CONF-8410173--8

A MIXED CORE CONVERSION STUDY WITH HEU AND LEU FUELS

CONF-8410173--8

DE85 005045

J. E. Matos and K. E. Freese
Argonne National Laboratory
Argonne, Illinois, USA

ABSTRACT

The results of a mixed core study are presented for gradual replacement of HEU fuel with LEU fuel using the IAEA generic 10 MW reactor as an example. The key parameters show that the transition can be accomplished safely and economically.

INTRODUCTION

Most research reactor operators are planning to convert their cores from HEU to LEU fuel by gradually replacing their HEU elements with LEU elements. This paper presents results for the key operational and safety parameters for the HEU and LEU equilibrium cores and for each step of a gradual transition from HEU fuel to LEU fuel using the IAEA generic 10 MW reactor as an example.

The light-water reactor design is described in IAEA-TECDOC-233.[1] The 5 x 6 element core consists of 23 MTR-type standard elements, 5 control elements, and two water-filled flux traps with 12 graphite reflector elements on two opposite faces. The HEU standard elements have 23 plates, UAl_x-Al fuel, and 280 g ^{235}U. The LEU replacement elements that were studied have the identical geometry, but contain 390 g ^{235}U and U_3Si_2-Al fuel with a uranium density of 4.45 g/cm^3 (40 vol% U_3Si_2).

The methods and codes that were used are described in Ref. 1. All of the calculations were performed in 3D using an outside-in fuel shuffling pattern in which two elements were replaced per cycle. Two previous studies of this reactor addressed fuel cycle costs (Ref. 2) and the safety parameters and transient behavior (Ref. 3) of equilibrium cores using a different 4-5 element outside-in fuel shuffling pattern.

EQUILIBRIUM CORES

The first objective was to compare the operating characteristics, fuel cycle costs, and steady-state thermal-hydraulic safety margins of the HEU and LEU equilibrium cores to ensure that these characteristics were satisfactory before beginning the mixed core calculations. The fuel element designs and the results are shown in Tables 1 and 2.

Table 1. Fuel Element Designs

	HEU	LEU
Fuel Type	UAl_x	U_3Si_2
Enrichment, %	93	19.75
U Density, g/cm^3	0.68	4.45
Plates per El. Std./Cntl.	23/17	23/17
Fuel Meat/Water Channel Thick., mm	0.51/2.19	0.51/2.19
Nom. Clad Thick., mm Inner/Outer Plates	0.38/0.495	0.38/0.495
^{235}U per El., g Std./Cntl.	280/207	390/288

Table 2. Operating Characteristics and Fuel Cycle Costs

	HEU	LEU	
Cycle Length, d	21.4	30.6	
EOC Excess React., % δk/k	2.3	2.3	
Ave. Disch. Burnup, % Std./Cntl.	49.9/55.3	48.5/53.8	
Margin to ONB/ Min. η, cm^3 K/Ws	1.55/230	1.58/234	
Relative Total Fuel Cycle Costs	1.0	x	R
R = LEU/HEU Total Fuel Cycle Cost Ratio		1.0	0.87
		1.5	0.98
x = LEU/HEU Fabrication Cost Ratio		2.0	1.09
		2.5	1.20

R = 0.65 + 0.22 x

The cycle length was computed to be 21.4 days in the HEU core and 30.6 days in the LEU core because of the much higher fissile loading of the LEU elements. (A ^{235}U content of about 320 g per LEU standard element is required to match the cycle length and EOC excess reactivity of the HEU core.) Total fuel cycle costs for the LEU core would be equal to (15% greater than) those for the HEU core if the LEU/HEU fabrication cost ratio were about 1.6 (2.3). Details of the cost calculations can be found in Ref. 4.

Total nuclear power peaking factors (Fig. 1) with all five absorbers 50% withdrawn are within about 10% of each other, but the limiting value in core position C2 is slightly smaller in the LEU core.

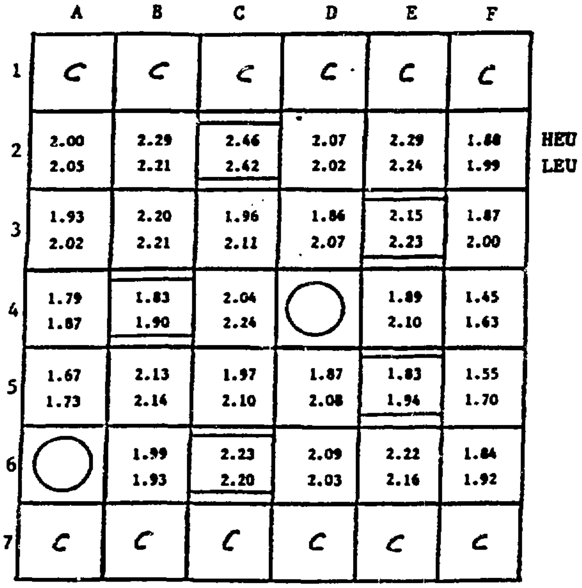

Fig. 1. Total Power Peaking Factors at BOC (Absorbers 50% Withdrawn)

	A	B	C	D	E	F	
1	C	C	C	C	C	C	
2	2.00 2.05	2.29 2.21	2.46 2.42	2.07 2.02	2.29 2.24	1.88 1.99	HEU LEU
3	1.93 2.02	2.20 2.21	1.96 2.11	1.86 2.07	2.15 2.23	1.87 2.00	
4	1.79 1.87	1.83 1.90	2.04 2.24	○	1.89 2.10	1.45 1.63	
5	1.67 1.73	2.13 2.14	1.97 2.10	1.87 2.08	1.83 1.94	1.55 1.70	
6	○	1.99 1.93	2.23 2.20	2.09 2.03	2.22 2.16	1.84 1.92	
7	C	C	C	C	C	C	

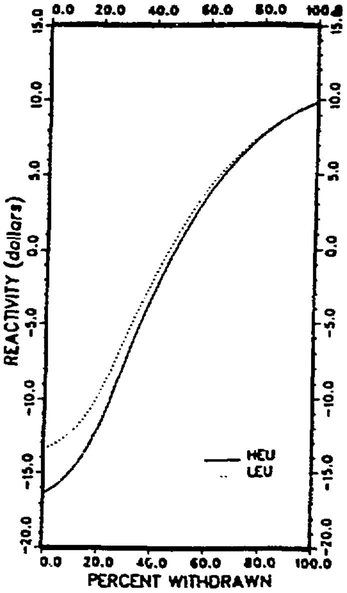

Fig. 2. Reactivity vs Rod Position

For the following input parameters,

Inlet Temperature: 38°C
Inlet Pressure : 1.7 bar
Flow Rate : 1000 m^3/h

Nuclear Peaking Factors	HEU	LEU
Radial x Local :	1.64	1.61
Axial :	1.5	1.5
Total Nuclear :	2.46	2.42
Total Engineering Hot-Channel Factor:	1.58	1.58

the data in Table 2 show that the margins to onset of nucleate boiling (ONB) using the Dittus-Boelter correlation and the minimum values of the flow instability parameter ($\eta = v \cdot \Delta T_s/q''$) are satisfactory and nearly the same in the two cores. The parameters v, ΔT_s, and q" are the local values of the coolant velocity, coolant subcooling and heat flux, respectively.

Reactivity balance tables, control rod worths, and three examples of shutdown margins at BOC are shown in Table 3. One shutdown margin is based on the total excess reactivity and all rods in; the second is based on the total excess reactivity multiplied by a factor of 1.5 and all rods in, and the third is based on the total excess reactivity and the rod of maximum worth fully withdrawn. These shutdown margins are 18 - 25% smaller (measured in dollars) in the LEU core than in the HEU core, but are fully adequate to guarantee the safety of the facility.

Table 3. Reactivity Balance Tables, Control Rod Worths and Shutdown Margins at BOC for the HEU and LEU Equilibrium Cores

Reactivity Balance Tables

Reactivity Component	Δρ, %/$ HEU	Δρ, %/$ LEU
Burnup	1.90/2.50	1.65/2.26
Xe Poison	3.30/4.35	3.17/4.34
Experiments	1.50/1.98	1.50/2.05
Control Reserve	0.50/0.66	0.50/0.68
Cold-to-Hot Swing	0.30/0.40	0.30/0.41
Total Excess Reactivity	7.50/9.89	7.12/9.74
Total Excess React. × 1.5	11.25/14.84	10.68/14.61

Control Rod Worths and Shutdown Margins

Control Rod Worths	Δρ, %/$ HEU	Δρ, %/$ LEU
All Rods In	19.89/26.22	16.95/23.18
Max. Worth Rod Out	11.42/15.05	10.01/13.69
Shutdown Margins		
Total Excess Reactivity and All Rods In	12.39/16.33	9.83/13.44
Total Excess React. × 1.5 and All Rods In	8.64/11.38	6.27/8.57
Total Excess Reactivity and Max. Worth Rod Out	3.92/5.16	2.89/3.95

Profiles of reactivity worth in dollars versus percent withdrawal of the tips of the five absorbers are shown in Fig. 2 for the BOC, cold, xenon-free equilibrium cores with no experimental loads. The shapes and magnitudes of the two curves are very similar in the important operating range with the absorbers more than 50% withdrawn, even though the total LEU absorber worth is smaller by about 12%. As a result, critical absorber positions for various operational states of the reactor would be nearly the same in both cores.

Spent fuel storage studies (Ref. 5) show that these LEU elements could be stored safely in the pool using the same racks that are currently used with HEU fuel. Radiological consequence analyses (Ref. 6) show that there are no significant differences between these HEU and LEU fuels for the same hypothetical accidents. The transient behavior of the two equilibrium cores is compared in a section that follows.

MIXED CORES

Over the years, many reactors have been safely operated with numerous mixed cores composed of elements with different geometries, different fissile loadings, different enrichments, or a combination of these. The same principles and safety considerations apply to the current conversions from HEU to LEU fuel.

For the same element geometry, the most important variable is the relative fissile loading of the current and replacement elements and the most important safety parameters are the shutdown margins and the margin to ONB.

Since the HEU elements in this study contain 280 g ^{235}U and the LEU elements contain 390 g ^{235}U, nuclear power peaking will be larger in mixed cores of these elements than in the individual equilibrium cores and the margins to ONB will be smaller as a result. Shutdown margins will also be smaller in both the mixed cores and the LEU equilibrium core because the neutron spectrum is harder in the more highly loaded LEU elements.

Procedures

Two sets of calculations are shown here, starting from the EOC ^{235}U loadings of the HEU xenon-free equilibrium core, for each of the 14 cycles that are needed to replace the 28 element core. In the first set, HEU elements were replaced with HEU elements using a standard calculational fuel replacement pattern in order to determine typical operating parameters and safety characteristics. One control element was discharged in each of cycles 4, 6, 8, 12, and 13 when it reached an average ^{235}U burnup of 55-60%.

In the second set, HEU elements were replaced with LEU elements, but the replacement pattern was different from the HEU case in order to minimize power peaking in the LEU control elements.

Before beginning the neutronics calculations, it is prudent to determine the maximum total nuclear power peaking factor that will yield an acceptable margin to ONB. Since the calculations for the mixed cores are performed sequentially, the adequacy of the margin to ONB and the limiting shutdown margin must be checked after each cycle. If one choice of LEU element positions does not satisfy the safety criteria, others must be tried until a successful solution is found.

Using the thermal-hydraulic input parameters shown above for the equilibrium cores, the maximum acceptable total nuclear peaking factor (including axial peaking) with the five absorbers 50% withdrawn would be 3.18 if the minimum acceptable margin to ONB is assumed to be 1.2 in this example. The value of the flow instability parameter, η_{min}, that corresponds to this peaking factor would be 130. The smallest acceptable value for the shutdown margin with the rod of maximum worth fully-withdrawn was assumed to be 1% $\delta k/k$.

LEU Replacement Pattern

Conceptually, the core for the LEU replacement was divided into two regions: (1) an outer region consisting of 15 standard elements on the periphery of the core plus the standard element in location B6, and (2) an inner region consisting of the 7 remaining standard elements plus the 5 control elements. The LEU replacement pattern for all 14 mixed cores is shown in Fig. 3. Triangles indicate LEU elements and a tick mark in one corner indicates the element with the largest total nuclear power peaking factor.

Fresh LEU standard elements were always introduced in locations A2 and F6. Replacement of the outer core was completed by first replacing rows 2 and 6 (Cores 1-5 in Fig. 3) and then columns A and F plus the element in B6 (Cores 6-8). In the inner core, the standard elements in B3 and E4 were replaced first (Core 9), leaving the 5 HEU control elements with an adjacent HEU standard element. These control-standard element pairs were then replaced counterclockwise in successive cycles beginning with Core 10 and ending with Core 14 .

Results

Table 4 shows a cycle-by-cycle comparison of key operational and safety characteristics for the typical HEU core and the mixed core with HEU and LEU fuel. The main results for the mixed cores (Fig. 3) are summarized below:

- All of the shutdown margins and margins to ONB are fully adequate and satisfy the reasonable safety criteria that were assumed for these example calculations.

- Cores 1-7 were run with the same cycle length (21.4 days) as the HEU equilibrium core since the excess reactivity added by introducing the HEU elements on the periphery of the core was relatively small. Note that the margins to ONB are smaller than in either the HEU or LEU equilibrium cores because the total nuclear peaking factors are larger in the mixed cores.

- Core 8, which completed replacement of the outer core, was run for 30.6 days (the cycle length expected when the full LEU equilibrium core is reached) in anticipation of the faster buildup of excess reactivity when partially burned LEU elements are introduced into the inner core positions.

- Core 9 had the lowest margin to ONB (1.24) of all the mixed cores. The limiting element in position E4 is adjacent to a water-filled flux trap and had a ^{235}U content of 298 g - the highest burnup LEU element available.

- Cores 10-13 were run for 30.6 days since sufficient excess reactivity for burnup was available during replacement of the inner core. The HEU control elements which were replaced had average ^{235}U discharge burnups of 60-70%.

Fig. 3. LEU Replacement Pattern for Each of the Fourteen Cycles Needed To Convert the HEU Core. Triangles Indicate LEU Elements. Tick Mark in Corner Indicates Element With Largest Nuclear Power Peaking Factor.

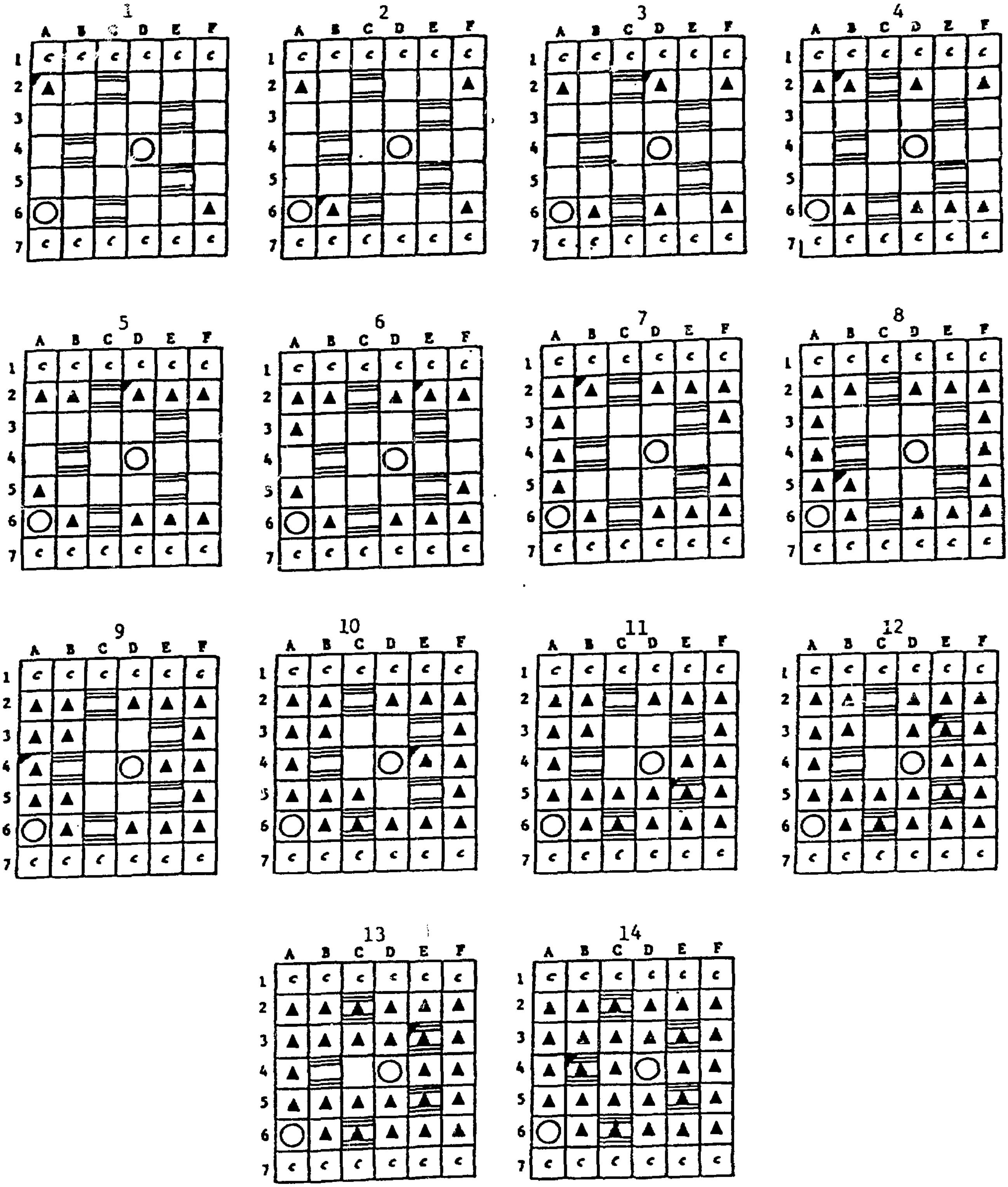

Table 4. Cycle-by-Cycle Comparison of Key Operational and Safety Characteristics for a Typical HEU Core and a Mixed Core of HEU and LEU Fuel. The Fuel Replacement Patterns are Different for the Two Cases (See Text).

Cycle No. and Replacement Fuel	Cycle Length, Days	Total Excess Reactivity, %		Shutdown Margins at BOC (no Xe), %			Total Nuclear Peaking Factor (5 Rods 50% Out),		Margin to ONB
		BOC	EOC	Based on Total Excess Reactivity, All Rods In	Based on Total Excess React. x 1.5, All Rods In	Based on Total Excess Reactivity, Max. Rod Out	Factor	Location	
1 - HEU	21.4	7.59	2.40	12.17	8.38	3.76	2.42	B2	1.58
LEU	21.4	7.64	2.48	12.05	8.23	3.68	2.45	A2	1.56
2 - HEU	21.4	7.26	2.04	12.78	9.15	4.61	2.36	E2	1.62
LEU	21.4	7.38	2.24	12.47	8.78	4.38	2.69	B6	1.42
3 - HEU	21.4	7.26	2.04	12.66	9.03	4.43	2.44	D2	1.56
LEU	21.4	7.41	2.36	12.12	8.43	4.06	2.98	D2	1.28
4 - HEU	21.4	7.36	2.13	12.47	8.79	3.66	2.57	C6	1.48
LEU	21.4	7.50	2.50	11.69	7.94	3.57	2.93	B2	1.30
5 - HEU	21.4	7.40	2.19	12.42	8.72	3.75	2.49	C6	1.53
LEU	21.4	7.51	2.57	11.64	7.89	3.73	2.79	D2	1.37
6 - HEU	21.4	7.37	2.14	12.72	9.03	4.25	2.62	C2	1.46
LEU	21.4	7.37	2.47	11.54	7.86	3.61	2.71	E2	1.41
7 - HEU	21.4	7.33	2.11	12.63	8.96	4.19	2.48	C6	1.54
LEU	21.4	7.44	2.59	11.21	7.49	3.29	2.90	B2	1.32
8 - HEU	21.4	7.41	2.19	12.66	8.96	4.34	2.58	C2	1.48
LEU	30.6	7.39	1.90	11.21	7.51	3.54	2.87	B5	1.33
9 - HEU	21.4	7.27	2.05	12.75	9.12	4.56	2.49	C2	1.53
LEU	21.4	6.82	2.07	11.66	8.25	4.07	3.07	E4	1.24
10 - HEU	21.4	7.02	1.79	13.02	9.52	4.80	2.34	C6	1.63
LEU	30.6	7.36	2.10	10.76	7.08	2.92	2.89	E4	1.32
11 - HEU	21.4	7.11	1.88	12.88	9.33	4.71	2.36	E6	1.62
LEU	30.6	7.51	2.38	10.36	6.61	3.12	2.94	E5	1.30
12 - HEU	21.4	7.04	1.79	13.06	9.54	4.87	2.63	C6	1.45
LEU	30.6	7.60	2.60	9.95	6.15	3.24	2.89	E3	1.32
13 - HEU	21.4	7.23	1.99	12.89	9.28	4.23	2.71	C2	1.41
LEU	30.6	7.58	2.68	9.69	5.90	3.04	2.77	E3	1.38
14 - HEU	21.4	7.30	2.08	12.63	8.98	3.83	2.65	C2	1.44
LEU	50.0	7.97	2.19	8.83	4.85	1.76	2.75	B4	1.39
15 - HEU	21.4	7.25	2.02	12.69	9.06	4.04	2.44	C2	1.56
LEU	30.6	6.96	2.11	10.22	6.75	3.01	2.59	B4	1.47
16 - HEU	21.4	7.31	2.10	12.63	8.98	4.11	2.37	E2	1.61
LEU	30.6	6.86	2.00	10.34	6.91	3.25	2.46	B4	1.55

- Core 14, which completed the LEU replacement, had the highest excess reactivity at BOC and the smallest shutdown margin (1.76% δk/k) with the rod of maximum worth fully withdrawn. This full LEU core was operated for 50 days to run down the excess reactivity to a value near that expected for the LEU equilibrium core and to maximize the burnup in two LEU elements that need to be replaced for next cycle.

- Cores 15 and 16 have characteristics similar to those of the LEU equilibrium core.

There are many possible variations in the sequence just described. All of them are valid if the safety criteria are shown to be satisfactory.

TRANSIENT ANALYSIS

Equilibrium Cores

The basic kinetics parameters and isothermal reactivity feedback coefficients for the HEU and LEU equilibrium cores are shown below.

Parameter		HEU	LEU
Generation Time Λ, μs		54.6	42.4
Delayed Neutron Fraction β_{eff}, %		0.7587	0.7311
Water Temp. Only	$\delta\rho/\delta T \times 10^{-3}/°C$ (38-50°C)	0.1046	0.0737
Water Density Only		0.0806	0.1051
Fuel Temp. Only		0.0006	0.0247
Void Coefficient $\delta\rho/\%$ (0-10%)		21.0	27.0

The transients that were analyzed and the results obtained using the PARET code (Ref. 7) are summarized in the following paragraphs.

- Loss-of-Flow: Exponential flow decay with a time constant of 1.0 s from a power level of 12 MW. Trip setting at 85% of nominal flow. Time delay of 200 ms before shutdown reactivity insertion of -$10/0.5s. Engineering hot-channel factor of 1.58.

The peak temperatures reached at the clad surface were 114°C with HEU fuel and 113°C with LEU fuel. These values are far below the solidus temperature of 582°C for 6061 alloy cladding.

- Slow Reactivity Insertion: Ramp rates of 16¢/s for HEU and 14¢/s for LEU from power levels of 1 W and 10 MW. Trip setting at 12 MW and 25 ms time delay before shutdown reactivity insertion of -$10/0.5s. Ramp rates correspond to maximum insertion rates (Fig. 2) of 75.7¢/cm for HEU and 66.1¢/cm for LEU with maximum ORR rod withdrawal speed of 0.212 cm/s. Engineering hot-channel factor of 1.58.

From an initial reactor power of 1 W, the peak temperatures reached at the clad surface were 84°C with HEU fuel and 81°C with LEU fuel. From an initial reactor power of 10 MW, the corresponding peak clad temperatures were 102°C and 101°C, respectively. Again, these values are far below the temperature needed to initiate melting of the cladding.

- Reactivity Insertion Limits for Clad Melting: Steps and 0.5 s ramps from a power level of 1 W with and without scram at 12 MW. Time delay of 25 ms before shutdown reactivity insertion of -$10/0.5 s for cases with scram.

As noted in Ref. 3 and shown in Ref. 7, the results for the HEU core with a hot-channel factor of 1.0 would be in very good agreement with the SPERT I experimental data. Thus, our preference for these transients is to compute the limiting reactivity insertions with a hot-channel factor of 1.0 and reduce this value for purposes of conservatism. The results are shown in Table 5.

Table 5. Summary of Limiting Reactivity Insertions from a Power Level of 1 W to Initiate Melting of 6061 Alloy Cladding at a Surface Temperature of 582°C for HEU and LEU Equilibrium Cores.

	Limiting Reactivity Insertion, $	
Scram	HEU	LEU
	Step Insertions, $	
Yes	2.3	2.9
No	2.3	2.9
	Ramp Insertions, $/0.5s	
Yes	3.3	8.1
No	2.8	7.9

All of the limiting reactivity insertions are larger in the LEU equilibrium core because of its significant prompt Doppler coefficient and larger void coefficient.

Mixed Cores

Selected transients were recomputed for two of the mixed cores: Core 9 (Fig. 3) because it has the largest total nuclear power peaking factor and Core 3 because it has the largest nuclear peaking factor in a core composed mostly of HEU fuel with essentially no Doppler coefficient or enhanced void coefficient.

The kinetics parameters and reactivity feedback coefficients were computed for Core 9 and also for Core 14, which has the highest ^{235}U content and the hardest neutron spectrum. The results are shown below.

Kinetic Parameters and Reactivity Feedback Coefficients for Core 9 and Core 14.

Parameter		Core 9	Core 14
Generation Time Λ, μs		49.7	41.3
Delayed Neutron Fraction β_{eff}, %		0.7495	0.7334
Water Temp. Only	$\delta\rho/\delta T \times 10^{-3}/°C$ (38-50°C)	0.0813	0.0698
Water Density Only		0.0954	0.1043
Fuel Temp. Only		0.0101	0.0268
Void Coefficient $\delta\rho/\%$ (0-10%)		24.1	27.0

The Core 14 values are very close to those of the LEU equilibrium core. Core 3 data were not recomputed since they would be nearly identical with those for the HEU equilibrium core. In Core 9, the prompt neutron generation time and Doppler coefficient are about 40% of the way between the values for the HEU and LEU equilibrium cores and the void coefficient is about half way between. The data are not proportional to the relative numbers of HEU and LEU elements in Core 9 because the smaller number of HEU elements near the center of the core have a greater importance than the larger number of HEU elements on the periphery.

The reactivity insertion limits for clad melting that were computed for Core 3 and Core 9 are shown in Table 6.

Table 6. Summary of Limiting Reactivity Insertions from a Power Level of 1 W to Initiate Melting of 6061 Alloy Cladding at a Surface Temperature of 582°C for Core 3 and Core 9 in Fig. 3.

	Limiting Reactivity Insertion, $	
Scram	Core 3	Core 9
	Step Insertions, $	
Yes	2.1	2.2
No	2.0	2.2
	Ramp Insertions, $/0.5s	
Yes	2.7	3.8
No	2.4	3.5

In Core 3, the kinetics parameters and reactivity feedback coefficients of the HEU core were used, but the total nuclear peaking factor was increased from 2.46 to 2.98. This resulted in decreases of $0.10 - 0.20 for the step insertions and $0.40 - 0.60 for the ramp insertions relative to the HEU equilibrium core values.

In Core 9, computed values of the kinetics paramenters and reactivity feedback data were used along with a total nuclear peaking factor of 3.07. The limiting reactivity is slightly larger than in Core 3 for step insertions, and is considerably larger for ramp insertions because of the larger Doppler and void coefficients.

Thus, the limiting mixed core for transients in this example is Core 3 because of the increased power peaking with a few highly loaded LEU elements in the HEU equilibrium core.

CONCLUSION

Extensive studies of a generic 10 MW reactor indicate that a gradual transition from HEU fuel with a fissile loading of 280 g per standard element to LEU fuel with a fissile loading of 390 g per standard element can be accomplished safely.

Total fuel cycle costs for the LEU equilibrium core would be equal to those of the HEU equilibrium core if the LEU/HEU fabrication cost ratio were about 1.6. If the fabrication cost of an LEU element were larger by a factor of 2.3, the total fuel cycle costs would be larger by about 15%.

REFERENCES

1. Guidebook on "Research Reactor Core Conversions from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels," IAEA-TECDOC-233 (August 1980).

2. J. E. Matos and K. E. Freese, "Fuel Cycle Cost Comparisons With Oxide and Silicide Fuels," Proceedings of the International Meeting on Research and Test Reactor Core Conversions from HEU to LEU Fuels, Argonne National Laboratory, Argonne, Illinois, 8-10 November 1982, ANL/RERTR/TM-4, CONF-821155, (September 1983), pp. 517-542.

3. J. E. Matos, K. E. Freese, and W. L. Woodruff, "Comparison of Safety Parameters and Transient Behavior of a 10 MW Reactor With HEU and LEU Fuels," Proceedings of the International Meeting on Reduced Enrichment for Research and Test Reactors, 24-27 October 1983, Tokai, Japan, JAERI-M 84-073 (May 1984), pp. 270-288.

4. J. E. Matos and K. E. Freese, "A Fuel Cycle Cost Study With HEU and LEU Fuels," these proceedings.

5. R. B. Pond and J. E. Matos, "Nuclear Criticality Assessment of LEU and HEU Fuel Element Storage," JAERI-M 84-073 (May 1984), pp. 416-425.

6. W. L. Woodruff, D. K. Warinner, and J. E. Matos, "A Radiological Consequence Analysis with HEU and LEU Fuels," these proceedings.

7. W. L. Woodruff, "A Kinetics and Thermal-Hydraulics Capability for the Analysis of Research Reactors," Nuclear Technology 64, 196 (1984) and "The PARET Code and the Analysis of the SPERT I Transients," ANL/RERTR/TM-4, CONF-821155 (September 1982), pp. 560-579.