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SAFETY ANALYSIS OF A NOMINAL 3700-LITER UO_2 CORE IN THE ZPR-6 AND -9 FACILITY

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Reactor Physics Division

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INTRODUCTION

The use of ZPR-6 and -9 is presently authorized for studies of ^{235}U-fueled core sizes to approximately 2600 liters. Permission to do so was granted on the basis of an addendum to the Safety Analysis Report (SAR)[1] entitled "Analysis for Large Fast Critical Assemblies."[2]

This report presents the results of a safety analysis performed for a nominal 3700-liter UO_2 core. (Oxygen will be introduced into the core in the form of depleted U_3O_8 plates. The number of uranium plates and U_3O_8 plates will be apportioned so as to simulate UO_2.) Approval has been requested to build the nominal 3700-liter core in ZPR-6 or -9, which may have a core volume up to 4500 liters because of uncertainties in the critical-mass calculations. An arbitrary limit of 4500 liters for the core volume has been chosen since relevant safety characteristics (e.g., expansion and Doppler coefficients, neutron lifetime, control-rod worth) vary slowly with size and, thus, all hazards including the magnitudes of the Maximum Credible Accidents (MCAs) do not vary significantly in the size range. Although more calculations in addition to the ones presented in this report for the 3700-liter core could be done to substantiate the request to build up to 4500 liters (for example, by making a calculation of our proposed system with arbitrarily perturbed basic data to lead to a critical size of 4500 liters), this is believed unnecessary and would add nothing to our knowledge of the safety of the system.

PROCEDURE

A hypothetical MCA was calculated for the 3700-liter UO_2 core. As in the SAR[1] and its addendum,[2] the accident was assumed to be initiated by table motion and an overloaded assembly. The excursion was calculated by using a point-reactor, one-energy-group, kinetics code (ANL's R101). A 1/T Doppler feedback dependence was assumed. The excess reactivity was calculated using the following equation:

$$k_{ex} = At + C \ln \frac{T}{T_0} + E \int_0^t n dt', \qquad (1)$$

where

A = reactivity addition or subtraction rate,

C = ^{235}U Doppler coefficient,

T_0 = initial temperature of the reactor,

T = reactor temperature at time t,

n = average neutron density at time t,

and

$$E = \left(\frac{1}{L} \cdot \frac{dL}{dT}\right)\left(\frac{dk}{k}\Big/\frac{dL}{L}\right)\left(\frac{1}{\rho \cdot V.F. \cdot S_H \cdot \bar{\nu} \cdot \ell}\right)$$ E is thus proportional to the expansion coefficient for a specific core.

In the above expression for E,

$\left(\frac{1}{L} \cdot \frac{dL}{dT}\right)\left(\frac{dk}{k}\Big/\frac{dL}{L}\right)$ is the expansion reactivity coefficient,

ρ is the density of the uranium plate,

V.F. is the ^{235}U volume fraction,

S_H is the specific heat of uranium,

$\bar{\nu}$ is the average number of neutrons produced per fission,

and

ℓ is the prompt-neutron lifetime.

Table I lists the critical parameters for Assembly 6 as calculated using the MACH 1 code[3] and listed isotopes from cross-section Set 224.[4]

The expansion coefficient was evaluated by calculating the change in reactivity from a reference core due to increasing the length and decreasing the density of the fuel columns by a corresponding amount to simulate expansion. Three inches of the axial blanket were assumed to be pushed axially away from the center of the core as the fuel expanded; the other 9 in. of the axial blanket were assumed to remain in place. The quotient $(\Delta k/k)/(\Delta L/L)$ was evaluated using the results of this calculation, and the expansion coefficient was determined using Eq. 2. A constant value of 14×10^{-6} was used for $(1/L) \cdot (dL/dT)$.

$$\text{Expansion Coefficient} = \left(\frac{1}{L} \cdot \frac{dL}{dT}\right)\left(\frac{\Delta k}{k}\Big/\frac{\Delta L}{L}\right) \qquad (2)$$

TABLE I. Critical Parameters for ZPR-6 Assembly 6

Critical mass ^{235}U	1644 kg
Core diameter	174.8 cm
Core height	152.4 cm
Core volume	3658 liters
Blanket thickness ^{238}U	27 cm
k_{eff} of one-half	0.80
k_{eff} of one-half with 20-cm Benelex	0.87

Material				
	Isotope No.		Atom Densities x 10^{-24}	
Element	Set 224	Set 801	Core	Blanket
^{235}U (500°K)*		44	0.0011522	0.0000827
^{235}U (300°K)	4	43	0.0011522	0.0000827
^{238}U	1	37	0.005801	0.04008
Na	34	7	0.00920	-
O	35	8	0.01468	-
Fe	37	4	0.014254	0.0042282
Ni	38	5	0.001385	0.0005665
Cr	39	6	0.002970	0.001215
^{10}B	57	-		

*Since only the Doppler coefficient is desired, density changes due to fuel expansion are neglected. The expansion effects are calculated separately as stated in the text.

The ^{235}U Doppler coefficient was obtained by calculating the change in reactivity with cross sections from Set 801 for ^{235}U temperatures of 300 and 500°K and using the following equation:

$$C = \Delta k/\ln(5/3). \tag{3}$$

Since the R-101 kinetics code calculates $\int$ ndt rather than temperatures, the Doppler feedback term appears in the code as the right side of the following equation:

$$C \ln(T/T_0) = C \ln\left[1 + D\int_0^t (n - n_0)\, dt'\right], \tag{4}$$

where

$D = (\rho \cdot V.F. \cdot S_H \cdot \bar{\nu} \cdot \ell \cdot T_0)^{-1}$ and converts the integral to a dimensionless quantity.

Measured values of the positive ^{235}U Doppler coefficient indicate that calculated values are too high by about a factor of three; thus the coefficients are conservative. In addition, no consideration of the negative ^{238}U Doppler coefficient has been incorporated into the calculation, although this would contribute shutdown reactivity if the core became heated.

The gap worth used in the Assembly 6 kinetics calculations was the same (0.007 $\Delta k/k$ cm^{-1}) as that used in the Assembly 5 kinetics calculations. In both cases, the intermediate table-drive speed was used to determine the reactivity addition rates. This is expected to result in a conservative reactivity addition rate, i.e., greater than actual, since the measured gap-worth for Assembly 5 was approximately a factor of 2 less than that used in the calculation. Assembly 6 is expected to have lower gap-worths than Assembly 5 since Assembly 6 is a larger reactor; however, no credit is taken for this in the calculation.

Dual-purpose (D.P.) and ^{10}B rods are usually located in rings about the center of the reactor. The worth of the rods is determined by calculating the reactivity change resulting from a change of material volume fractions in these rings due to insertion or removal of the rods. This technique resulted in overestimating the D.P. rod worth for Assembly 5 by about 10% and the ^{10}B rod worth by about 25%.

The D.P. rod-worth calculation for Assembly 6 assumed the rods to have the same composition as the remainder of the core. On this basis, the total D.P. rod worth of 0.45% $\Delta k/k$ was obtained. However, initially (at least until criticality has been attained and the rod worths have been accurately measured) these rods will have three times the normal core fuel complement. The extra fuel will be loaded in the drawer as was done in Assembly 3 of ZPR-6, by removing fuel from adjacent drawers and placing it into the D.P. rod drawers. The resulting estimated total D.P. rod worth will then be approximately 1.35% $\Delta k/k$. (Fuel-bunching measurements in Assembly 5 showed the specific worth of ^{235}U to be constant within about 8% for fuel thicknesses from 0.005 to 0.250 in. Therefore the assumption that the rod worth will increase in proportion to the quantity of fuel within the drawer is reasonably valid for three 1/16-in. columns of fuel as proposed for the D.P. rods in Assembly 6.)

Because of self-shielding within the rods, it is difficult to accurately calculate the ^{10}B rod worths. Perhaps the most reliable method of estimating the ^{10}B rod worth for Assembly 6 uses the ratio of the measured worth of a 2 x 2 x 1-in. sample of ^{10}B to the calculated worth of the same sample to correct the calculated worth of the ^{10}B rods. For Assembly 5, this ratio was found to be 0.65. (Self-shielding within this block is expected to be greater than that within the ^{10}B rods since the ^{10}B rods are only about 3/8 in. thick.) If one corrects the calculated ^{10}B rod worth in Assembly 5 by this ratio, the corrected calculated worth is about 1.1%, compared to a measured worth of 1.3% for 200-gm ^{10}B rods. Thus the greater self-shielding in the 2 x 2 x 1-in. block manifests itself in overcorrecting for self-shielding of the ^{10}B rods in Assembly 5. Correcting the calculated worth (3.2 $\Delta k/k$) of the 365-gm ^{10}B rods of Assembly 6 by this ratio results in a total ^{10}B rod worth of $0.65 \times 3.23\% \Delta k/k = 2.1\% \Delta k/k$.

Other methods of obtaining the ^{10}B worth have been examined, but are not expected to be as accurate as the above. For example, the measured worth of the 365-gm ^{10}B rods in Assembly 5 (1.7% $\Delta k/k$) can be multiplied by the ratio of the importance-weighted production integrals for Assemblies 5 and 6 to obtain an estimated ^{10}B rod worth in Assembly 6 of 1.3% $\Delta k/k$. This should significantly underestimate the Assembly 6 ^{10}B worth since it implicitly assumes the spectrum of Assembly 6 to be the same as Assembly 5, whereas calculations indicate a softer spectrum in Assembly 6.

Although the 2.1% $\Delta k/k$ is our best estimate for the ^{10}B worth, the ^{10}B rod worth was arbitrarily reduced to 1.4% $\Delta k/k$ in the kinetics calculation for Assembly 6 for conservatism.

Within reasonable limits, the magnitude of a calculated excursion is not very sensitive to the ^{10}B rod worth even when the D.P. rod worth is assumed to be only 0.45%. For example, if the ^{10}B rod worth is increased from 1.4 to 2.8% and the reactor is assumed to be scrammed when it reaches prompt critical--the rods starting to move 90 msec later--the MCA for Assembly 6 results, respectively, in peak fuel temperatures of 187 and 215°C, and average temperatures of 105 and 121°C.

In any event, the procedure to be followed during assembly will ensure that a shutdown margin in excess of 2% as required by the SAR will be achieved: i.e., 1.35% in the D.P. rods, and at least 1.3% in the ^{10}B rods.

"Fatman-effect" calculations were made using the MACH 1 code and cross-section Set 201, which contains a hydrogen isotope. The k_{eff} of a half was calculated both with and without a 20-cm-thick slab of Benelex across the normally open (i.e., unreflected midplane) face of the half. As shown in Table III, the k_{eff} of Assembly 6 is calculated to be less than that of Assembly 5, both with and without Benelex. Fatman-effect measurements on Assembly 5 indicated no observable increase in multiplication with the Benelex in place. Fatman multiplication measurements will be made on Assembly 6, and barriers used in the same manner as outlined in Ref. 2 until measurements show they are not needed.

RESULTS

Table II compares the 50-liter core analyzed in the SAR,[1] the 2600-liter core analyzed in the SAR Addendum,[2] and the 3700-liter UO_2 core. For this comparison, k_{ex} was calculated using Eq. 1. In each case, the reactor was assumed to be scrammed at prompt critical* so that the

*Previous MCA calculations for the 2600-liter case in Ref. 2 assumed that a signal that tripped the safety circuits occurred when the neutron-flux level increased by a factor of 100 over the initial neutron flux. However, to bring in the effects of reactivity feedback, the calculations in this report assumed that the scram signal occurred when the reactor reached prompt critical.

feedback coefficients became effective. The Assembly 6 MCA results in a somewhat lower average fuel temperature than the other two cases. This is due primarily to the longer prompt-neutron lifetime. Additional information is shown in Table III.

TABLE II. Summary of MCA for Each of Three Cores

	3700-liter UO_2 Assembly 6	2600-liter UC Assembly 5	50-liter Metal
Peak fuel temp after MCA, °C	215	258	-
Avg fuel temp after MCA, °C	121	144	164
Reactivity addition rate, $\Delta k/k$ sec^{-1}	1.75×10^{-3}	1.75×10^{-3}	3.55×10^{-3}
Time to reach prompt critical, sec	3.92	3.96	2.02
Reactivity removal rate due to ^{10}B rods, $\Delta k/k$ sec^{-1}	0.064	0.087	-
Reactivity removal rate due to D.P. rods, $\Delta k/k$ sec^{-1}	0.011	0.025	0.55
Doppler coefficient	$+8.08 \times 10^{-4}$	$+8.05 \times 10^{-4}$	$+3.0 \times 10^{-4}$
E of Eq. 1. (See text.)	-3.53×10^{-9}	-5.93×10^{-9}	-2.58×10^{-9}
Total fissions[a]	5.94×10^{17}	6.82×10^{17}	8.30×10^{16}

[a]Total fissions $= \iint \phi \Sigma_f dtdv = \dfrac{\text{Volume} \int ndt}{\bar{\nu} \ell}$.

TABLE III. Other Reactor Parameters

	3700-liter UO_2 Assembly 6	2600-liter UC Assembly 5	50-liter Metal
Critical mass, kg	1644	1550	
Core diameter, cm	174.8	151.2	
Core height, cm	152.4	142.2	
Core volume, liters	3658	2600	50
Blanket thickness ^{238}U, cm	30	30	30
k_{eff} for one-half of reactor	0.80	0.84	
k_{eff} for one-half of reactor + 20-cm Benelex	0.87	0.91	
Effective beta	0.00687	0.00692	0.0073
Prompt-neutron lifetime, sec	4.7×10^{-7}	2.1×10^{-7}	7.0×10^{-8}
Expansion coefficient $\left(\frac{1}{L}\frac{dL}{dT}\right)\left(\frac{\Delta k}{k}\Big/\frac{\Delta L}{L}\right)$, $\Delta k/k(°C)^{-1}$	-6.7×10^{-6}	-6.62×10^{-6}	-5.2×10^{-6}
Gap worth, cm^{-1}	$0.007 \Delta k/k$	$0.007 \Delta k/k$	$0.014 \Delta k/k$
^{10}B rod worth,[a] $\Delta k/k$	1.4%	1.74%	-
Dual-purpose-rod worth,[b] $\Delta k/k$	0.45%	1%	11%
Edge worth of fuel, Δk kg^{-1}	7.2×10^{-5}	8.9×10^{-5}	-
Weight per table, tonnes	<50	31.7	-
Compressive force on matrix tubes, $kg\text{-}cm^{-2}$	3.0	2.3	-
Time after scram for ^{10}B rods to start into core, sec	0.090	0.110[b]	
Time after scram for D.P. rods to start out of core, sec	0.090	0.090	
D of Eq. 4	1.769×10^{-6}	2.978×10^{-6}	1.654×10^{-6}

[a]Values used to determine reactivity removal rates for the kinetics calculations.
[b]The ^{10}B rods start moving 0.090 sec after the scram and start entering the core 0.110 sec after the scram. The time difference is due to about 3 in. of gap between the end of the core and the start of the ^{10}B blade in Assembly 5. No such gap exists in Assembly 6. (See Ref. 2.)

In the above kinetics calculations, the three cases were treated identically as to format. Only the physical constants associated with the cores were different in the calculations. The procedures for calculating the expansion coefficients, Doppler coefficients, etc., for Assemblies 5 and 6 were, for practical purposes, identical except that the entire axial blanket was assumed moved by the expanding fuel in Assembly 5, while only 3 in. moved in Assembly 6. The 50-liter core coefficients were derived from the SAR.[1]

ADDITIONAL COMMENTS

The weight of the 3700-liter core is less than 50 tonnes per half, which is well under the 81-tonne load at which the tables were tested.

The force per unit area on the matrix tubes is about 3.0 $kg\text{-}cm^{-2}$, compared to about 2.3 $kg\text{-}cm^{-2}$ for the 2600-liter core and a tested failure (columnar buckling) load of about 11.2 $kg\text{-}cm^{-2}$ for a prototype steel matrix tube.

Therefore, the mechanical properties of the facility should be more than adequate to accommodate the 3700-liter core.

Operation of Assembly 6 will be in accordance with existing operating limits.[5] The available shutdown reactivity, limits on rod worths and reactivity addition rates, and other portions of the operating limits strictly apply to Assembly 6.

CONCLUSION

The relevant safety characteristics and MCA for a 3700- and 2600-liter system have been compared. The calculations presented demonstrate adequately that the proposed system can be built safely with no additional hazard, compared to previously approved systems.

ACKNOWLEDGMENT

We wish to acknowledge the contribution of Jim Marshall who performed many of the MACH 1 calculations for Assembly 6.

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