USE OF SILICIDE FUEL IN THE FORD NUCLEAR REACTOR TO LENGTHEN FUEL ELEMENT LIFETIMES*
(Preliminary Analyses)

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Presented at the
1995 International Meeting on
Reduced Enrichment for Research and Test Reactors

September 18-21, 1994
Paris, France

*Work supported by the US Department of Energy
Office of Nonproliferation and National Security
under Contract No. W-31-109-38-ENG.

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ABSTRACT

Based on economic considerations, it has been proposed to increase the lifetime of LEU fuel elements in the Ford Nuclear Reactor by raising the ^{235}U plate loading from 9.3 grams in aluminide (UAl_x) fuel to 12.5 grams in silicide (U_3Si_2) fuel. For a representative core configuration, preliminary neutronic depletion and steady state thermal hydraulic calculations have been performed to investigate core characteristics during the transition from an all-aluminide to an all-silicide core. This paper discusses motivations for this fuel element upgrade, results from the calculations, and conclusions.

INTRODUCTION

University of Michigan personnel have operated the Ford Nuclear Reactor (FNR) with low-enriched (<20% ^{235}U) uranium aluminide (UAl_x) fuel since 1984. The MTR-type fuel elements each contain 167 grams ^{235}U. To extend the fuel element lifetime, it has been suggested that the UAl_x fuel be replaced with silicide (U_3Si_2) fuel containing 225 grams ^{235}U per element.

There are two primary incentives for increasing the lifetime of the FNR fuel elements. The first advantage is an economic one. For a given time period, fewer fresh elements would be needed, fewer spent fuel shipments would be required, and fewer elements would need to be prepared for disposal. The second advantage is the reduced radiation exposure to reactor personnel resulting from fewer fuel handling operations.

This study suggests that the proposed silicide fuel will more than double the lifetime of the aluminide elements. The FNR currently uses about nine standard fuel elements per year. Decreasing the annual fuel element consumption from nine to four elements would result in a substantial savings. The cost of a fresh, FNR fuel element is about $25,000. Based on spent fuel shipments to the Savannah River Laboratory in 1992, the shipping cost per element is about $2,500. There is also a spent fuel disposal cost, now estimated to be $35,000 per element[1]. Therefore, use of the proposed silicide fuel in the FNR is expected to reduce total fuel cycle costs by about $300,000 per year.

To fully use the current inventory of aluminide fuel, it is desirable to approach the silicide equilibrium core through a succession of UAl_x/U_3Si_2 transition cores while maintaining the core size of about 42 elements. Throughout the transition from aluminide to the more heavily loaded silicide fuel elements, important operational limits must be maintained. To comply with requirements in the Safety Analysis Report, power peaking must be so limited as to prevent boiling under any circumstance. Control rod worths need to be maximized throughout the transition to maintain acceptable shutdown margins, excess reactivities must be kept below the allowed maximum value, and the decrease in neutron fluxes at the experiment positions should be made as small as possible. This paper presents results obtained from preliminary neutronic and thermal hydraulic calculations based on a fuel element shuffling scheme which approximates current practice. Peak power densities, shim-safety rod worths, and region-averaged neutron fluxes are evaluated at a number of stages during the gradual transition from the initial, aluminide core to an all-silicide core. During the transition, the cycle length steadily increases and then levels off to a value approximating that of the equilibrium silicide core. Thermal hydraulic calculations based on peak power densities have been used to determine the margin to boiling throughout the transition. This paper discusses some of the results obtained from these calculations.

At the beginning of this study consideration was given to limiting power peaking effects by using a burnable poison (boron carbide) uniformly mixed with the fuel meat. The poison concentration was chosen so that the silicide element matched the initial reactivity of the aluminide fuel. However, it was found that the reduction in the peak power density was small and for this reason a burnable poison was not used in these preliminary studies.

FNR Fuel Elements, Shim-Safety Rod Compositions, and Core Configuration

Figure 1 is a sketch of the FNR 18-plate standard fuel element (SFE) and the 9-plate control fuel element (CFE). The plate thickness, the watergap thickness, the active fuel width, and the height of the fuel column are 0.1524 cm (0.060 in.), 0.2976 cm (0.117 in.), 6.096 cm (2.40 in.) and 59.69 cm (23.5 in.), respectively. These dimensions are the same for both the aluminide and silicide fuel elements. For the UAl_x fuel, the meat thickness, the clad thickness, and the uranium density in fuel meat are 0.0762 cm (0.030 in.), 0.0381 cm (0.015 in.), and 1.72 g/cm^3. The corresponding values for the proposed U_3Si_2 fuel are 0.0508 cm (0.020 in.), 0.0508 cm (0.020 in.) and 3.4 g/cm^3. The nominal ^{235}U loading per plate is 9.3 g for the UAl_x fuel and 12.5 g for U_3Si_2. For both fuel types, the enrichment is <20%. The fuel plate used for these preliminary studies is the "standard" plate for U.S. university reactors,[2] except for having 0.0508-cm-thick rather than 0.0381-cm-thick cladding. This thicker cladding has the advantage of preserving the plate and coolant channel thicknesses in the FNR fuel elements which simplifies the thermal hydraulic calculations and reduces power peaking by about as much as a burnable poison in the fuel meat does.

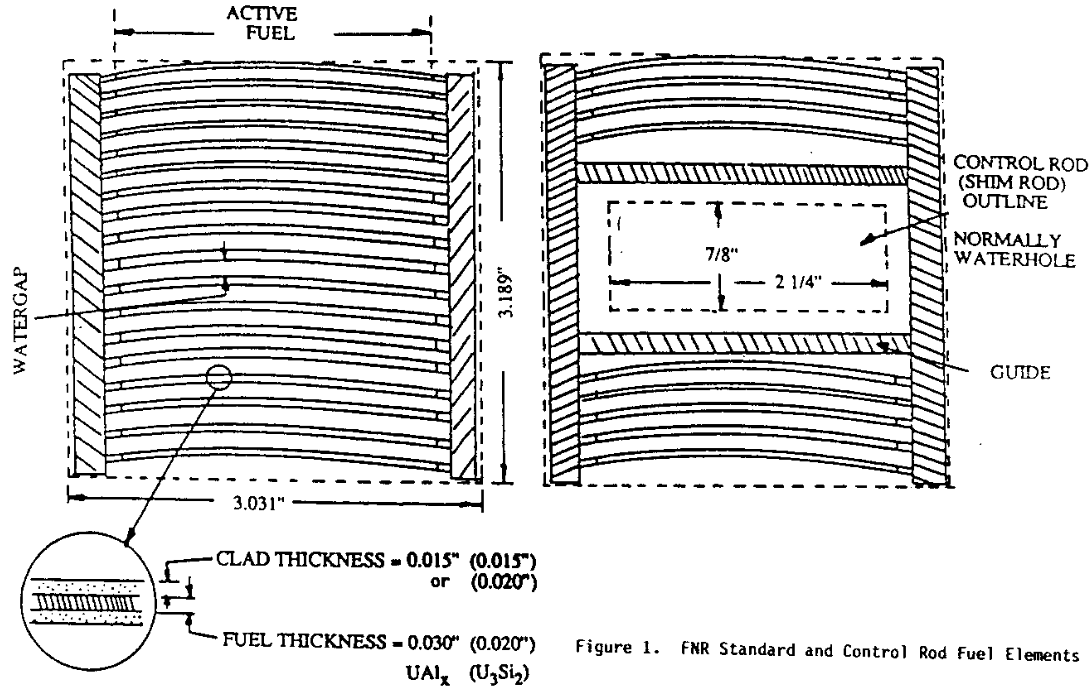


Figure 1. FNR Standard and Control Rod Fuel Elements

Shim-safety rods in current use are composed of borated stainless steel with a concentration of 1.5 wt. % natural boron. These are soon to be replaced with rods composed of an alloy of titanium diboride (TiB_2) in Al-6351. The alloy contains 1.0 wt. % boron enriched to more than 95% ^{10}B. Both shim-safety rod compositions are "black" to thermal (E<0.625 eV) neutrons. In the resonance range, however, the TiB_2 rods are more absorbing than the borated stainless steel rods and so have a somewhat larger worth.

Figure 2 shows the configuration of a recent FNR aluminide core (349A) and includes beginning-of-cycle (BOC) ^{235}U fuel element masses. This core operated at 2.0 MW for 9.43 days. The end-of-cycle (EOC) region-dependent atom densities were used as the starting point for the UAl_x/U_3Si_2 transition. Experimental facilities in the D_2O reflector on the north face of the core and in the H_2O reflector on the east, south, and west faces of the core were not modeled in this study.

Four-group, burnup-dependent, cross sections were generated for the standard and control fuel elements (with and without the shim-safety rod inserted) for both aluminide and silicide fuel. The WIMS-D4M code[3] together with a library based on ENDF/B-V was used for this purpose. Energy boundaries (eV) for the 4-group cross sections are 1.0E+7, 8.21E+5, 5.52E+3, 6.25E-1, and 1.0E-5. Appropriate cross sections for the reflector regions, the fuel element side plate regions, the internal water hole, the shim-safety rods, and the stainless steel (no boron) regulating rod also were obtained from WIMS-D4M. In general, the WIMS cross sections are in good agreement with VIM[4] Monte Carlo calculations. For diffusion calculations, the strongly absorbing shim-safety rods are described by a set of group-dependent internal boundary conditions (current-to-flux ratios) obtained from TWODANT[5] transport calculations.

Figure 2. FNR Core Configuration

FNR CYCLE 349A
D20 REFLECTOR

N

75	65 122.59	55 142.39	45 155.41	35 153.03	25 159.23	15 150.36	05
76 113.19	66 106.48	56 133.91	46 CFE A 70.94	36 166.26	26 CFE C 81.39	16 150.43	06 CFE 50.18
77 113.82	67 H_2O	57 135.82	47 150.35	37 160.18	27 155.68	17 130.94	07 137.37
78 98.39	68 104.83	58 143.12	48 CFE B 70.96	38 160.07	28 CFE RR 81.32	18 128.04	08 137.11
79	69 121.97	59 116.23	49 127.19	39 136.23	29 125.62	19 115.05	09 108.81
80	70 105.80	60 105.16	50 105.47	40 102.31	30 108.87	20 107.03	10 125.98

Code:
Grid Location (46), Control fuel Element (CFE)
Rod Identification (A)
Beginning-of-Cycle ^{235}U Mass (g)

Fuel Element Shuffling Scheme For the UAl_x/U_3Si_2 Transition Study

The FNR operating cycle consists of 10 successive days at 2.0 MW followed by four days of shut down for maintenance. Rod calibrations are performed approximately every fourth cycle on the last shut-down day in a nearly xenon-free core. Partially burned elements are added to grid positions 06, 79, and 80 over the four cycle period to compensate for ^{235}U burnup. Thus, the core size ranges from 42 - 45 elements. After the fourth cycle, one or two new standard elements are added near the center of the core and a corresponding number of depleted elements are removed from the edge of the core. At this time elements in grid positions 06, 79, and 80 are removed. Once a year, two fresh control fuel elements are inserted into positions 26 and 28, the removed elements are re-located into positions 46 and 48, and the last control elements are removed from the core. Since the rods are not symmetrically located in the core, this fuel management procedure effectively balances rod reactivities. During the course of a year, the FNR operates for 25 2-week periods and consumes about 9 SFE's and 2 CFE's.

Table 1 approximates this fuel management scheme and is the fuel shuffling scheme used in these UAl_x/U_3Si_2 mixed core studies. Each macrocycle consists of 25 microcycles and corresponds to one year of FNR operation for the aluminide fuel. Following a four-day shutdown period, fresh fuel is added to the core at the beginning of microcycles 2, 6, 11, 16, and 21. A partially burned control fuel element is removed from storage and replaces the water in the 06 location at the beginning of cycles 4, 8, 13, 18, and 23. Table 1 shows the cycles when partially burned standard fuel elements are added to and removed from grid locations 79 and 80. For macrocycle 1, the beginning core configuration is the all-aluminide core 349A shown in Fig. 2. Thereafter, fresh silicide fuel is gradually added to the core following the Table 1 shuffling scheme. Initially, the cycle length is 10.0 full power (2.0 MW) days (FPD), but this is gradually increased as more and more silicide fuel is added to the core and aluminide fuel is removed. An all-silicide core is reached at BOC-6 of macrocycle 5. However, as many as six more macrocycles are needed before the core approaches an equilibrium configuration. When fresh fuel is added to the core, the banked shim-safety rods (A, B, and C) are lowered to an elevation where the reactor is approximately critical. They are then gradually withdrawn and are fully withdrawn at the end of cycles 5, 10, 15, 20 and 25. For calculational convenience, the stainless steel regulating rod (RR) in location 28 is fully withdrawn throughout the transition. Note that at the beginning of macrocycle n (for $n > 1$), the first microcycle is used only for the purpose of allowing the depletion code to shuffle the fuel and so has an effectively zero cycle length.

TABLE 1
UAl_x to U_3Si_2 Transition Beginning with the FNR 349A Core Configuration
Fuel Element Shuffling Scheme for Macrocycle n

Micro Cycle	Fresh Fuel	Grid Location	H_2O or Stored Fuel	Grid Location
1		EOC-25 Configuration for Macrocycle n-1		
2	SFE CFE CFE	F→36→39→08→09→78→S F→26→46→S F→28→48→S	H_2O H_2O H_2O	W→06→D W→79→D W→80→D
3		No Change		
4			CFE46	46→06→D
5			SFE78	78→79→D
6	SFE SFE	F→36→38→16→10→77→S F→37→35→56→07→76→S	H_2O H_2O	W→06→S W→79→D
7		No Change		
8			CFE46	46→06→D
9			SFE77	77→79→D
10			SFE76	76→80→D
11	SFE SFE	F→36→25→17→19→30→S F→37→45→57→59→50→S	H_2O H_2O H_2O	W→06→S W→79→D W→80→D
12		No Change		
13			CFE46	46→06→D
14			CFE48 SFE30	48→06→D 30→79→D
15			SFE50	50→80→D
16	SFE SFE	F→36→27→18→69→20→S F→37→47→58→65→60→S	H_2O H_2O H_2O	W→06→S W→79→S W→80→S
17		No Change		
18			CFE48	48→06→D
19			SFE20	20→79→D
20			SFE60	60→80→D
21	SFE SFE	F→36→15→29→68→40→S F→37→55→49→66→70→S	H_2O H_2O H_2O	W→06→S W→79→D W→80→D
22		No Change		
23			CFE48	48→06→D
24			SFE40	40→79→D
25			SFE70	70→80→D

SFE = 18-plate Standard Fuel Element
CFE = 9-plate Control Fuel Element
F = Fresh Leu U_3Si_2 Element with 12.5g ^{235}U per plate and 0.020-inch clad
D = Discharged Fuel Element
S = To/From Storage Pool
W = Water

Results from Neutronic Calculations

The REBUS[6]/DIF3D[7] code package was used to perform the 24 (25 for n = 1) successive microcycle nonequilibrium depletion calculations which constitute one macrocycle. Region- and depletion-dependent atom densities at the EOC-25 were used to start the next macrocycle. Table 2 summarizes some of the eigenvalues obtained at the end of several stages for the first seven macrocycles. Note that two versions of macrocycle 1 are provided; one for continued aluminide fuel use and a second for the gradual transition to silicide fuel. The large EOC eigenvalues obtained from the first few macrocycles show that these cycle length guesses are too short and will need to be adjusted so that excess reactivities do not exceed the limits in the FNR technical specifications. We think that such adjustments will have little effect on the calculated peak power densities; therefore, they have been deferred to future calculations. A number of additional macrocycle calculations will be needed to attain quasi-equilibrium conditions. The cycle length for the near-equilibrium silicide core is expected to fall between 23 and 24 full FPD.

Table 3 summarizes region-averaged neutron fluxes in several light and heavy water reflector zones and in the in-core water hole at grid position 67. In this table, the regions identified by the letter A are adjacent to the core whereas the B regions are deeper into the reflector. All the values apply at EOC-25 where the shim-safety rods are fully withdrawn. Thermal neutron fluxes in the light water regions for the silicide core (macrocycle 7) are reduced by 4-6% relative to the UAl_x case. In the heavy water reflector, the thermal fluxes are increased by about 5%.

The total reactivity worth of the three shim-safety rods was evaluated for each macrocycle at the time (BOC-2) when two fresh control fuel elements are put into the core (at locations 26 and 28). Table 4 shows the results of these calculations. Note that the TiB_2 shim-safety rods have a somewhat larger worth than the borated stainless rods. At the beginning of macrocycle 7, an all-silicide core, the rod worth is larger than that of the aluminide reference core with borated stainless steel shim-safety rods. At BOC-2 for each macrocycle shut-down and stuck rod margins are appreciably larger than the minimum values required in the FNR technical specifications.

The ^{235}U burnups of the silicide fuel elements discharged during the 6th and 7th macrocycles are summarized in Table 5. Most of these discharge burnups are in the 50-63% range and show that equilibrium conditions have not been reached. For the currently used aluminide fuel in the FNR, the ^{235}U discharge burnups average about 38% for standard fuel elements and 21% for control elements.

Peak power densities are used in steady state thermal hydraulic calculations to determine the margin to boiling. These maximum power densities, calculated by the REBUS code, are summarized in Table 6. The code determines these peak values by sampling the fluxes at the center and on the surfaces of each mesh cell. For all macrocycles, the largest power densities occur at the BOC-2 in the fresh control fuel element located in position 28. The location of the peak is on the mesh cell surface separating the homogenized fuel region from the corner of the side plate and guide plate regions nearest to the center of the core (see Figs. 1 and 2).

TABLE 2
EOC EIGENVALUES FOR THE FNR $UAl_x \rightarrow U_3Si_2$ TRANSITION CORES
(Shim-Safety Rods Fully Withdrawn at EOC)

Macro Cycle	Core	Ave. Cycle Length,* FPD's	EOC-5	EOC-10	EOC-15	EOC-20	EOC-25
1	UAl_x	10.00	1.0191	1.0171	1.0177	1.0192	1.0192
1	Transition	11.54	1.0265	1.0310	1.0348	1.0419	1.0432
2	Transition	16.25	1.0467	1.0475	1.0493	1.0518	1.0527
3	Transition	22.12	1.0526	1.0511	1.0484	1.0463	1.0415
4	Transition	24.00	1.0409	1.0406	1.0374	1.0374	1.0331
5	Transition	25.00	1.0324	1.0320	1.0284	1.0283	1.0223
6	U_3Si_2	25.00	1.0221	1.0207	1.0181	1.0190	1.0132
7	U_3Si_2	25.00	1.0153	1.0146	1.0129	1.0147	1.0091

*Note: The cycle length is averaged over the macrocycle.

TABLE 3
REGION-AVERAGED NEUTRON FLUXES AT EOC-25 FOR THE FNR $UAl_x \rightarrow U_3Si_2$ TRANSITION CORES
($E+12\ n/cm^2$-sec at P = 2.0 MW)

Macro Cycle	Core	Core Region Loc. 67		Reflector Regions[a]					
				D20ZA	D20ZB	RF40A	RF40B	RF08A	RF08B
		Total	Thermal	Thermal	Thermal	Thermal	Thermal	Thermal	Thermal
1	UAl_x	37.25	22.70	13.09	11.07	11.01	2.96	10.50	3.06
1	Transition	34.84	21.27	13.32	11.40	10.02	2.69	9.89	2.87
2	Transition	34.34	20.83	12.54	10.76	10.40	2.77	9.73	2.82
3	Transition	36.44	21.71	12.77	10.95	10.29	2.74	9.59	2.82
4	Transision	36.95	22.19	12.55	10.75	10.69	2.93	9.64	2.85
5	U_3Si_2	36.85	22.12	13.11	11.23	10.40	2.82	9.56	2.79
6	U_3Si_2	36.14	21.73	13.55	11.60	10.41	2.80	9.80	2.86
7	U_3Si_2	36.03	21.69	13.74	11.76	10.41	2.79	9.85	2.87

Note: The thermal neutron flux for neutrons with energies ≤ 0.625 eV.

[a]D20ZA is in the heavy water tank on the north side of core.
RF40A is on the south side of core next to grid location 40.
RF08A is on the east side of core next to grid location 08.
The "B" regions are next to the "A" regions, but deeper into the reflector.

TABLE 4
TOTAL REACTIVITY WORTH OF THE FNR SHIM-SAFETY RODS AT BOC-2 FOR THE $UAl_x \rightarrow U_3Si_2$ TRANSITION CORES

Macro Cycle	Core	Shim-Safety Rod Composition	Worth, % δk/k
1	UAl_x	Borated Stainless Steel[a]	6.22
1	UAl_x	Al-TiB_2[b]	6.55
1	Transition	Al-TiB_2	6.32
2	Transition	Al-TiB_2	6.38
3	Transition	Al-TiB_2	6.07
4	Transition	Al-TiB_2	6.10
5	Transition	Al-TiB_2	6.11
6	U_3Si_2	Al-TiB_2	6.38
7	U_3Si_2	Al-TiB_2	6.55

[a] 1.5 wt. % natural boron in stainless steel.

[b] TiB_2 dissolved in Al-6351 at a boron concentration of 1.0 wt. %. The ^{10}B enrichment is > 95%.

TABLE 5
FNR ^{235}U BURNUP IN DISCHARGED U_3Si_2 FUEL
CYCLE LENGTH = 25.0 FPD's

EOC	Final Fuel Shuffle	Macrocycle 6		Macrocycle 7	
		^{235}M, g	^{235}BU, %	^{235}M, g	^{235}BU, %
5	SFE78→S→SFE79→D	119.64	46.8	108.07	52.0
10	SFE77→S→SFE79→D	110.98	50.7	99.01	56.0
10	SFE76→S→SFE80→D	104.50	53.6	92.30	59.0
13	CFE46→S→CFE06→D	57.28	49.1	55.33	50.8
15	SFE30→S→SFE79→D	94.61	57.9	86.06	61.8
15	SFE50→S→SFE80→D	91.33	59.4	82.04	63.5
20	SFE20→S→SFE79→D	94.85	57.8	86.11	61.7
20	SFE60→S→SFE80→D	94.11	58.2	84.36	62.5
25	SFE40→S→SFE79→D	92.50	58.9	87.07	61.3
25	SFE70→S→SFE80→D	102.37	54.5	95.71	57.4
25	CFE48→S→CFE06→D	52.67	53.2	50.97	54.7

SFE = 18-plate Standard Fuel Element

CFE = 9-plate Control Fuel Element

S = To/From storage pool

D = Discharged fuel element

TABLE 6
PEAK POWER DENSITIES (W/cm^3) IN THE FNR
$UAl_X \rightarrow U_3Si_2$ TRANSITION CORES
(P = 2.0 MW)

Macro Cycle	Core	BOC-2	BOC-6	BOC-11	BOC-16	BOC-21	EOC-25
1	UAl_x	52.50	50.69	47.77	46.53	45.00	42.32
1	Transition	63.31	60.70	56.76	54.28	51.97	49.11
2	Transition	59.32	57.39	53.88	51.97	50.00	45.59
3	Transition	59.30	56.61	52.74	49.96	46.45	44.75
4	Transition	58.36	54.62	50.35	48.03	45.18	44.50
5	Transition	58.92	55.12	50.62	48.34	46.39	46.16
6	U_3Si_2	60.55	57.66	52.86	50.09	48.37	48.55
7	U_3Si_2	61.56	58.43	53.59	50.67	49.18	48.60

Note: The peak power density occurs in CFE28 except at EOC-25 where it shifts to either CFE26 or SFE36.

It is clear from the results presented in this section that more macrocycle calculations are needed to establish equilibrium core conditions. Some adjustment of the cycle length will be necessary to assure that at EOC there is sufficient excess reactivity to account for the reflector experiments and for a bias in the diffusion calculations. The worth of the experiments is about 0.4% dk/k. Based on BOC calculations of the FNR 349A core with the shim-safety rods elevated to the observed critical location, the bias in the diffusion calculations is estimated to be about 0.5% dk/k. Thus, a cycle length which gives an EOC excess reactivity of the order of 1.0 - 1.5% is needed.

Results from Thermal Hydraulic Calculations

Steady state thermal hydraulic calculations have been performed using the PLTEMP code[8,9] and power density distributions from the REBUS/DIF3D calculations discussed in the previous section. The primary purpose of these thermal hydraulic studies is to estimate the minimum margin to boiling throughout the UAl_X-to-U_3Si_2 transition. A requirement of the FNR technical specifications is that the maximum cladding temperature in the hot channel will not reach the boiling point of water at a depth of 5.5m (18 feet).

Results from these thermal hydraulic calculations are subject to a number of input uncertainties. Engineering hot channel factors have not been evaluated for the FNR. However, representative values, based on a statistical combination of uncertainties, have been obtained from Ref.'s 8 and 10. Values used in these analyses for F_q (heat flux), F_b (bulk water temperature rise), and F_h (heat transfer coefficient) are 1.25, 1.25, and 1.45, respectively. The coolant pressure drop across the FNR core also is unknown. The value of this pressure drop was adjusted to give an average core temperature rise of the coolant equal to 8°C to correspond to the value given in Ref. 11. This temperature rise corresponds to a pressure drop of about 5.5E-4 MPa (0.080 psi). Most of the remaining PLTEMP input parameters were calculated from the geometry and loading of the FNR fuel elements and from the REBUS results.

Figure 3 is a plot of the axial power density distribution for the U_3Si_2 control fuel element CFE28 at the BOC-2 of the first macrocycle. The plot is normalized by dividing the average value of the mesh-centered power densities on each axial plane of the fuel element by the fuel element average power density. Thus, the maximum value in this plot is the axial peaking factor. Note that the peak value lies somewhat below the bottom plane of the banked shim-safety rods which is below the core midplane. The total peaking factor is defined here as the ratio of the maximum power density in CFE28 divided by the average value in CFE28. Finally, the radial peaking factor is taken to be the ratio of the total peaking factor to the axial peaking factor.

Table 7 summarizes some of the results of the thermal hydraulic calculations. Note that for the silicide fuel, the minimum margin to boiling (Bergles-Rohsenow correlation for subcooled boiling) is either 1.15 or 1.25 depending on whether the peak power density is evaluated on the outer surface of the mesh cell or at the center of the mesh cell. The actual margin to boiling is probably somewhere between these two values. The margins tend to increase with burnup and are substantially larger for the UAl_x fuel. Figure 4 is a plot of the axial temperature distributions for the fuel meat, clad, and coolant corresponding to the CFE28 fuel plate having the peak power density at a core power of 2.0 MW. These temperature profiles were calculated using the Sieder-Tate heat transfer correlation.

Figure 3. U3Si2 CFE28 Axial Power Peaking Factor at BOC-2, MC-1

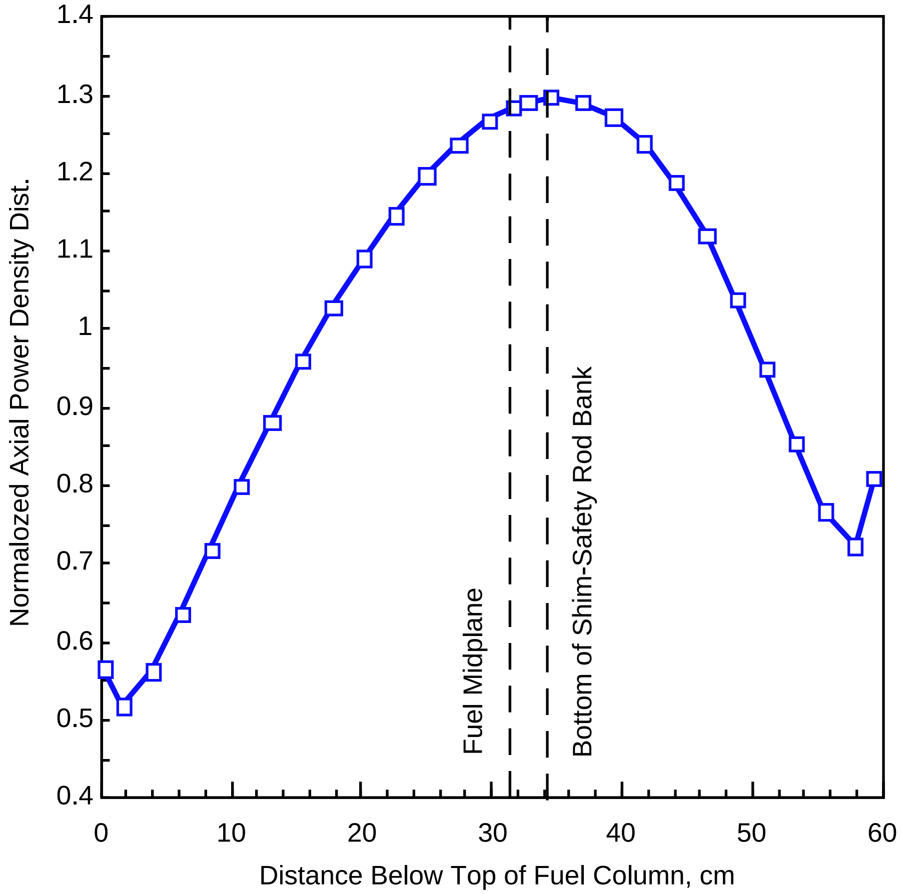
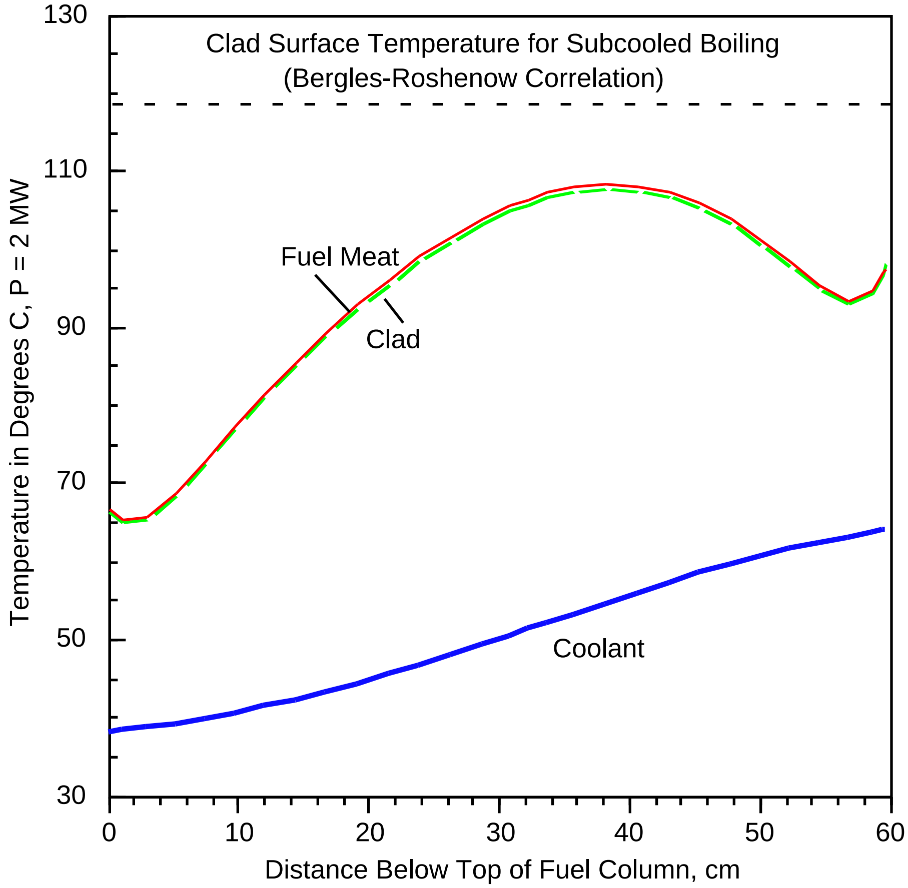


TABLE 7 SUMMARY OF THERMAL HYDRAULIC CALCULATIONS FOR THE FNR FUEL PLATE HAVING THE PEAK POWER DENSITY (BOC-2)						
Quantity	**CFE28 = UAl_x**		**CFE28 = U_3Si_2**		**CFE28 = U_3Si_2**	
Macrocycle	1		1		6	
Reactor Power, MW	2.0		2.0		2.0	
CFE28 Power, kW	49.45		58.16		54.32	
T_{inlet} (coolant), °C	38.0		38.0		38.0	
Outlet Pressue, MPa	0.165		0.165		0.165	
Axial Peaking Factor	1.296		1.296		1.302	
Mesh Cell:	**Surface**	**Center**	**Surface**	**Center**	**Surface**	**Center**
Peak PD, W/cm^3	52.50	48.22	63.31	58.77	60.55	55.37
Total Peaking Factor	1.565	1.437	1.604	1.489	1.643	1.502
Radial Peaking Factor	1.207	1.109	1.238	1.149	1.262	1.154
Press. Drop, E-4 MPa	5.5	5.5	5.5	5.5	5.5	5.5
T_{max} (fuel), °C	97.9	93.7	108.3	104.0	105.6	100.7
T_{max} (clad), °C	97.4	93.2	107.6	103.4	104.9	100.0
T_{max} (coolant), °C	59.7	58.0	64.1	62.3	62.9	60.8
Max. Heat Flux, MW/m^2	0.147	0.135	0.178	0.165	0.170	0.155
Margin to subcooled Boiling	1.40	1.55	1.15	1.25	1.20	1.30

Figure 4. CFE28 Hot Plate Temperatures at BOC-2 of MC-1



Conclusions

There is a significant economic advantage to extending the lifetime of LEU fuel elements by increasing the fuel loading. By increasing the ^{235}U fuel plate content from 9.3 g to 12.5 g in the University of Michigan's Ford Nuclear Reactor, the annual cost reduction is of the order of $300,000. With fewer elements consumed per year, most of this saving results from lower annual fuel fabrication and spent fuel disposal costs.

A fuel element shuffling scheme, approximating the way the FNR operates, has been used to determine power peaking effects, total shim-safety rod worths, shut-down margins, neutron fluxes, and excess reactivities during the transition from the UAl_x fuel now in use to U_3Si_2 fuel with a ^{235}U plate loading of 12.5 g. The largest power density occurs in the regulating rod fuel element at the beginning of the transition and is obtained by extrapolating mesh-centered power densities to the surface of the cell. The minimum margin to boiling corresponding to this extreme power density is 1.15.

By the time the transition reaches an all-silicide core, thermal neutron fluxes at experiment positions in the light water reflector will have been reduced by 4-6% relative to the initial aluminide core. However, fluxes in the heavy water reflector on the north face of the core will have increased by 5-6%. At this point in the transition, shim-safety rod worths will have increased a small amount relative to the initial all-aluminide case. This increase is a direct result of using Al-TiB_2 (>95% ^{10}B) shim-safety rods in the transition cores in place of the original borated stainless rods.

Neutronic calculations have not, as yet, established the characteristics of the equilibrium silicide core. Each depletion calculation (i.e. one macrocycle) corresponds to 24 successive burn cycles during which time 9 standard and 2 control rod fresh fuel elements are cycled into the core and an equal number of spent elements removed. During the fifth macrocycle the last of the aluminide fuel is discharged. Results from the end of the 7th macrocycle show that equilibrium conditions have not been reached and that a 25-day cycle length is too long to provide sufficient end-of-cycle excess reactivity to account for experiments and for calculational biases.

Nevertheless, the results to date clearly indicate the benefits of using more heavily loaded U_3Si_2 LEU fuel in the FNR. Power peaking effects, though certainly larger than in the initial aluminide core, do not result in boiling and so satisfy the FNR technical specifications. The behavior of the calculations through seven macrocycles suggests that an acceptable cycle length for the equilibrium core will fall in the range of 23-24 full power days.

We plan to continue this study, focusing on several issues. Foremost will be the use of the "standard" U_3Si_2 plate for the FNR conversion. A number of US research reactors are using this standard plate design. Preliminary calculations show that the thinner clad will somewhat increase the peak power density, but the thicker water channel leaves the margin to boiling essentially unchanged. Cladding corrosion rates depend mostly on water quality (desired pH < 6.5), temperature, and time-integrated heat flux. Research reactor experience shows that for a 0.0381-cm clad, the probability of radioactivity release from corrosion is very remote in the 2-MW FNR provided good water quality is maintained at all times.

Methods for increasing the minimum margin to boiling, i.e., minimizing the peak power density, will be explored. For example, changing the fuel shuffling scheme so that fresh fuel is not placed at the position of the regulating rod increases the minimum margin to boiling from 1.15 to 1.25.

As mentioned previously, cycle lengths need to be adjusted to reduce EOC reactivities. Even then, during the early phases of the transition BOC excess reactivities may need to be reduced so as not to violate FNR technical specifications. This reduction could be achieved by changing the fuel element shuffling scheme so that only one fresh silicide element, rather than two, is added at BOC. Once an inventory of partially burned silicide fuel is obtained, a fuel element shuffling scheme like that shown in Table 1 could be used.

REFERENCES

1. "Draft Environmental Impact Statement on a Proposed Nuclear Weapons Nonproliferation Policy Concerning Foreign Research Reactor Spent Fuel," U.S. Department of Energy, DOE/EIS-0218D, March 1995.

2. K. R. Brown and J. E. Matos, "Conversion and Standardization of US University Reactor Fuels Using LEU - Status 1989,"XII International RERTR Meeting, Berlin, Germany, pp. 193 - 202, September 10-14, 1989.

3. J. R. Deen, W. L. Woodruff, and C. I. Costescu, "WIMS-D4M User Manual," ANL/RERTR/TM-23, July 1995.

4. R. Bloomquist, "VIM - A Continuous Energy Neutronics and Photon Transport Code," ANS Proceedings of the Topical Meeting on Advances in Reactor Computations, Salt Lake City, Utah, pp. 222-224, March 1983.

5. R. E. Alcouffe, F. W. Brinkley, D. R. Marr, and R. D. O'Dell, "User's Guide for TWODANT," LA-10049-M, Rev. February 1990.

6. B. J. Toppel, "A User's Guide for the REBUS-3 Fuel Cycle Analysis Capability," ANL-83-2, March 1983.

7. K. L. Derstine, "DIF3D": A Code to Solve One-, Two-, and Three-Dimensional Finite-Difference Diffusion Theory Problems," Argonne National Laboratory Report ANL-83-2 (March 1983).

8. K. Mishima, K. Kanda, and T. Shibata, "Thermal-Hydraulic Analysis for Core Conversion to the Use of Low-enriched Uranium Fuels in the KUR," KURRI-TR-258, December 1984.

9. S. Smith, Argonne National Laboratory, Unpublished Information, 1985.

10. W. L. Woodruff, "Evaluation and Selection of Hot Channel (Peaking) Factors for Research Reactor Applications, X International RERTR Meeting, Buenos Aires, Argentina, September 18 - October 2, 1987.

11. R. R. Burn, Editor, "Research, Training, Test, and Production Reactor Directory", American Nuclear Society, Third Edition, 1988.