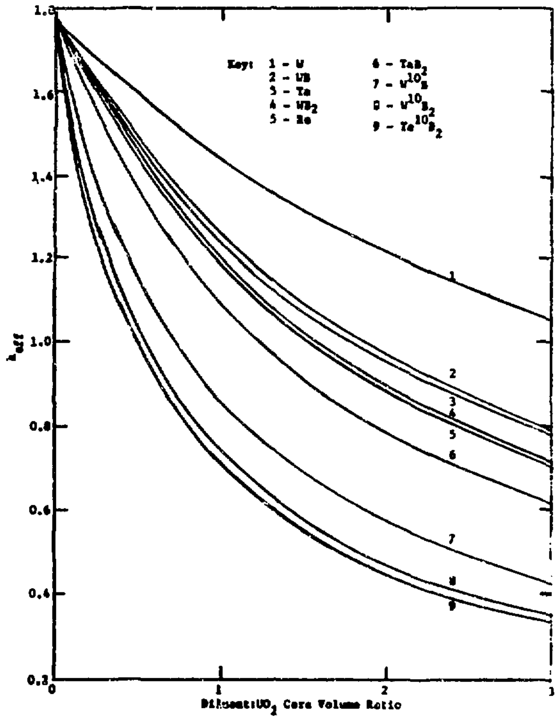


Fig. 5. Reflected sphere survey calculations.

TABLE XIII

DILUENT:UO_2 VOLUME RATIO AND DILUENT MASS REQUIRED TO REDUCE k_{eff} TO UNITY (Bare Sphere Case)

...t	Diluent:UO_2 Volume Ratio	Diluent Mass (kg)
	0.42	420
	0.47	480
	0.64	810
	1.10	1100
	1.36	2240
	1.42	1450
	1.54	2060
	1.68	2120
	2.98	4620

...attainable with the "diluent spheres" scheme ..., a different scheme would have to be used ....

...n the bare sphere calculations, thirty equal ...l mesh intervals were used. In the reflected ...ations, the mesh used was twenty equal inter... n the core and ten equal intervals in the re...r. Typically, the median fission energy occurred in Group 4, which covers the range 0.4 to 0.9 MeV (Table III).

IV. TWO-DIMENSIONAL CALCULATIONS

Two-dimensional calculations were performed for a particular diluent-UO_2 mixture in order to obtain an indication of how the one-dimensional results relate to more realistic geometrical models. The calculations were performed with the TWOTRAN codes[6,7] in S_4 approximation using seven energy groups. Seven-group cross sections were obtained from the 16-group sets by collapsing Groups 7 through 16 into a single group. Fluxes from the corresponding 16-group one-dimensional reflected sphere calculation were used to perform the collapse of the cross sections.

Two-dimensional calculations were performed for two different models. The first model, shown in Fig. 6, is based on a spherical pressure vessel and was calculated in R-ϕ spherical geometry. The inner radius of the pressure vessel (AM-355) is 93.98 cm (37 in.), its thickness is 2.54 cm (1 in.), and it is lined with 2.54 cm of tungsten (density 19.3 g/cm^3). The thermal insulation between the liner

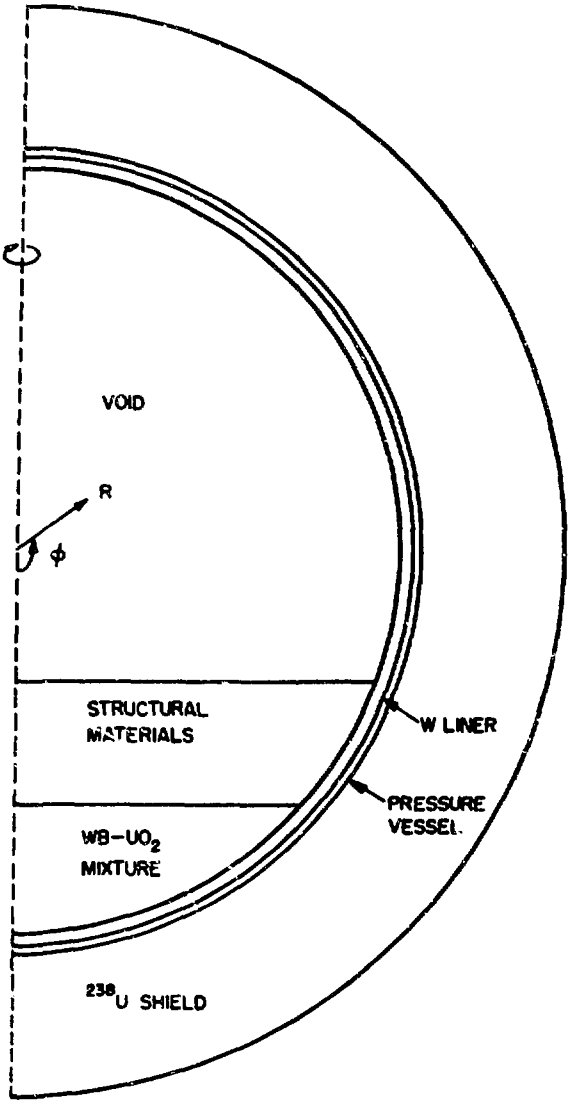


Fig. 6. Two-dimensional R-ϕ spherical model.

and the vessel was neglected in this simple model. At the bottom of the vessel is a homogenized region of WB and enriched UO_2 with a WB:UO_2 volume ratio of 2.0. The WB-UO_2 region (volume 2.4111×10^5 cm^3) contains 868 kg of enriched UO_2 and 2524 kg of WB. Floating on top of the WB-UO_2 mixture is a homogenized region containing structural materials. The volume of this region, 5.6818×10^5 cm^3 (20.1 ft^3), is based on an initial core volume of 2.4975×10^6 cm^3 (88.2 ft^3) containing 22.75 vol% structural materials. The remaining space within the pressure

TABLE XIV

ATOM DENSITIES FOR REGIONS OF TWO-DIMENSIONAL MODEL

Region	Element	Atom Density (10^{24} atoms/cm^3)
Structure	Mo	0.03928
	Ti	0.00039
	Ni	0.00590
	Cr	0.00300
	Fe	0.02322
Core	^{235}U	0.00755
	^{234}U	0.00007
	^{238}U	0.00047
	O	0.01623
	W	0.03238
	B	0.03238
Liner	W	0.06322
Vessel	Fe	0.08359
Shield	^{238}U	0.04731

TABLE XV

COMPOSITION OF STRUCTURAL MATERIALS

Material	Density (g/cm^3)	Volume Fraction of Structure	Element	Weight Fraction of Element in Material
Mo TZM	10.2	0.6066	Mo	0.9943
			Ti	0.005
Hastelloy X	8.23	0.1427	Ni	0.489
			Cr	0.220
			Fe	0.180
			Mo	0.090
AM-355	7.83	0.2505	Fe	0.99

vessel is void, as it was assumed that the moderator-reflector water was removed prior to meltdown. Outside the pressure vessel is a spherical shell 34.1 cm (13.4 in.) thick. This region, which represents the shield, contains 104,330 kg (230,000 lb) of ^{238}U at density 18.7 g/cm^3. (It was assumed that the shield water is not present.) Note that the meltdown configuration of Fig. 6 does not depend on the orientation of the system.

Atom densities for the various regions of the model are given in Table XIV. The composition of the WB-UO_2 mixture is the same as that used in the one-dimensional calculation for a WB:UO_2 volume ratio of 2.0. The composition of the structural material region is based on the information given in Table XV.

The horizontal surfaces of the WB-UO_2 and structural material regions cannot be represented exactly in R-ϕ geometry. These boundaries were approximated by portions of spherical surfaces as shown in Fig. 7. In the approximation, the volumes of the two regions

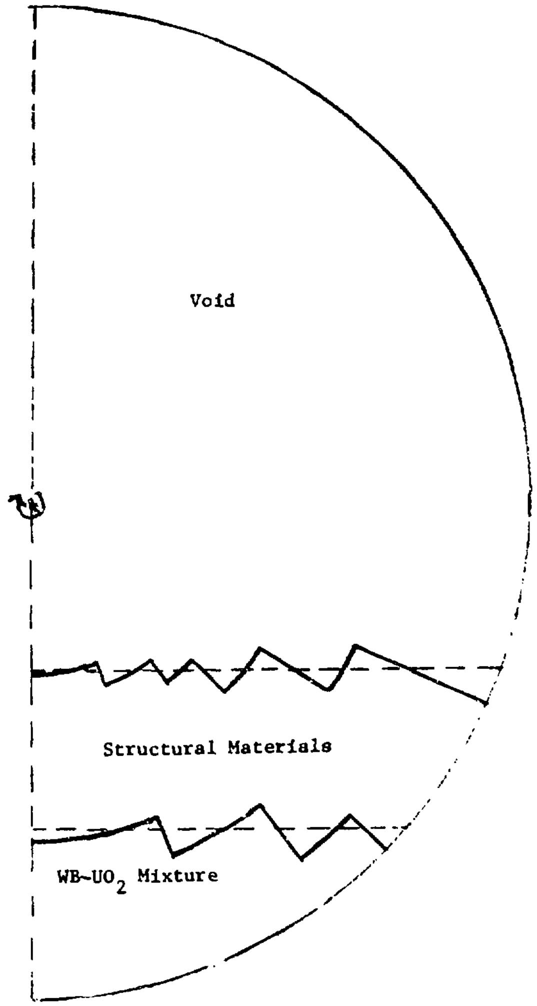


Fig. 7. Approximation of horizontal surfaces in R-ϕ model.

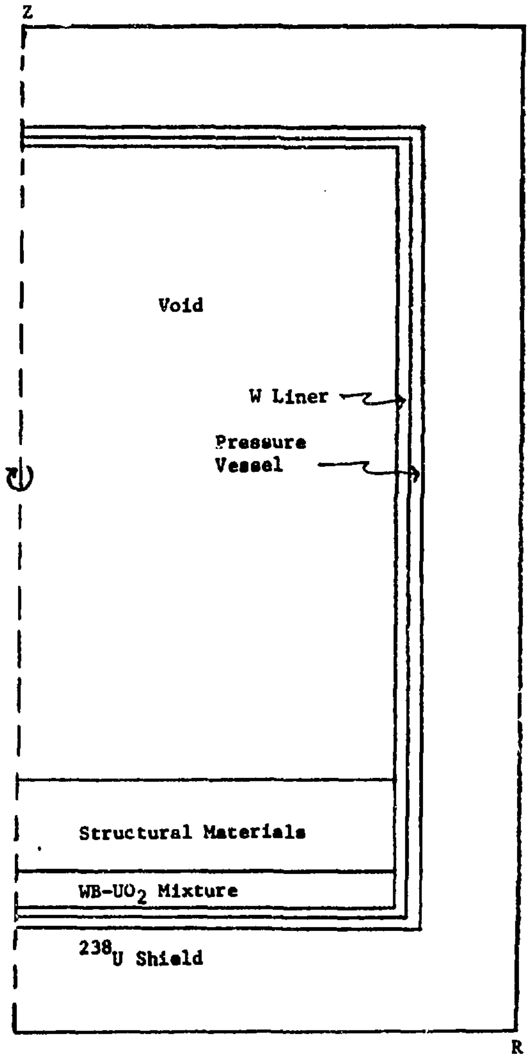


Fig. 8. Two-dimensional R-Z cylindrical model.

were conserved. The spatial mesh contained 26 radial intervals and 24 intervals in the ϕ direction.

The R-ϕ model yielded a multiplication factor of 0.901. For the same $WB:UO_2$ volume ratio, the one-dimensional calculations yielded 0.934 and 0.971 for the bare sphere and reflected sphere, respectively. Thus, it appears that the bare sphere results of Sec. III can be used conservatively to estimate the reactivity in a more realistic geometry.

Figure 8 shows the second model used in the two-dimensional calculations. This model is based on a cylindrical pressure vessel and was represented in R-Z geometry. The dimensions of the vessel are radius 37 in., height 74 in., and thickness 1 in., and the vessel is lined with 1 in. of tungsten. The volumes of the structural material, $WB-UO_2$, and shield regions are the same as before but in cylindrical geometry. Compositions of the various regions are exactly the same as for the R-ϕ calculation (Table XIV).

For the R-Z calculation, the spatial mesh used was 26 radial intervals and 30 axial intervals. This calculation yielded a multiplication factor of 0.677, considerably less than that (0.901) obtained for the spherical pressure vessel case. The reason is that, with a spherical vessel, the $WB-UO_2$ region is much more compact. An idea of the difference in compactness can be obtained from the fact that the surface area of the $WB-UO_2$ region is 3.14 times larger within the upright cylindrical vessel than within the spherical vessel.

With a cylindrical pressure vessel, the meltdown configuration will depend on the orientation of the vessel. The upright vessel case was calculated because this configuration can be represented exactly in two dimensions. If the vessel is horizontal, an R-θ cylindrical calculation with buckling to represent the leakage in the axial direction could be used to approximate the configuration. If the vessel is inclined at some angle, say 45°, a three-dimensional code would be required for the analysis.

The WB-UO_2 region in the horizontal cylindrical vessel case is more compact than in the upright case. However, the surface area of the WB-UO_2 region is still 2.37 times larger than in the spherical vessel case. For intermediate orientations, the surface area should lie between the vertical and horizontal cases. Thus, for a given volume of diluent and UO_2, the reactivity of the mixture should always be less in the cylindrical vessel than in the spherical vessel regardless of orientation of the cylindrical vessel. In this respect, the cylindrical vessel is to be preferred over the spherical vessel. The advantages of the spherical vessel are its independence of orientation and the fact that deformation of the vessel will result in a less reactive meltdown configuration.

V. DISCUSSION

It has been shown that several diluent materials could be used to solve the meltdown criticality problem. A decision on which diluent material to use will have to be based not only on the effectiveness of the material as a poison, but also on such factors as availability, ease of fabrication, weight, and cost. As evidenced by the uncertainty in the melting temperature of WB_2 and TaB_2, materials research will have to be carried out for some of the diluents.

Feasibility of using a diluent-poison to solve the meltdown criticality problem hinges on containment of the molten UO_2 within the pressure vessel and on assuring mixing of the diluant and UO_2. The scheme of surrounding the reflector regions of the reactor with an annulus containing small spheres of high-density and high-melting-point diluent material should be workable. The scheme, however, depends on movement of the diluent spheres to the bottom of the pressure vessel as the core melts. Tests on a small-scale model should be carried out to study this problem.

The "diluent spheres" schema also requires a diluent density and melting temperature greater than that for UO_2 and is limited to a maximum diluent:UO_2 volume ratio of about 3. A variation of this schema could be used that requires only that the diluent have a melting temperature higher than that for UO_2. In this variation, a fixed annular region of diluent material would surround the reflector regions. The diluent region would be in the form of a honeycomb structure with a void fraction and thickness depending on the diluent. For example, if the diluent is $Ta^{10}B_2$ and assuming a spherical pressure vessel, a void fraction of ≈0.7 and annulus thickness of ≈21 cm would be required. One disadvantage of this scheme is that a larger volume and mass of diluent would be required than with the mobile "diluent spheres" scheme. This is not a serious disadvantage in that the diluent can also serve as gamma shielding (and neutron shielding in the case of the borides) and thus reduce the amount of shielding required outside the pressure vessel. A more serious disadvantage is that deformation of the pressure vessel on impact might reduce or completely eliminate the void fraction in the diluent annulus.

For the meltdown configuration, use of a spherical pressure vessel has the advantage that the geometry is independent of orientation of the vessel. Another advantage is that deformation of the vessel will result in a less reactive meltdown geometry because the diluent-UO_2 region will be less compact than in the undeformed case. On the other hand, a cylindrical pressure vessel ($H/D = 1$ and D the same as for the spherical case) has the advantage of a much less reactive meltdown configuration than in the spherical case. However, deformation of the cylindrical pressure vessel could result in a more reactive meltdown geometry than in the undeformed case. Also, for vessel orientations deviating from the vertical or horizontal, the cylindrical vessel requires a three-dimensional code for analysis. Although three-dimensional transport theory codes are not presently available, the analysis could be performed with a three-dimensional diffusion theory program (e.g., the 3DDT code[8]).

Regardless of whether a cylindrical or spherical pressure vessel is used, deformation of the shield region outside the pressure vessel should have little effect on the reactivity of the meltdown configuration. This is because the configuration is already well reflected.

Future calculations should be directed toward determining the effect of the diluent on the critical mass of the normal configuration. Calculations are also required to determine the effect of deformations on both the normal and meltdown configurations. Quantitative results from impact tests should be factored into these calculations. As discussed above, deformations should not present serious problems for the meltdown case if the undeformed meltdown configuration is subcritical.

Since the thermal reactor concept is undermoderated, small compactions of the normal core configuration should reduce reactivity if the moderator-reflector water is still in the pressure vessel at impact. Extreme compaction, in which all the moderator and coolant passages and all the voids are squeezed out, may be a problem because the neutron spectrum will be hardened considerably.

In the fast reactor concept, any compaction of the normal core configuration will add reactivity unless the design incorporates a built-in safety feature, e.g., control elements that are driven into the core at impact. Such an engineered safety feature can be more easily incorporated if the core has a spherical shape.

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