Evaluation of the Use of Metal Alloy
Fuels In Pressurized Water Reactors
Progress Report
for the Period of
September 1989 through November 1990

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I. Summary

In the second quarter the project concentrated on model development. Three separate modeling programs were attacked. The reactor physics modeling involved establishing accurate models with PC versions of COMBINE and VENTURE. The thermal/hydraulics modeling included ordering a workstation version of RELAP5/MOD3. The fuel performance analysis will start with METAL-LIFE.

On February 27, 1990, Dr. Peter Lang came to Atlanta for a project review. Several issues were raised at that meeting. First, in order to justify a change of fuel to the metal alloy large benefits will have to be found. The cost benefits shown in the first quarterly report are not sufficient. Thus the emphasis should be on finding a large safety benefit. Second, the metal-water reaction needs more attention. In order to address this an experiment was added to next year's proposal. Third, the selection of a pin design should be solidified. It has been decided that the fuel pin will be annular and contacting the clad. The clad thickness will be that which will force the fuel to grow toward the central hole. Dr. Lang suggested a sphere pack concept which is the backup position.

Minor modifications and improvements to the design have been made and are addressed below.

II. Design Improvements (Misko and Lancaster)

Upon review of the swelling data it was found that there is not a clear choice on the amount of radial space to leave for swelling. The work on optimizing the pin diameter was redone using 20% and 30% radial expansion. In redoing the analysis the process was automated to the point that most changes can be fully reviewed with only about a days effort. During the automation two small changes from the original Marsh work were made. The first was to incorporate the reduction of the uranium density due to the alloying. The second change was in the handling of inflation in the economics. For these results no inflation was assumed. (Previous results used inflation adjusted interest rates but not prices.) The new results are shown on Tables 1 and 2 and Figures 1 and 2. Since it was found that there was no cost penalty due to a higher swell volume, it was decided to select the 30% radial swell volume. Further, the pin diameter of 7.1 mm (.28 inches) is the new reference. This pin diameter is the minimum cost diameter under a reasonable assumption for fabrication costs. The other advantage of this pin diameter is its similarity to AP600 in core volume, height, pressure drop, and number of feed batches.

III. Neutronic Model Development (Malo and Lancaster)

The reactor physics computer codes that are being used for the core calculations are being tested. The two codes being used are a microscopic cross-section generation code, COMBINE, and a finite difference diffusion theory code, VENTURE. Detailed data has been obtained for a Westinghouse design from the Philippines reactor which is being used to check neutronic results. For this plant, the materials used in the core, the assembly description, and the assembly loading pattern are completely described. The fuel pins for the different enrichments have been modelled in COMBINE and microscopic cross-sections for all of the materials in the pin have been determined. The burnable absorbers and water slots in the core have also been modelled and COMBINE cross-sections have been acquired for them. These cross-sections were then used in the VENTURE code to complete the core geometry.

The first parameter to check is the multiplication factor for the core at hot zero power, all control rods out, and no burnup, since this is the easiest case to model. Currently, the multiplication factor is in error by approximately 0.5%. However, the power distribution for the assemblies are severely different, 10% errors, from those calculated by Westinghouse. Many computer runs have been tried to attempt

to identify this problem including improving the burnable absorber modeling and baffle modeling. These changes did little to rectify the problem. Cross sections from other sources are being used to determine whether the problem is from COMBINE or VENTURE.

Since burn-up calculations are eventually going to be needed soon, generation of a lumped fission product, using the COMBINE code, has been completed. This pseudo-element includes all fission products except Xenon, Samarium, and the elements in their decay chain. The microscopic cross-sections were obtained by using the yield percentage for each element as the weighting factor (the weighted atom density of that element). Most of the actual fission products have very short half-lives and decay almost instantly so the first long-lived isotope was used as the fission product. A total of 50 fission product cross-sections were calculated and lumped into one (excluding the Xenon and Samarium chains). Cross-sections were also generated for the Uranium and Plutonium series. All of these cross-sections were then used in a burn-up calculation which demonstrated that the method is correct.

Although not all of the oxide fuel modelling problems have been solved, some calculations have been performed for the metal-fueled pin using the COMBINE code. There is a reactivity effect that depends on the pin pitch and

diameter. This effect was analyzed and the results are shown on Table 3. A smaller pin has a lower U-238 self-shielding factors and hence has more resonance captures which is a loss of reactivity. This reactivity loss requires a higher enrichment in the smaller pin diameters. These effects will be used in selecting the most economical pin diameter. Confirmation of the batch effect is not possible until the power distribution problem is solved.

IV. Modifications to COBRA Thermal-Hydraulics Computer Code (Pfeifer and Levin)

This task was described in the previous progress report. The COBRA code must be able to perform calculations for annular, as well as solid cylindrical, fuel. Work is progressing satisfactorily on this task.

V. Development of Reactor Kinetics Model (Ridha and Levin)

A point reactor kinetics code to use in conjunction with the COBRA code was developed, in order to predict the response of the metal-fueled core to a range of transients. COBRA does not have any neutronics modeling capability; therefore, the reactor power must be supplied as an input to the code. For transient calculations, this means that a separate reactor kinetics model must be used to calculate neutron flux as a function of time, since reactivity feedbacks during a transient will affect the neutron flux. The code appears to give good response to step reactivity changes but

would require more verification for cases where reactivity changes as a function of time.

VI. RELAP Computer Code (Pfeifer and Levin)

It has been decided to use the RELAP computer code to perform transient calculations in which system effects are important. RELAP models not only the reactor, but other key components in the primary and secondary systems (e.g., pressurizer, steam generators). RELAP also has neutronics calculational capability. A version of RELAP is currently available at Georgia Tech; however, attempts to run it on the university's computer system have proved unsuccessful. A new copy of RELAP5/MOD3 has been ordered from EG&G Idaho, configured for operation on a Sun computer (UNIX based). It is anticipated that this version of the code should be compatible with computers owned by the Nuclear Engineering Program. Delivery of this version of RELAP is expected shortly, at which time work will commence on more complex thermal-hydraulic analyses.

VII. Fuel Performance (Choi and Schneider)

The literature was reviewed for the kinetics of the reaction of U-Zr and water. The reaction rates reported show considerable variability and some experimental determinations were recommended for the second phase of this Project. The reaction rate decreases moderately by raising

the Zr content up to 10 wt% but a much more significant improvement was reported for alloys containing more than 15 wt% Zr (Table 4).

The possibility of using a Na bond was examined. While the energy generated by the Na-H₂O did not appear excessive by comparison with fission power rates, the production of hydrogen and the subsequent reaction with the Zr clad would lead to disintegration of the latter. Other liquid metals (Pb, Zn, Sn, and Bi) were examined as potential bonding agents but were found unacceptable because of the solubility of U in the liquid metals. The use of liquid metal bonding will not be considered further.

Contact was established with Hanford N-Reactor fuel specialists to obtain information on co-extruded Zircaloy and U-Zr alloys. A set of pertinent information was promised.

The following fuel concepts have been studied: co-extruded Zircaloy with an annular U-10Zr rod and a Zircaloy can filled with small spheres of U-10Zr alloy and pressurized with He.

A thorough review of the theories and experimental results for the irradiation growth of metallic fuels has been started. In addition, calculational techniques are being

developed to estimate the expansional forces resulting from fuel growth and the mechanical properties of Zircaloy.

The search for a suitable fuel performance code has been narrowed to the LIFE-METAL code which has given good results with EBRII/IFR fuel. This code, being primarily for liquid metal-cooled reactors, will require modifications to be of use in our Project.

Figure 1
Total Cost vs Rod O.D. 30% Swelling

Figure 2
Total Cost vs Rod O.D. 20% Swelling

Table 1
Geometric and Cost Parameters to Changes in Fuel Pin Diameter for 30% Radial Expansion

pin dia (mm)	AP-600							
	9.1	9.1	7.6	7.1	6.4	5.7	5.1	4.4
Geometric Data								
Core Volume (liters)	24500	49807.3	31873.3	26415.11	19010.83	13450.95	9212.77	5555.049
Delta Pressure (kPa)	11.39	6.7449	8.1797	9.3081	12.3986	17.9642	28.8028	57.5184
Number of fuel pins	38280	48325	53719	55342	57449	58125	59482	59203
Length (m)	3.66	4.63	3.99	3.75	3.36	2.99	2.64	2.23
Core Height/Diameter	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
DNBR from Cobra	2.936	2.936	2.938	2.937	2.936	1.936	2.936	2.936
Power W/(gram-u)	28.94	10.3347	16.463	20.0287	28.2966	40.7099	60.8621	104.4979
MTU Core Total	61.02	170.77	107.20	88.12	62.37	43.35	29.00	16.89
Cycle Burnup (MWD/MTU)	12027	4297	6845	8328	11766	16928	25307	43451
No. Batches Per Core	3.742	10.472	6.574	5.403	3.825	2.658	1.778	1.036
Initial Enrichment (%)	2.347	1.762	1.938	2.048	2.325	2.794	3.697	6.245
No. of Rods Refueled	10231	4615	8172	10242	15021	21865	33452	57165
Refuel Enrichment (%)	4.168	3.739	3.880	3.963	4.154	4.440	4.906	5.914
Linear Power (kW/m)	12.6	7.9	8.1	8.5	9.2	10.2	11.3	13.4
Pitch (mm)	12.6	14.2	11.6	10.8	9.5	8.4	7.3	6.2
Pin P/D	1.378	1.554	1.525	1.512	1.489	1.466	1.437	1.399
Cost Data Cost Data								
Initial Core Costs								
Fab. Minimum (\$)	1.30E+07	4.12E+06	2.95E+06	2.56E+06	1.99E+06	1.52E+06	1.15E+06	7.80E+05
Fab. Median (\$)	1.30E+07	8.96E+06	8.32E+06	8.09E+06	7.74E+06	7.34E+06	7.09E+06	6.70E+06
Fab. Maximum (\$)	1.30E+07	1.64E+07	1.83E+07	1.88E+07	1.95E+07	1.98E+07	2.02E+07	2.01E+07
Enrichment (\$)	9.66E+06	1.60E+07	1.21E+07	1.10E+07	9.71E+06	9.11E+06	9.25E+06	1.08E+07
Ore (\$)	1.74E+07	3.54E+07	2.48E+07	2.16E+07	1.76E+07	1.49E+07	1.35E+07	1.36E+07
Refueling Costs (Levelized)								
Fab. Minimum (\$)	3.48E+06	3.94E+05	4.48E+05	4.73E+05	5.20E+05	5.73E+05	6.45E+05	7.53E+05
Fab. Median (\$)	3.48E+06	8.55E+05	1.27E+06	1.50E+06	2.02E+06	2.76E+06	3.99E+06	6.47E+06
Fab. Maximum (\$)	3.48E+06	1.57E+06	2.78E+06	3.48E+06	5.11E+06	7.43E+06	1.14E+07	1.94E+07
Enrichment (\$)	9.32E+07	8.00E+07	8.44E+07	8.69E+07	9.27E+07	1.02E+08	1.16E+08	1.48E+08
Ore (\$)	9.28E+07	8.28E+07	8.61E+07	8.80E+07	9.25E+07	9.92E+07	1.10E+08	1.34E+08
Contain. & Vessel (\$)	1.00E+07	2.03E+07	1.30E+07	1.08E+07	7.77E+06	5.49E+06	3.76E+06	2.27E+06
Pump Capital (\$)	1.55E+05	9.20E+04	1.12E+05	1.27E+05	1.69E+05	2.45E+05	3.93E+05	7.84E+05
Pump Operating (\$)	4.47E+06	2.65E+06	3.21E+06	3.65E+06	4.86E+06	7.05E+06	1.13E+07	2.26E+07
Total Costs								
Max Total (\$)	2.83E+08	2.68E+08	2.74E+08	2.84E+08	3.12E+08	3.60E+08	4.47E+08	6.35E+08
Mid Total (\$)	2.83E+08	2.55E+08	2.50E+08	2.53E+08	2.67E+08	2.95E+08	3.48E+08	4.68E+08
Min Total (\$)	2.83E+08	2.37E+08	2.23E+08	2.21E+08	2.24E+08	2.36E+08	2.61E+08	3.27E+08

Table 2
Geometric and Cost Parameters to Changes in Fuel Pin Diameter for 20% Radial Expansion

AP-600						
pin dia (mm)	9.1	9.1	7.6	6.4	5.7	5.1
Geometric Data						
Core Volume (liters)	24500	56185.98	36500.83	22098.54	15998.78	10763.43
Delta Pressure (kPA)	11.39	6.4797	7.4526	10.4755	14.3447	22.7616
Number of fuel pins	38280	49579	55725	60269	61974	62742
Length (m)	3.66	4.82	4.17	3.53	3.17	2.78
Core Height/Diameter	1.25	1.25	1.25	1.25	1.25	1.25
DNBR from Coburn	2.936	2.936	2.934	2.935	2.935	2.936
Power W/(gram-U)	28.94	9.6767	15.1691	25.653	36.0364	54.7837
MTU Core Total	61.02	182.39	116.35	68.80	48.98	32.22
Cycle Burnup (MWD/MTU)	12027	4024	6307	10667	14984	22780
No. Batches Per Core	3.742	11.184	7.134	4.219	3.003	1.975
Initial Enrichment (%)	2.347	1.744	1.900	2.233	2.610	3.406
No. of Rods Refueled	10231	4433	7811	14286	20656	31761
Refuel Enrichment (%)	4.168	3.724	3.850	4.093	4.332	4.766
Linear Power (kW/m)	12.6	7.4	7.6	8.3	9.0	10.1
Pitch (mm)	12.6	14.6	11.9	9.7	8.6	7.5
Pin P/D	1.378	1.598	1.566	1.529	1.504	1.474
Cost Data						
Initial Core Costs						
Fab. Minimum (\$)	1.30E+07	4.40E+06	3.20E+06	2.20E+06	1.72E+06	1.27E+06
Fab. Median (\$)	1.30E+07	9.36E+06	8.77E+06	8.22E+06	7.92E+06	7.55E+06
Fab. Maximum (\$)	1.30E+07	1.69E+07	1.89E+07	2.05E+07	2.11E+07	2.13E+07
Enrichment (\$)	9.66E+06	1.68E+07	1.26E+07	1.00E+07	9.23E+06	9.13E+06
Ore (\$)	1.74E+07	3.74E+07	2.63E+07	1.86E+07	1.57E+07	1.37E+07
Refueling Costs (Levelized)						
Fab. Minimum (\$)	3.48E+06	3.94E+05	4.48E+05	5.20E+05	5.73E+05	6.45E+05
Fab. Median (\$)	3.48E+06	8.37E+05	1.23E+06	1.95E+06	2.64E+06	3.82E+06
Fab. Maximum (\$)	3.48E+06	1.51E+06	2.66E+06	4.86E+06	7.02E+06	1.08E+07
Enrichment (\$)	9.32E+07	7.96E+07	8.34E+07	9.09E+07	9.82E+07	1.12E+08
Ore (\$)	9.28E+07	8.24E+07	8.54E+07	9.11E+07	9.67E+07	1.07E+08
Contain. & Vessel (\$)	1.00E+07	2.30E+07	1.49E+07	9.03E+06	6.54E+06	4.40E+06
Pump Capital (\$)	1.55E+05	8.84E+04	1.02E+05	1.43E+05	1.96E+05	3.10E+05
Pump Operating (\$)	4.47E+06	2.54E+06	2.92E+06	4.11E+06	5.63E+06	8.93E+06
Total Costs						
Max Total (\$)	2.83E+08	2.72E+08	2.75E+08	3.08E+08	3.50E+08	4.30E+08
Mid Total (\$)	2.83E+08	2.60E+08	2.52E+08	2.65E+08	2.38E+08	3.36E+08
Min Total (\$)	2.83E+08	2.42E+08	2.25E+08	2.23E+08	2.31E+08	2.53E+08

Table 3:
Effect of Pin Diameter on Enrichment
due to Heterogeneity

	<u>ROD O.D. (mm)</u>	<u>ENRICHMENT*</u>	<u>COST (MILLION\$)</u>	
(AP 600)	9.1	3.00%	-	
	9.1	2.72%	17.6	SAVING
	7.6	2.87%	6.7	SAVING
	6.4	3.04%	1.5	EXPENSE
	5.7	3.17%	2.7	EXPENSE
	5.1	3.33%	13.1	EXPENSE
	4.4	3.55%	22.2	EXPENSE

* The enrichment to yield the same k_{inf} as the reference core, AP600.

TABLE 4
CORROSION RATES OF U AND U-Zr
ALLOYS BY PRESSURIZED WATER

<u>Zr(wt%)</u>	<u>Ave Temp. (°F)</u>	<u>Ave. Rate (mg/cm²-hr)</u>
0	582	4,910
	600	5,330
	603	3,190
	605	3,800
	610	4,850
5	600	4,860
	612	6,300
10	570	2,330
	590	13,000(?)
15	604	165
20	610	194

All tests were with unbonded pins with defective Zircaloy claddings.
Reference: BMI-1156

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