COMPARISON OF

SAFETY PARAMETERS AND TRANSIENT BEHAVIOR

OF A GENERIC 10 MW REACTOR WITH HEU AND LEU FUELS*

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ABSTRACT

Key safety parameters are compared for equilibrium cores of the IAEA generic 10 MW reactor with HEU and LEU fuels. These parameters include kinetics parameters, reactivity feedback coefficients, control rod worths, power peaking factors, and shutdown margins. Reactivity insertion and loss-of-flow transients are compared. The results indicate that HEU and LEU cores will behave in a very similar manner.

INTRODUCTION

This paper presents the results of a consistent systematic study of the key safety parameters and transient behavior of equilibrium cores of the IAEA generic 10 MW reactor with the reference HEU fuel element design and with two LEU fuel element designs.

The safety parameters include kinetic parameters, reactivity feedback coefficients, control rod worths, power peaking factors, and shutdown margins. Selected transients were studied within three broad categories: (1) loss-of-flow transients, (2) uncontrolled slow reactivity insertions that may occur during reactor startup, and (3) rapid reactivity insertions that may occur due to failure or malfunction of a core component or misoperation of the reactor.

REACTOR AND FUEL ELEMENT DESIGNS

The reactor design (Fig. 1) is described in detail in IAEA-TECDOC-233[1]. The 5x6 element core contains 23 MTR-type standard fuel elements and 5 control fuel elements. The core is reflected by graphite on two opposite faces and is surrounded by water. In these calculations, both water-filled flux traps were replaced with 77 mm x 81 mm blocks of aluminum with 50 mm square water holes in order to compute more realistic power peaking factors.

The fuel element designs that were studied are shown in Table 1. The HEU design with aluminide fuel has 23 fuel plates and 280 g ^{235}U per standard element. The water channel thickness is 2.19 mm. The first LEU design (LSI) has the HEU element geometry, but contains 390 g ^{235}U and U_3Si_2-Al fuel meat with a uranium density of 4.45 g/cm^3. The second LEU design (LOX) has 22 plates per standard element, a ^{235}U content of 391 g with U_3O_8-Al fuel meat (3.13 g U/cm^3), a fuel meat thickness of 0.76 mm, and a water channel thickness of 2.10 mm. Although explicit thermal-hydraulics calculations have not been performed for the LOX design, it is unlikely that a decrease of less than 0.1 mm in the nominal water channel thickness will significantly affect the thermal-hydraulic safety margins in most reactors.

Fig. 1.

Core and Shuffling Pattern

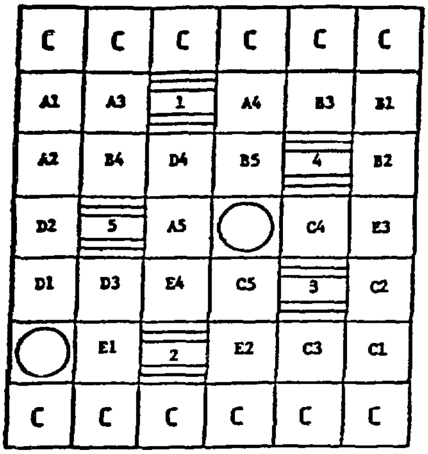

Table 1. Fuel Element Designs Studied

	HEU	LSI	LOX
Fuel Type	UAl_x	U_3Si_2	U_3O_8
Enrichment, %	93	19.75	19.75
Plates per El. Std./Cntl.	23/17	23/17	22/16
Fuel Meat Thick., mm	0.51	0.51	0.76
Water Channel Thick., mm	2.19	2.19	2.10
U Density, g/cm^3	0.68	4.45	3.13
^{235}U per Std. El., g	280	390	391

CALCULATIONAL METHODS

The methods and codes used for cross section generation and for burnup calculations are described in App. A of Ref. 1. There are three exceptions: (1) all of the burnup and static diffusion theory calculations were performed in three dimensions, (2) fueled and non-fueled regions of each standard and control element were modeled separately, and (3) the fuel shuffling pattern was changed from the single-element inside-out scheme used in Ref. 1 to the five-batch outside-in scheme described in Ref. 2.

The transient calculations were performed using the PARET code as modified[3] at ANL to include a selection of flow instability, departure from nucleate boiling, single and two-phase heat transfer correlations, and a properties library applicable to the low pressures, temperatures, and flow rates encountered in research reactors. A description of the current PARET code and a detailed comparison with the SPERT I experiments can be found in Ref. 3.

BURNUP AND FUEL CYCLE COST RESULTS

A burnup search was first performed to determine the cycle length in the equilibrium HEU and LEU cores that would yield an end-of-cycle (EOC) excess reactivity of 2.3% δk/k: 1.5% δk/k for experimental loads, 0.5% δk/k for control reserve, and 0.3% δk/k for the cold-to-hot reactivity swing. The cycle length (average ^{235}U discharge burnup in standard elements) for the HEU, LSI, and LOX cores were computed to be 54.4 days (45%), 77.3 days (44%), and 69.3 days (40%), respectively.

The model and assumptions that were used in computing the annual costs for each component of the fuel cycle are described in detail in Ref. 2. The only change in the cost assumptions is that the price of natural uranium feed was updated from its September 1982 average price of \$16.95/lb U_3O_8 to its July 1983 average price of \$23.70/lb U_3O_8. If it is assumed (unrealistically) that fabrication costs for the HEU, LSI, and LOX fuel elements are equal, the total annual fuel cycle costs at 100% duty factor were computed to be \$900,000 for the HEU design, \$751,000 for the LSI design, and \$815,000 for the LOX design. In order to have the same total annual cost as the HEU design, the LSI (LOX) fabrication costs would need to be 1.64 (1.34) times the fabrication costs for HEU fuel.

SAFETY PARAMETERS

Results of 3D calculations are presented on the safety-related neutronics parameters needed for transient analyses. Several states of the reactor were studied, but results are presented here only for the beginning-of-equilibrium cycle (BOC), xenon-free core. The complete results will be presented in Ref. 4.

Prompt Neutron Generation Time and Delayed Neutron Fraction

The prompt neutron generation times (Λ) and the effective delayed neutron fractions (β_{eff}) for the HEU and LEU cores at BOC, computed using standard perturbation methods, are shown below.

Λ, μs			β_{eff}		
HEU	LSI	LOX	HEU	LSI	LOX
50.7	40.1	41.2	0.00758	0.00736	0.00741

Isothermal Reactivity Feedback Coefficients

Isothermal reactivity feedback coefficients were computed separately as functions of temperature or void fraction for each of three physical effects: (1) the hardening of the neutron spectrum caused by increasing the temperature of the water only, (2) the increase in neutron leakage due to the change in density of water as the water heats (or boils), and (3) the increase in absorption in the ^{238}U epithermal resonances as the temperature increases in the fuel meat. Slopes of the reactivity components between 38°C and 50°C at BOC are listed below along with the whole-core void coefficient for 0-10% change in water density only.

	HEU	LSI	LOX
Effect	$\delta\rho/\delta T \times 10^{-3}/°C$	$\delta\rho/\delta T \times 10^{-3}/°C$	$\delta\rho/\delta T \times 10^{-3}/°C$
Water Temperature	0.0903	0.0646	0.0609
Water Density	0.0793	0.1021	0.1063
Fuel Temperature	0.0006	0.0240	0.0236
Total	0.1702	0.1907	0.1908
Void Coefficient (0-10%)	20.7	26.3	27.2

The HEU and LEU cores have nearly the same feedback coefficient when the water temperature and density effects are combined. However, since the Doppler coefficient is significantly larger in the LEU cores, the total feedback coefficient is slightly larger with LEU fuel. The whole-core void coefficient is significantly larger in the LEU cores.

Control Rod Worths

The reactivity worths of fork-type control rods with Ag-In-Cd absorber blades were computed in the HEU and LEU equilibrium cores at BOC. The control rod configurations studied were: (1) all five rods fully-withdrawn, (2) all five rods fully-inserted, (3) the rod of maximum worth fully-withdrawn and four rods fully-inserted, and (4) all five rods 50% withdrawn.

To validate the methods used for computing control rod worths with diffusion theory, 3D Monte Carlo and diffusion theory calculations were run for the fresh HEU and LEU cores for the first three rod configurations described above. The diffusion theory calculations were performed using internal boundary conditions derived using data from the Monte Carlo calculations.

The diffusion theory control rod worths relative to all five rods fully with-drawn in the equilibrium HEU and LEU cores at BOC are shown below in % and in \$. The same internal boundary conditions were used in these calculations as in the fresh cores for the Monte Carlo validation studies.

	$\Delta\rho$, %			$\Delta\rho$, \$		
Control Rod Worths	HEU	LSI	LOX	HEU	LSI	LOX
All Rods In	18.64	16.03	17.01	24.59	21.78	22.96
Max. Worth Rod Out	11.94	10.43	11.05	15.75	14.17	14.91
All Rods 50% Out	6.64	5.86	6.16	8.67	7.96	8.31

The worth (computed in \$) with all rods inserted in the LSI (LOX) core is lower by 11% (7%) than in the HEU core, even though the ^{235}U content of the fresh LEU elements is about 1.4 times larger than the fresh HEU elements. Similarly, the worths with the maximum-worth rod withdrawn are lower by about 10% (5%) in the LSI (LOX) core than in the HEU core.

Power Peaking Factors

In these 3D calculations, the total power peaking factor is defined as the product of two components: (1) a radial factor defined as the average power in each element divided by the average power in the core, and (2) an element factor defined as the peak power in each element when the control rods are 50% withdrawn divided by the average power in that element. For the element factor, the peak power is determined at the edge of the mesh cell that coincides with the edge of the fuel meat.

Radial Power Peaking Factors at BOC

	A	B	C	D	E	F
1	C	C	C	C	C	C
2	0.93 0.90 0.90	0.96 0.95 0.94	1.14 1.12 1.10	0.97 0.98 0.98	0.91 0.91 0.90	0.85 0.83 0.83
3	1.02 0.99 0.98	1.07 1.06 1.05	1.11 1.13 1.13	1.15 1.18 1.20	0.94 0.96 0.97	0.94 0.92 0.92
4	0.96 0.95 0.95	0.91 0.95 0.97	1.22 1.24 1.25	○	1.11 1.13 1.15	0.89 0.89 0.90
5	0.98 0.98 0.98	0.98 0.98 0.98	1.07 1.09 1.10	1.12 1.15 1.17	1.03 1.04 1.04	0.94 0.92 0.92
6	○	0.99 0.99 0.98	0.98 0.99 0.98	1.07 1.06 1.04	0.90 0.90 0.89	0.85 0.84 0.83
7	C	C	C	C	C	C

←HEU→
←LSI→
←LOX→

Total Power Peaking Factors at BOC

	A	B	C	D	E	F
1	C	C	C	C	C	C
2	1.83 1.90 1.88	1.89 1.88 1.84	2.59 2.53 2.47	1.79 1.80 1.79	2.00 1.99 1.97	1.81 1.92 1.91
3	1.93 2.03 2.03	2.18 2.18 2.15	1.90 2.05 2.07	2.02 2.25 2.33	1.93 2.05 2.10	1.97 2.11 2.11
4	1.76 1.85 1.87	1.73 1.82 1.87	2.03 2.25 2.29	○	2.25 2.44 2.46	1.68 1.85 1.87
5	1.90 1.95 1.95	2.10 2.10 2.08	1.88 2.03 2.06	1.98 2.21 2.28	2.19 2.27 2.29	1.98 2.12 2.11
6	○	2.12 2.05 1.98	2.16 2.16 2.12	2.11 2.06 2.00	1.94 1.95 1.93	1.82 1.94 1.91
7	C	C	C	C	C	C

The radial peaking factor and total peaking factor at BOC in each element of the three cores are shown above. Generally, the total peaking factors are comparable or slightly larger in the LEU cores than in the HEU core. However, for the limiting element (the control element in core position C2), the total peaking factor is slightly smaller in the LEU cores.

Shutdown Margins

As stated previously, the cycle length in the 3D burnup calculations for the HEU and LEU cores was chosen so that each core had an EOC excess reactivity of 2.3 δk/k to account for experimental loads, control reserve, and the cold-to-hot reactivity swing. The remaining components of the BOC reactivity balance table are the reactivity losses due to burnup and to equilibrium xenon concentrations.

The values computed for each of the three cores are tabulated below along with the control rod worths for all five rods fully-inserted and for the rod of maximum worth fully withdrawn.

EOC Reactivity Balance Tables and Shutdown Margins for HEU and LEU Cores. All Cases Have an EOC Excess Reactivity of 2.3% δk/k.

Reactivity Component	Δρ, %			Δρ, $		
	HEU	LSI	LOX	HEU	LSI	LOX
Burnup	4.49	3.88	3.38	5.92	5.27	4.56
Xe Poison	3.25	3.15	3.18	4.29	4.28	4.29
Experiments	1.50	1.50	1.50	1.98	2.04	2.02
Control Reserve	0.50	0.50	0.50	0.66	0.68	0.68
Cold-to-Hot Swing	0.30	0.30	0.30	0.40	0.41	0.41
Total Excess Reactivity	10.04	9.33	8.86	13.25	12.68	11.96
Total Excess React. x 1.5	15.06	14.00	13.29	19.88	19.02	17.94
Control Rod Worths						
All Rods In	18.64	16.03	17.01	24.59	21.78	22.96
Max. Worth Rod Out	11.94	10.43	11.05	15.75	14.17	14.91
Shutdown Margins						
Total Excess Reactivity and All Rods In	8.60	6.70	8.15	11.34	9.10	11.00
Total Excess React. x 1.5 and All Rods In	3.58	2.03	3.72	4.71	2.76	5.02
Total Excess Reactivity and Max. Worth Rod Out	1.90	1.10	2.19	2.50	1.49	2.95

Three examples of shutdown margins are shown for each core: one based on the total excess reactivity and all rods in, a second based on the total excess reactivity multiplied by a factor of 1.5 and all rods in, and the third based on the total excess reactivity and the rod of maximum worth fully withdrawn. All of these shutdown margins are considered to be fully adequate.

Shutdown margins can decrease or increase in LEU cores relative to the HEU core depending mainly on the relative changes in the reactivity loss due to burnup and in the worth of the control rods. In the table above, it was assumed that the experiments had the same reactivity worth at EOC and BOC. Since the fissile content of each core is larger at BOC, the worth of the experiments will be smaller than 1.5% δk/k and the shutdown margins in all three cores will be slightly larger.

TRANSIENT STUDIES

Selected transients were studied within three broad categories: (1) loss-of-flow transients, (2) uncontrolled slow reactivity insertions that may occur during reactor startup, and (3) rapid reactivity insertions that may occur due to failure or malfunction of a core component or misoperation of the reactor.

For all cases, a two channel model was utilized in the PARET code. One channel represented the hottest plate and flow channel in the core and the second represented the average plate and flow channel in a volume weighted sense. The axial power distributions were represented by chopped cosine shapes having calculated peak-to-average powers of 1.52, 1.50, and 1.45 in the hot channel and 1.47, 1.51, and 1.56 in the average channel of the HEU, LSI, and LOX cores, respectively. Additional nuclear peaking factors of 1.70, 1.69, and 1.70 multiplied the respective hot channel power distributions. The thermal conductivities and heat capacities that were utilized were derived from data in Ref. 5 and are shown in the references. All calculations were done with a full flow of 1000 m^3/h, a coolant inlet temperature of 38 °C, and an inlet pressure of 1.7 bar absolute.

The calculated values described above were used for the nuclear power peaking factors. Additional factors, often called "engineering hot-channel factors" were used to further multiply the power in the hot channel. These factors (Ref. 1, p. 640) included (1) a factor of 1.2 for the coolant temperature rise due to manufacturing tolerances on the coolant channel spacing, (2) a factor of 1.2 for the film temperature rise (sometimes called the "hot spot factor") due to uncertainties in the heat transfer coefficient and inhomogeneities in the ^{235}U distribution, etc., and (3) a factor of 1.1 for uncertainties in the calculated power distribution. The high power trip setting for the reactivity insertion transients was taken to be 12 MW, implying an "overpower factor" of 1.2.

Loss-of-Flow Transients

Loss-of-flow transients were computed starting from a power of 12 MW. The coolant flow rate was assumed to decrease exponentially with a decay constant of 1.0 s after operation at 12 MW for 1 s. Reactor scram was initiated when the flow decreased to 85% of full flow (1.16 s), with delay time of 200 ms for the shutdown reactivity insertion. The results are tabulated below.

	T, °C (t, s)		
Peak	HEU	LSI	LOX
Fuel Center Line	116.7 (1.37)	115.8 (1.37)	128.0 (1.37)
Clad Surface	114.0 (1.37)	112.8 (1.37)	110.3 (1.37)
Coolant Outlet	75.2 (1.47)	74.7 (1.46)	74.9 (1.46)
At 15% of Nominal Flow (2.92 s)			
Fuel Center Line	70.2	69.8	70.3
Clad Surface	69.9	69.4	68.3
Coolant Outlet	52.3	52.1	52.6

All three cores behave in a similar manner for this unrealistically fast flow-coastdown. The peak temperatures reached at the clad surface were 110 - 114 °C, which are far below the melting point of 582 °C for 6061 aluminum alloy.

Slow Reactivity Insertion Transients

In this hypothetical startup accident, it is postulated that, due to circuit malfunctions, all of the control rods are withdrawn simultaneously at their maximum rate of travel with the reactor initially critical at power levels of 1 W and 10 MW. A full-flow rate of 1000 m^3/h was assumed along with a safety trip setting of 12 MW. A time delay of 25 ms was assumed between attainment of the trip level and the start of shutdown rod insertion (- $10/0.5 s). An "engineering factor" of 1.58 was included in the power distribution for the hot channel.

Using the ORR maximum rod withdrawal speed of 5.0 in./min. (2.12 mm/s), the reactivity worth vs rod position curve for the IAEA safety benchmark studies (Ref. 4, App. F-1), and the calculated rod worths described above, the maximum reactivity insertion rate was estimated to be 14.7 ¢/s for the HEU, LSI, and LOX cores. The results of the calculations are shown below.

Fuel Element Design	Slow Reactivity Insertion Rate, ¢/s	Min. Period, s	Trip Time at 12 MW, s	Time To Peak Power, s	Peak Power, MW	Energy Release at Peak Power, MJ	Peak Fuel Temp., °C	Peak Clad Temp., °C	Peak Coolant Outlet Temp., °C
			Initial Power:	1 W					
HEU	14.7	0.065	7.45	7.48	17.4	1.23	86.5	84.3	53.1
LSI	14.7	0.063	7.38	7.41	15.5	1.23	83.7	81.3	52.2
LOX	14.7	0.064	7.39	7.42	15.7	1.23	91.6	76.1	51.5
			Initial Power:	10 MW					
HEU	14.7	5.20	1.17	1.19	12.1	13.0	104.8	102.1	68.3
LSI	14.7	5.56	1.22	1.25	12.1	13.6	104.1	101.0	68.1
LOX	14.7	5.19	1.22	1.25	12.0	13.6	117.4	98.8	67.8

The results for the transients that begin from a power level of 1 W in the HEU, LSI, and LOX cores are very similar. The peak temperatures reached at the surface of the cladding are 76 - 84 °C, far below the melting point of 582 °C for 6061 aluminum alloy. As expected, the transients that begin from a power level of 10 MW have very different characteristics than those that begin at 1 W, but all of the three cores behave in a similar manner. The peak temperatures reached at the clad surface in the 10 MW case are only 99 - 102 °C.

Step Reactivity Insertions With Scram

Step reactivity insertions from an initial power of 1 W with full flow and a safety system trip at 12 MW were studied to determine the input reactivities necessary to initiate clad melting. A delay of 25 ms was assumed between the reactor trip and the start of shutdown rod insertion (- $10/0.5 s). An "engineering hot channel factor" of 1.58 was included in the power distribution for the hot channel. The results are tabulated below:

Step Insertion $	Min. Period, s	Trip Time @ 12 MW, s	Time to Peak Power, s	Peak Power, MW	Energy Release at Peak Power, MJ	Peak Fuel Temp., °C	Peak Clad Temp., °C
			HEU				
1.65	9.4	0.19	0.23	417	6.8	513	510
1.75	8.3	0.17	0.21	609	8.0	567	565
			LSI				
1.65	7.8	0.16	0.20	418	5.8	458	452
1.75	7.0	0.15	0.18	588	6.6	496	493
1.85	6.2	0.13	0.16	759	7.3	532	529
1.95	5.6	0.12	0.15	944	8.0	569	564
			LOX				
1.65	8.0	0.16	0.20	402	6.4	593	421
1.75	7.1	0.15	0.19	612	8.5	741	483
1.80	6.7	0.14	0.18	733	9.2	802	530
1.85	6.4	0.13	0.17	856	9.7	864	575

These data indicate that the 582 °C melting temperature of 6061 aluminum alloy cladding will be reached for step insertions of about $1.75-$1.80 in the HEU core, about $1.95-$2.00 in the LSI core, and about $1.85-$1.90 in the LOX core. Thus, all three cores have about the same reactivity limits for this transient, with the LEU cores having a slight advantage.

Ramp insertions of the same reactivities in 0.5 s yield nearly the same peak clad temperatures as step insertions. For example, with an insertion of $1.65/0.5 s, the computed peak clad temperatures were 497, 460, and 426 °C in the HEU, LSI, and LOX cores, respectively.

Ramp Reactivity Insertions Without Scram

Ramp reactivity insertions without scram from an initial power of 1 W with full flow were also investigated to determine clad melting limits for cases with "engineering hot channel factors" of 1.58 and 1.0. The results are shown below.

Eng. Hot Channel Factor	Ramp React. Insertion, $/0.5 s	Min. Period, ms	Time to Peak Power, s	Peak Power, MW	Energy Release to Time of Peak Power, MJ	Peak Fuel Temp., °C	Peak Clad Temp., °C
			HEU				
1.58	1.60	11	0.60	604	8.5	588	586
1.0	2.85	6.0	0.39	1407	9.6	569	565
	2.90	5.9	0.38	1435	9.8	615	611
			LSI				
1.58	2.40	6.3	0.41	969	8.1	587	583
1.0	7.80	3.3	0.18	2532	10.6	578	574
			LOX				
1.58	1.70	8.0	0.54	713	9.4	805	544
	1.75	7.6	0.53	800	9.9	855	592
1.0	5.30	4.1	0.24	2708	16.0	983	574
1.0*	7.80	3.3	0.18	2995	12.3	580	569

*Thermal conductivity is the same (1.0 W/cmK) as LSI instead of 0.11 W/cmK for LOX.

These results show that the reactivity insertions necessary to initiate clad melting are strongly dependent on the engineering hot-channel factors that are utilized, especially in the LEU cores. With a hot-channel factor of 1.0, the LSI and LOX cores can tolerate much higher ramp rates[3] than the HEU core primarily because of their larger Doppler coefficients and larger void coefficients. The limiting ramp rate in the LOX core is less than that in the LSI core due primarily to the low thermal conductivity of oxide fuel. To illustrate this point, one LOX case was run with the same thermal conductivity as used for the LSI fuel with the result that the limiting ramp rate is very close to that of the LSI core. With an engineering hot-channel factor of 1.58, the limiting ramp rates in all three cores are much less than with a factor of 1.0, and the reactivity differential between each LEU core and the HEU core is much smaller as well.

It is important to note that the SPERT I cores had peak-to-average powers of about 2.5. The same is true for the three cores calculated here. Thus, with an engineering hot-channel factor of 1.0, the results calculated for the HEU core would agree[3] very well with the values measured in the SPERT I experiments. If conservative, multiplicative engineering hot-channel factors are utilized, they could unnecessarily restrict the licensed maximum excess reactivity available for experiments if reactivity limits for clad melting without scram are an important licensing consideration.

CONCLUSIONS

Key safety parameters and the transient behavior of equilibrium cores of the IAEA generic 10 MW reactor have been studied with HEU aluminide fuel (280 g ^{235}U per fresh element) and with LEU silicide and oxide fuels (390 g ^{235}U per fresh element). The main conclusions are outlined below:

- The total reactivity feedback coefficient due to increasing temperature is slightly larger in the LEU cores than in the HEU core.
- The prompt Doppler coefficient and the whole-core void coefficient are significantly larger in the LEU cores.
- The prompt neutron generation time is smaller in the LEU cores mainly because of the hardening of the neutron spectrum with increased ^{235}U loading.
- The total power peaking factor in the limiting control fuel element with the absorber blades 50% withdrawn is slightly lower in the LEU cores.
- The reactivity worth of the five fully-inserted control rods is 7-11% lower in the LEU cores, even though the ^{235}U loading of the fresh LEU elements is larger by a factor of about 1.4. With the rod of maximum worth fully-withdrawn, the worth of the four inserted rods is 5-10% lower in the LEU cores. These reductions in rod worths have meaning only in the context of the total reactivity balance table.
- Shutdown margins based on (1) all control rods fully-inserted and a total excess reactivity that is 50% larger than calculated and (2) the rod of maximum worth fully-withdrawn and the calculated total excess reactivity are shown to be fully-adequate for this reactor. Shutdown margins can increase or decrease in LEU cores relative to the HEU core depending mainly on relative changes in the reactivity loss due to burnup and in the worth of the control rods.

- Loss-of-flow transients in the HEU and LEU cores starting from a power of 12 MW with reactor scram initiated at 85% of full flow yield peak temperatures of 110-114°C at the clad surface, far below the melting point of 582°C for 6061 aluminum alloy.

- Slow reactivity insertion (14.7 ¢/s) transients with full flow and reactor scram at 12 MW that may occur during startup of the HEU and LEU cores yield peak clad surface temperatures of 76-84 °C when initiated from a power of 1 W and 99-102 °C when initiated from a power of 10 MW.

- Step reactivity insertions from an initial power of 1 W with full flow, reactor scram at 12 MW, and an engineering hot-channel factor of 1.58 indicate that the clad melting temperature will be reached for insertions of about $1.75 in the HEU aluminide core, $1.85 in the LEU oxide core, and $1.95 in the LEU silicide core.

- Ramp reactivity insertions ($/0.5 s) necessary to inititate clad melting without scram starting from a power of 1 W with full flow indicate that: (1) the reactivity limits are a strong function of the engineering hot-channel factors that are assumed, especially in the LEU cores, (2) the LEU cores with an engineering hot-channel factor of 1.0 can tolerate much higher ramp rates than the HEU core because of their larger Doppler and void coefficients, (3) limiting ramp rates are lower in the LEU oxide core than in the LEU silicide core because of the low thermal conductivity of the oxide fuel, (4) with an engineering hot-channel factor of 1.58, the limiting ramp rates are significantly reduced in all three cores, and the reactivity differential between each LEU core and the HEU core is much smaller as well, (5) assumed conservative engineering hot-channel factors can unnecessarily restrict the licensed maximum excess reactivity available for experiments if reactivity limits for clad melting without scram are an important licensing consideration.

REFERENCES

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2. J. E. Matos and K. E. Freese, "Fuel Cycle Cost Comparisons with Oxide and Silicide Fuels," ANL/RERTR/TM-4: Proceedings of the International Meeting on Research and Test Reactor Core Conversions from HEU to LEU Fuels, Argonne National Laboratory, Argonne, Illinois, November 8-10, 1982; pp 517-542.

3. W. L. Woodruff, "The PARET Code and the Analysis of the SPERT I Transients," ibid., pp. 560-579.

4. Guidebook on "Safety and Licensing Issues Related to Research Reactor Core Conversions from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels," Volume 1 (to be published).

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Thermal conductivities and heat capacities (T in °K) used in this paper:

HEU: 1.58 W/cm K and 1.985 + 0.0010 T J/cm^3 K
LSI: 1.00 W/cm K and 1.929 + 0.0007 T J/cm^3 K
LOX: 0.11 W/cm K and 1.626 + 0.0017 T J/cm^3 K
Al: 1.80 W/cm K and 2.069 + 0.0012 T J/cm^3 K