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THE DESIGN AND ECONOMICS OF LARGE LMFBR'S

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INTRODUCTION

The design of an LMFBR core is a complex process which is strongly dependent upon design philosophy, design criteria, material properties, and the calculational procedure involved. The development of a core design with optimum characteristics, whether it be a minimum doubling time, a minimum power cost, or a minimum sodium void worth, requires a close coupling of the disciplines of reactor physics, thermohydraulics, mechanical design, and fuel pin performance. This is true regardless of whether the fuel is oxide, carbide, nitride, or metal, and regardless of whether the fuel cycle is Pu/U or U-233/Th.

DESIGN PROCEDURE

The multidiscipline approach requires an iterative design procedure to obtain a closely-coupled design. The philosophy used at HEDL requires that the designs should be coupled to the extent that the life of the design limiting fuel pin, the life of the design limiting duct, and the reactivity life of the core times the number of batches in the core, should all be equal. The methodology by which this is accomplished was presented in a previous paper,(1) however, it will be reviewed here for the sake of completeness. The logical flow of the design procedure is illustrated in Fig. 1. The procedure consists of an iterative loop comprising three stages. Stage 1 consists of general mechanical design and reactor physics scoping calculations to arrive at

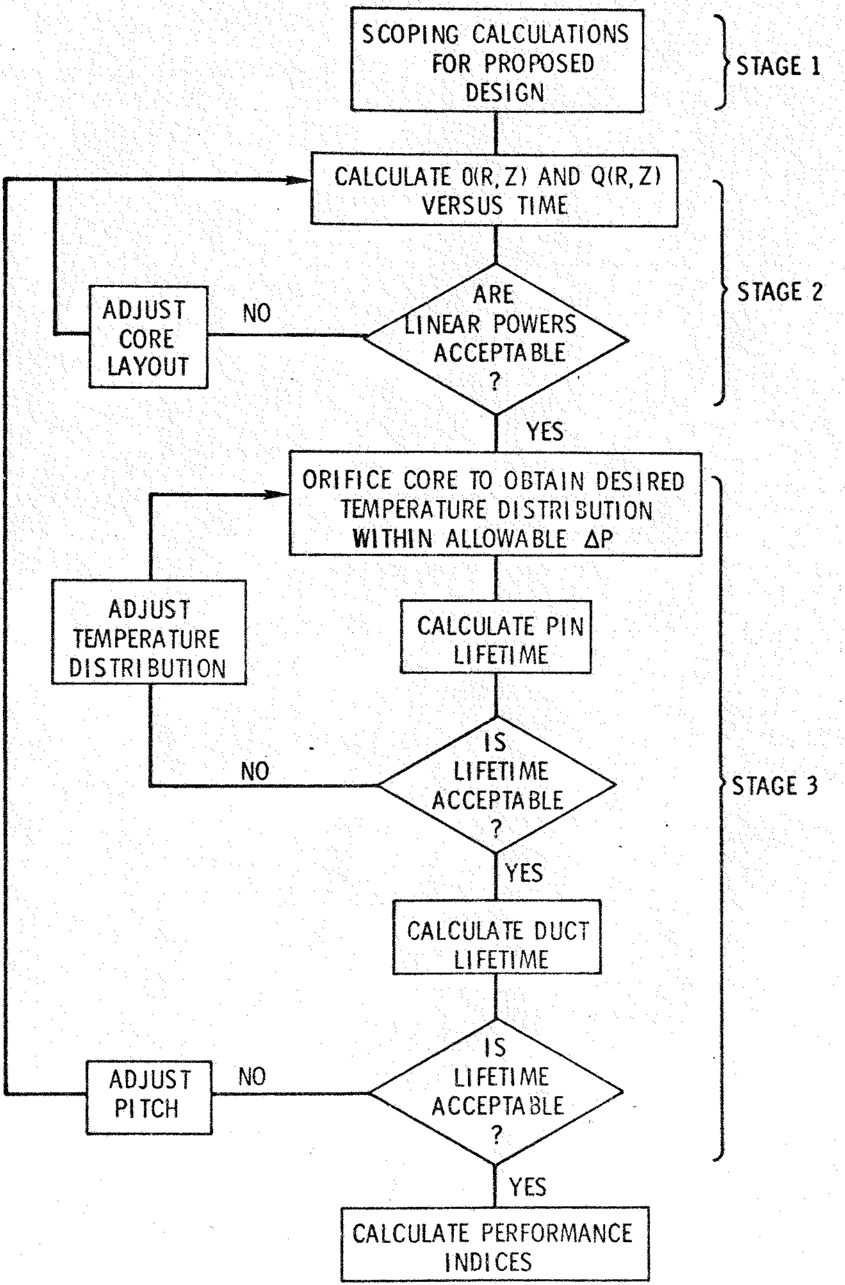

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Fig. 1. Calculational Flow for the HEDL Design Procedure

an initial core layout. Stage 2 consists of detailed reactor physics calculations for the core configuration developed in Stage 1. Based upon the detailed reactor physics results, a decision is made either to alter the design and return to Stage 1 or proceed to Stage 3. Stage 3 consists of thermohydraulic and detailed mechanical design calculations. At this point, an assessment is made regarding design adequacy. If the design is inadequate, the entire procedure is repeated until the design is acceptable.

The detailed reactor physics calculations in Stage 2 are performed using a two-dimensional multigroup diffusion code with an isotope depletion module.(2) The calculational procedure which is utilized in the reactor physics analysis is illustrated in Fig. 2. The goal of this analysis is to provide the flux and linear power as a function of position for use in the thermohydraulic, fuel pin lifetime, and duct lifetime calculations. The procedure, as illustrated in Fig. 2, consists of adjusting the core layout and subassembly design to meet the following design criteria:

- the enrichment will be sufficient to maintain criticality during the entire equilibrium cycle with no excess reactivity at the end of the equilibrium cycle ($k_{eec} = 1.000$)
- the linear power of the fuel and blanket pin must be within acceptable limits during the equilibrium cycle
- the power distribution shall be reasonably flattened during the equilibrium cycle
- the above criteria shall be met with the minimum number of subassemblies in order to minimize the fuel cycle cost.

The next step of the design procedure is to orifice the core using a full-core thermohydraulic analysis. This is accomplished with the multichannel

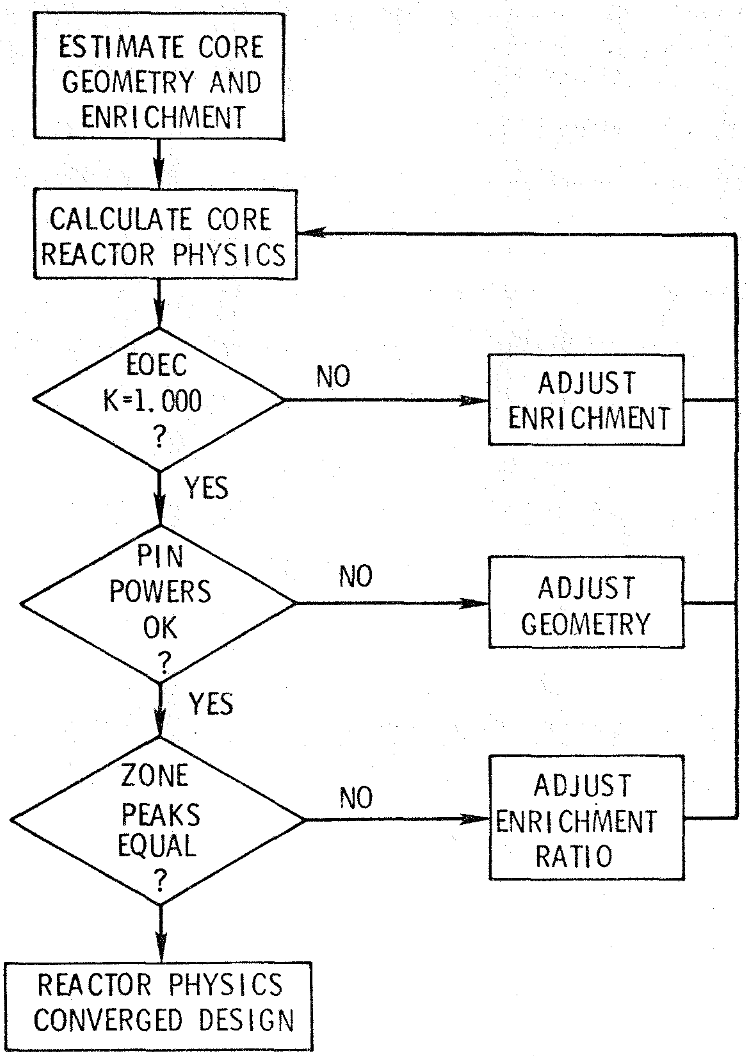

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Fig. 2. Calculational Flow for the HEDL Reactor Physics Analysis

thermohydraulic code ORIFIS. This code distributes a specified coolant flow to obtain a desired subassembly outlet temperature distribution across the core. The design procedure, as illustrated in Fig. 3, is usually to develop a mixed mean subassembly outlet temperature distribution such that the life of the design limiting fuel pin in each orifice zone is equal. This is obtained by iterating between the ORIFIS code and the fuel pin lifetime code.

The fuel pin lifetime is calculated using the computer code SIFAIL, which is based on the SIEX(3) fuel pin model, and is illustrated in Fig. 4. The code calculates the fuel and cladding temperature, the gas release rate, the cladding stress due to gas pressure loading, and the cladding dimensional change due to wastage, irradiation swelling, thermal creep, and irradiation creep. SIFAIL also calculates the cladding Cumulative Damage Fraction (CDF) based on stress rupture properties. The CDF is generally used as the fuel pin life limiting parameter.

Figure 5 schematically illustrates the deflection model used in the code DEFLECT to calculate duct lifetime. The model is based on the method developed by Wire and Straalsund(4) for calculating an inelastic deflection from an elastic stress analysis.

The computer code POROSTY is used to calculate bundle/duct interaction across the flats. The flux and temperature for the pin and duct are held constant at the worst case conditions and no credit is taken for duct dilation due to irradiation creep. Credit is taken, however, for duct dilation due to irradiation swelling.

DESIGN CRITERIA AND MATERIAL PROPERTIES

The characteristics of the designs which emerge from this design procedure are strongly dependent upon the material correlations employed and upon the

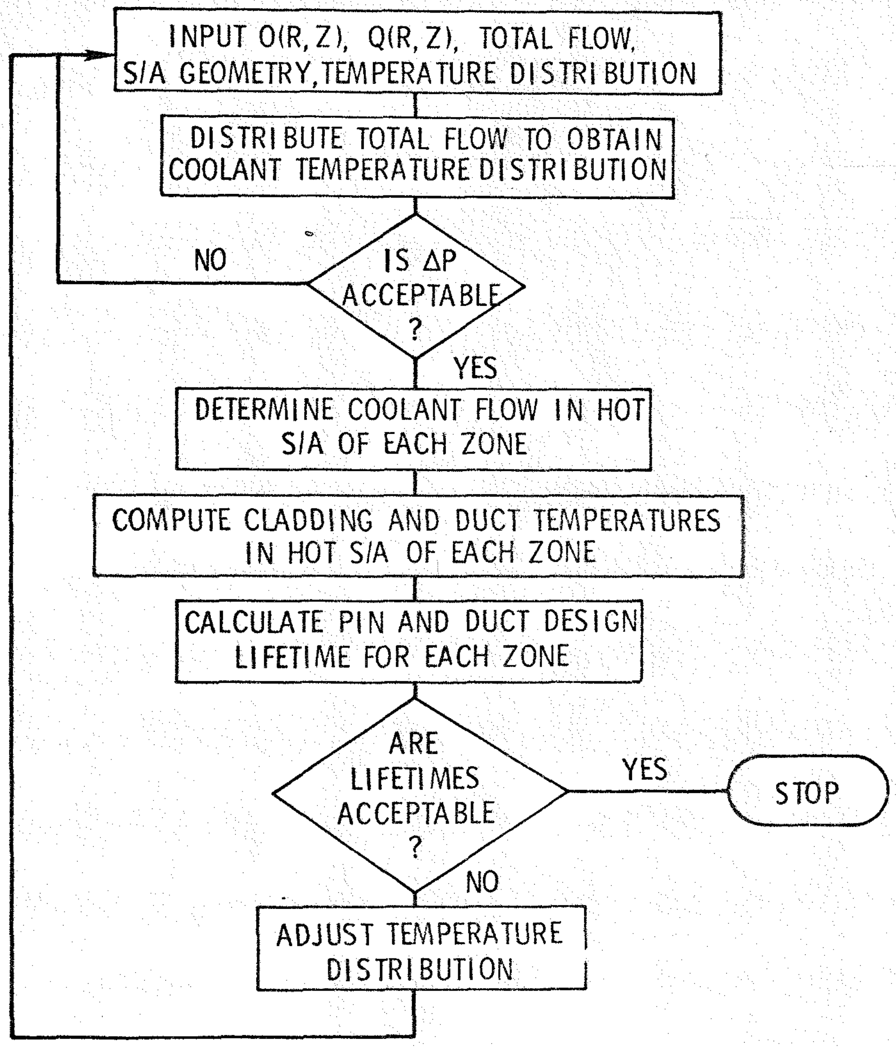

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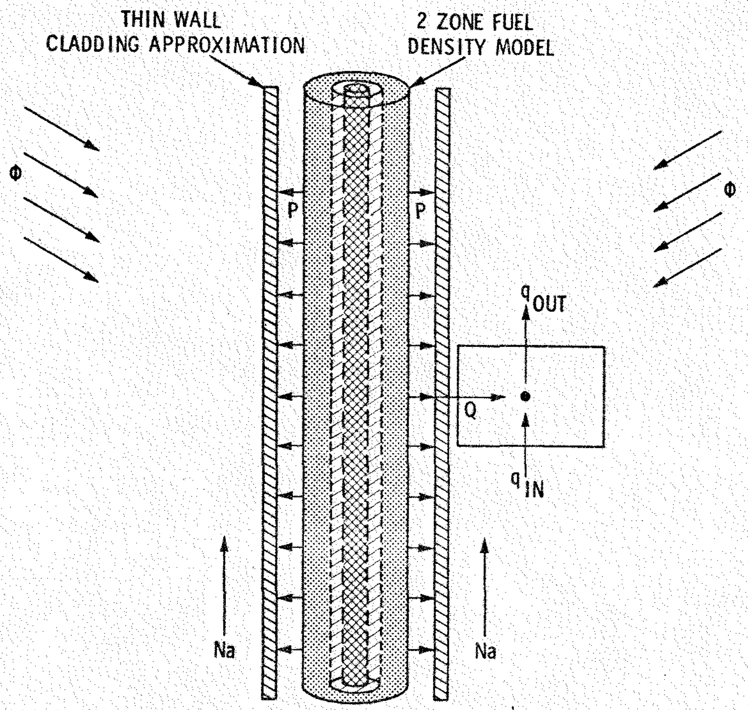
Fig. 3. Calculational Flow for HEDL Core Orificing Analysis



INPUT: LINEAR POWER DENSITY, COOLANT FLOW RATE, NEUTRON FLUX

CALCULATE:
- TEMPERATURE OF SODIUM, CLAD, AND FUEL
- GAS RELEASE RATE
- CLADDING STRESS DUE TO GAS PRESSURE LOADING
- CLADDING IRRADIATION SWELLING, IRRADIATION CREEP, AND THERMAL CREEP

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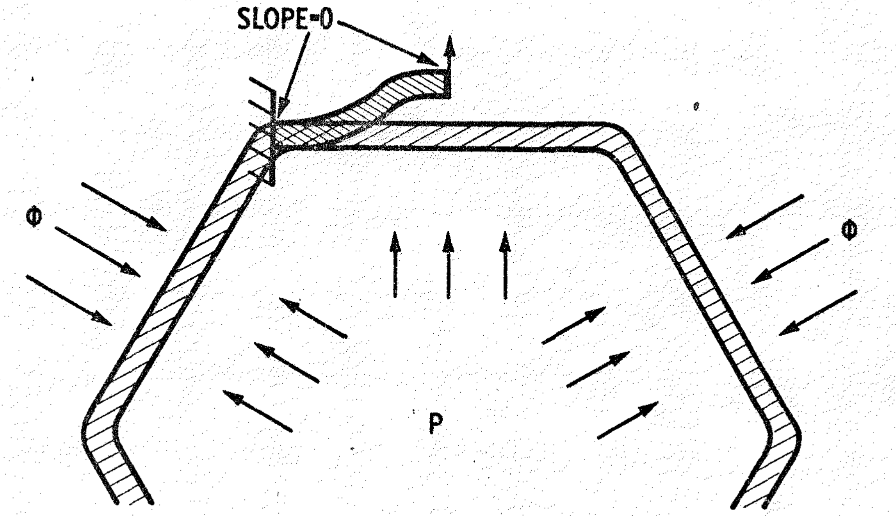
Fig. 4. The Fuel Pin Lifetime Model SIFAIL



INPUT: COOLANT PRESSURE, DUCT WALL TEMPERATURE, NEUTRON FLUX

CALCULATE: STRESS, IRRADIATION SWELLING, IRRADIATION CREEP, DEFLECTION

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Fig. 5. The Duct Lifetime Model DEFLECT

design criteria. Generally, HEDL uses nominal values of the latest NSMH* material property correlations. As these equations change, so do the characteristics of the designs. Changes in design criteria have a similar effect. Currently, HEDL utilizes criteria specific to: (1) peak linear power of the fuel pin, (2) the life of the fuel pin, (3) the life of the duct, and (4) the amount of duct/bundle interaction. Conservatism is introduced into the design by using hot channel uncertainty factors. The maximum fuel pin linear power is calculated using direct plus statistical hot channel factors at the 3σ uncertainty level. The maximum allowable fuel pin linear power is specified to avoid incipient melting under a 15% overpower condition. The fuel pin performance is calculated using cladding and plenum temperatures based on direct plus statistical hot channel factors at the 2σ level. The design limiting parameter currently employed for oxide fuel pins is the CDF; the limiting value of the CDF for steady state design is usually taken to be 0.5. The fuel pin cladding strain is limited only by bundle/duct interaction. The allowable extent of interaction is specified to prevent the fuel pins from contacting the duct wall with operating temperatures calculated using direct hot channel factors. The duct lifetime is limited by contact of adjacent ducts due to irradiation swelling and creep dilation. The duct dilation is calculated using temperatures based on direct plus statistical hot channel factors at the 2σ level.

ADVANCED CORE DESIGNS

The preliminary characteristics of six mixed oxide core designs developed using the design procedure described above are summarized in Tables I through

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*Nuclear Systems Material Handbook

VI. These particular designs were developed using 20% C.W. 316 stainless steel as the structural material. The first three designs--i.e., HEDL Small Pin, HEDL Large Pin, and HEDL Advanced Large Pin--are advanced designs which were developed to determine the maximum breeding ratio and minimum compound system doubling time(5,6) obtainable with mixed oxide fuel. The next three designs--i.e., HEDL Level I Homogeneous, HEDL Level II Homogeneous, and HEDL Level II Heterogeneous--were developed to determine the maximum breeding ratio, minimum compound system doubling time, minimum sodium void worth, and minimum fuel cycle cost which could be obtained using the CRBR fuel pin design.

The Small Pin design, shown in Table I, has a fuel pin 230 mils (5.84 mm) in outer diameter with a 10 mil (0.254 mm) cladding thickness. The pitch-to-diameter ratio is 1.19 and the active core length is 36 inches (91 cm). The core inlet temperature is 600 °F (589 °K), the core outlet temperature is 900 °F (755 °K), and the pressure drop across the pin bundle is 75 psi (517 kPa). The cross sectional geometry of the fuel pin in this design is identical to that of the P-40 test which was irradiated in EBR-II. It is noted that this particular test recently achieved a burnup of 128 MWD/kg, which is 45% higher than the discharge exposure for the Small Pin Design shown in Table I. The breeding ratio of this design is 1.37 and the compound system doubling time is 13.1 years. The fuel cycle cost is 5.0 mills/kwh.

The Large Pin design, shown in Table II, has a fuel pin 300 mils (7.62 mm) in outer diameter with a 13 mil (0.330 mm) cladding thickness. The thickness-to-diameter ratio of the cladding for this design is identical to that of the Small Pin design. The pitch-to-diameter ratio of the Large Pin design is 1.17 and the active core length is 36 inches (91 cm). The core inlet temperature is 600 °F (589 °K), the core outlet temperature is 900 °F (755 °K), and the

Table I
HEDL Small Pin Design

Plant Design	
Electrical Power (MWe)	800
Thermal Power (Mwt)	2500
Core Inlet Temperature (°F/°K)	600/589
Core Outlet Temperature (°F/°K)	900/755
Core Design	
Active Fuel Length (in/cm)	36/91
Plenum Length* (in/cm)	36/91
Pin Outer Diameter (mils/mm)	230/5.84
Cladding Thickness (mils/mm)	10/0.254
Fuel Pin P/D	1.19
Pins per Subassembly	271
Duct Wall Thickness (mils/mm)	87/2.21
Duct Spacing (mils/mm)	229/5.82
Duct Outside Flat-to-Flat (in/cm)	4.7854/12.15
Subassembly Pitch (in/cm)	5.0144/12.74
Bundle Pressure Drop (psi/kPa)	75/517
Volume Fractions in Active Core	
Fuel	0.41
Steel	0.17
Sodium	0.40
Control	0.02
Performance Parameters	
Average Linear Heat Rate (kW/ft/w/cm)	6.44/211
Peak Linear Heat Rate (kW/ft/w/cm)	10.0/328
Ave. Discharge Exposure (MWD/kg)	59.0
Peak Discharge Exposure (MWD/kg)	88.0
Peak Flux, E > 0.1 MeV (n/cm^2-sec)	4.1×10^{15}
Peak Fluence, E > 0.1 MeV (n/cm^2)	1.9×10^{23}
Fuel Residence Time (yrs) @ 72% CF	2.0
Average Core Enrichment (%)	16.6
Fissile Mass in Core (kg-BOEC)	2549
Core Conversion Ratio	0.9285
Breeding Ratio	1.37
Compound System Doubling Time** (yrs)	13.1
Fuel Cycle Cost (mills/kwh)	5.0

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* Bottom plenum

**Combined fabrication and reprocessing losses = 2%; out of reactor time = 1 yr.

Table II
HEDL Large Pin Design

Plant Design	
Electrical Power (MWe)	800
Thermal Power (Mwt)	2500
Core Inlet Temperature (°F/°K)	600/589
Core Outlet Temperature (°F/°K)	900/755
Core Design	
Active Fuel Length (in/cm)	36/91
Plenum Length* (in/cm)	36/91
Pin Outer Diameter (mils/mm)	300/7.62
Cladding Thickness (mils/mm)	13/0.330
Fuel Pin P/D	1.17
Pins per Subassembly	271
Duct Wall Thickness (mils/mm)	114/2.90
Duct Spacing (mils/mm)	302/7.67
Duct Outside Flat-to-Flat (in/cm)	6.1394/15.59
Subassembly Pitch (in/cm)	6.4414/16.36
Bundle Pressure Drop (psi/kPa)	75/517
Volume Fractions in Active Core	
Fuel	0.42
Steel	0.17
Sodium	0.39
Control	0.02
Performance Parameters	
Average Linear Heat Rate (kW/ft/w/cm)	11.3/371
Peak Linear Heat Rate (kW/ft/w/cm)	17.5/574
Ave. Discharge Exposure (MWD/kg)	61.0
Peak Discharge Exposure (MWD/kg)	90.0
Peak Flux, E > 0.1 MeV (n/cm^2-sec)	4.3×10^{15}
Peak Fluence, E > 0.1 MeV (n/cm^2)	2.0×10^{23}
Fuel Residence Time (yrs) @ 72% CF	2.0
Average Core Enrichment (%)	16.2
Fissile Mass in Core (kg-BOEC)	2420
Core Conversion Ratio	0.9411
Breeding Ratio	1.38
Compound System Doubling Time** (yrs)	12.2
Fuel Cycle Cost (mills/kwh)	3.5

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* Bottom plenum

**Combined fabrication and reprocessing losses = 2%; out-of-reactor time = 1 yr.

pressure drop across the pin bundle is 75 psi (517 kPa). The breeding ratio of the Large Pin design is 1.33 and the compound system doubling time is 12.2 years. The fuel cycle cost is 3.5 mills/kwh.

It is important to note that the breeding ratio and doubling time of the Small Pin and Large Pin designs are quite similar. Furthermore, this was achieved even though both designs have the same active core length, the same inlet and outlet temperatures, and the same pin bundle pressure drop. The similarity in the breeding ratio and doubling time was obtained by lowering the average linear heat rate in the Small Pin design, and consequently obtaining a fuel volume fraction identical to that of the Large Pin design. The high breeding ratio and short doubling time of the Small Pin design was not obtained without penalty, however. A design with a lower average linear heat rate requires more fuel pins to produce a given amount of power, and consequently such a design will have a higher fuel cycle cost. This is reflected in the fuel cycle cost for the Small Pin design--i.e., 5.0 mills/kwh--versus 3.5 mills/kwh for the Large Pin design.

The Large Pin and Advanced Large Pin designs are distinguished by the fuel pin lifetime criteria used. The Large Pin design was based on a CDF = 0.5, while the Advanced Large Pin design was based on a CDF = 1.0. Thus, the Advanced Large Pin design presumes that additional experimental data may show the design criteria of CDF = 0.5 to be unduly conservative. The breeding ratio for the Advanced Large Pin design is 1.42 and the compound system doubling time is 11.6 years. The fuel cycle cost is 2.2 mills/kwh. Note that an increase in the CDF of 100% produced only a 37% decrease in the fuel cycle cost and essentially no change in the breeding ratio and doubling time. This is because the measure of cumulative damage is increasing quite rapidly as the

Table III

HEDL Advanced Large Pin Design

Plant Design	
Electrical Power (MWe)	800
Thermal Power (Mwt)	2500
Core Inlet Temperature (°F/°K)	600/589
Core Outlet Temperature (°F/°K)	900/755
Core Design	
Active Fuel Length (in/cm)	36/91
Plenum Length* (in/cm)	36/91
Pin Outer Diameter (mils/mm)	300/7.62
Cladding Thickness (mils/mm)	13/0.330
Fuel Pin P/D	1.14
Pins per Subassembly	271
Duct Wall Thickness (mils/mm)	114/2.90
Duct Spacing (mils/mm)	346/8.79
Duct Outside Flat-to-Flat (in/cm)	5.9757/15.18
Subassembly Pitch (in/cm)	6.3217/16.06
Bundle Pressure Drop (psi/kPa)	75/517
Volume Fractions in Active Core	
Fuel	0.43
Steel	0.17
Sodium	0.37
Control	0.03
Performance Parameters	
Average Linear Heat Rate (kW/ft/w/cm)	9.0/295
Peak Linear Heat Rate (kW/ft/w/cm)	13.4/440
Ave. Discharge Exposure (MWD/kg)	69.0
Peak Discharge Exposure (MWD/kg)	98.0
Peak Flux, E > 0.1 MeV (n/cm^2-sec)	3.4×10^{15}
Peak Fluence, E > 0.1 MeV (n/cm^2)	2.3×10^{23}
Fuel Residence Time (yrs) @ 72% CF	3.0
Average Core Enrichment (%)	15.5
Fissile Mass in Core (kg-BOEC)	2906
Core Conversion Ratio	0.9863
Breeding Ratio	1.42
Compound System Doubling Time** (yrs)	11.6
Fuel Cycle Cost (mills/kwh)	2.2

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* Bottom plenum

**Combined fabrication and reprocessing losses = 2%; out-of-reactor time = 1 yr.

fuel pin approaches its end of life; consequently, a doubling of the design limiting value does not produce a corresponding change in the performance of the reactor.

The Level I Homogeneous, Level II Homogeneous, and Level II Heterogeneous designs are shown in Tables IV, V, and VI, respectively. These designs were developed with a methodology which tightly constrained the choice of design variables. The principal constraints applied to the Level I design were:

- fuel pin identical to CRBR
- fuel assembly identical to CRBR
- fuel operating conditions identical to CRBR
- cladding condition at two years no worse than CRBR at two years.

The principal constraints applied to the Level II designs were:

- fuel pin identical to CRBR--except for core and plenum height
- fuel assembly design open
- operating conditions no worse than CRBR
- cladding end-of-life cumulative damage fraction less than 0.75.

The Level I Homogeneous design, shown in Table IV, is essentially a scale-up of the current CRBR design to 1200 Mwe--with the exception of the interduct gap. The fuel pin is 230 mils (5.84 mm) in outer diameter with a 15 mil (0.381 mm) cladding thickness, and the active core height is 36 inches (91 cm). The reactor inlet temperature is 716 °F (653 °K) and the reactor outlet is 965 °F (791 °K). The core consists of 678 driver assemblies, 43 control assemblies, and 420 radial blanket assemblies. A feature unique to this design, however, is that the core was orificed for incoherence. The subassembly mixed

Table IV
HEDL LHRFDS Level I Homogeneous Design

Plant Design	
Electrical Power (MWe)	1200
Thermal Power (MWt)	3333
Reactor Inlet Temperature (°F/°K)	716/653
Reactor Outlet Temperature (°F/°K)	965/791
Number of Core Orifice Zones	8
Core Design	
Active Fuel Length (in/cm)	36/91
Plenum Length (in/cm)	41/104
Pin Outer Diameter (mils/mm)	230/5.84
Cladding Thickness (mils/mm)	15/0.381
Fuel Pin P/D	1.24
Pins per Assembly	217
Duct Wall Thickness (mils/mm)	120/3.05
Duct Spacing (mils/mm)	205/5.21
Duct Outside Flat-to-Flat (in/cm)	4.575/11.62
Subassembly Pitch (in/cm)	4.780/12.14
Nozzle-to-Nozzle ΔP (psi/kPa)	137/946
Maximum Mixed Mean Outlet Temperature (°F/°K)	1044/835
Volume Fractions in Active Core	
Fuel	0.3240
Sodium	0.4239
Steel	0.2316
Control	0.0205
Performance Parameters	
Fuel Linear Power (kW/ft/w/cm)	
Average	7.1/233
Nominal Peak	10.8/354
3σ + 15% Peak	14.2/466
Average Discharge Exposure (MWd/kg)	69
Peak Discharge Exposure (MWd/kg)	100
Maximum CDF	0.52
Peak Neutron Flux, E > 0.1 MeV ($n/cm^2/sec$)	4.23×10^{15}
Peak Fluence, E > 0.1 MeV (n/cm^2)	1.87×10^{23}
Peak Cladding Temperature (°F/°K)	
Nominal	1189/916
2σ	1338/999

Table IV

(cont'd)

Fuel Residence Time (calendar yrs)	2
Number of Subassemblies	
Drivers - Zone 1	354
Drivers - Zone 2	324
Control	43
Radial Blanket	420
Core Enrichment (Pu/Pu+U) (%)	
Inner Zone	18.1
Outer Zone	21.8
Total Fissile Inventory (kg-BOEC)(1,2)	3548
Total Heavy Metal (kg-BOEC)(2)	40278
Breeding Ratio	1.17
Compound System Doubling Time (yrs)	36.7
Sodium Void Worth ($)	
Fresh	+2.58
EOEC	+4.28
Fuel Cycle Cost (mills/kwh)	3.2

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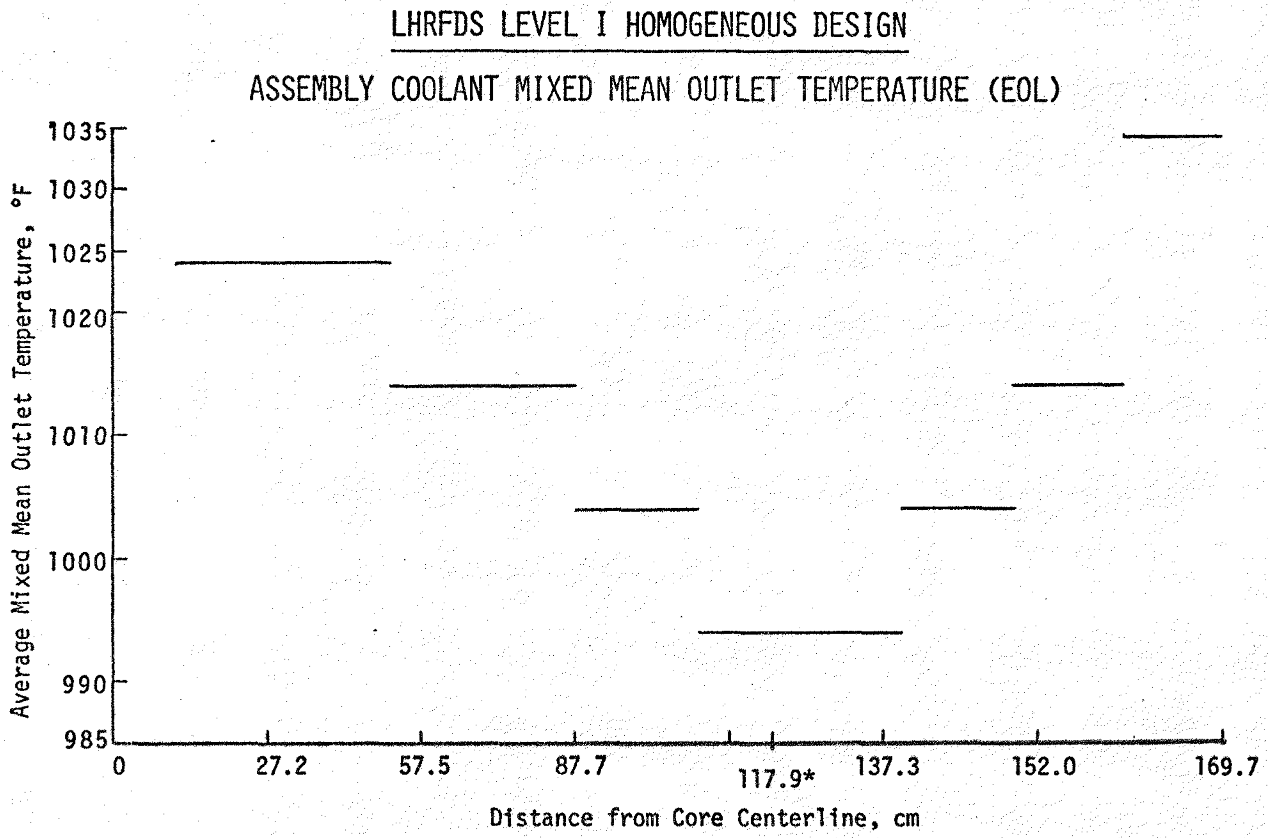
(1) U-235 + Pu-239 + Pu-241

(2) Driver fuel region including axial blankets

mean outlet temperature distribution was chosen so that the lowest worth subassemblies would void first in the unlikely event of a loss-of-flow accident. The radial distribution of the subassembly mixed mean outlet temperature is shown in Fig. 6, and the radial distribution of the volumetric sodium void worth in ¢/cm of radial ring is shown in Fig. 7. The volumetric sodium void worth is small near the core center because the volume of a radial ring one centimeter thick is small there, and the volumetric sodium void worth is negative near the core edge because the sodium worth per unit mass is negative there. Note that the Level I Homogeneous core is designed such that the highest coolant outlet temperatures occur in the regions of lowest volumetric sodium void worth. Consequently, the accident potential of this design may be less than that indicated by the whole-core sodium void worth since the core is designed to void incoherently beginning with the low worth regions. The end-of-equilibrium cycle sodium void worth is 4.28$. The breeding ratio for the Level I Homogeneous design is 1.17, the compound system doubling time is 36.7 years, and the fuel cycle cost is 3.2 mills/kwh. The sodium void worth, for all designs discussed in this paper, consists of the worth of flowing sodium in the active core region. It does not include sodium in the control rods, in the gaps between subassemblies, in the axial or radial blankets, nor in the internal blankets.

The Level II Homogeneous design, shown in Table V, is a 1200 Mwe unit utilizing the CRBR fuel pin. The design, however, differs considerably from the CRBR, even though the fuel pin is identical. The reactor inlet temperature is 595 °F (586 °K), the reactor outlet is 895 °F (752 °K), the fuel pin pitch-to-diameter ratio is 1.17, and the active fuel length is 24 inches (61 cm). The core consists of 768 driver assemblies, 49 control assemblies, and 444



*Scale change at 127.013 cm.

Fig. 6. Radial Distribution of the Subassembly Mixed Mean Coolant Outlet Temperature for the Level I Homogeneous Design

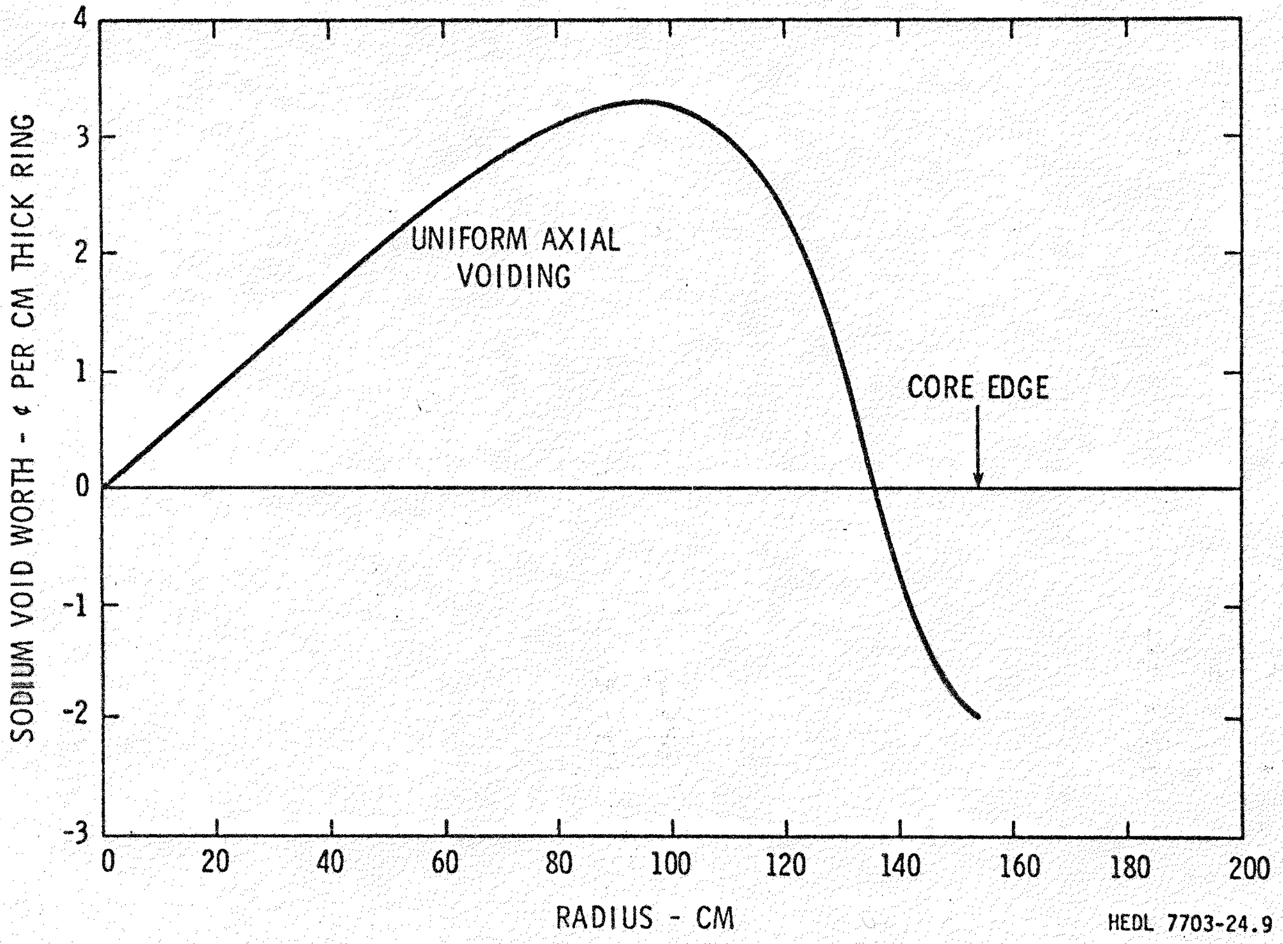


Fig. 7. Radial Distribution of the Volumetric Sodium Void Worth in ¢/cm of Radial Ring

Table V

HEDL LHRFDS Level II Homogeneous Design

Plant Design

Electrical Power (MWe)	1200
Thermal Power (MWt)	3750
Reactor Inlet Temperature (°F/°K)	595/586
Reactor Outlet Temperature (°F/°K)	895/752
Number of Core Orifice Zones	5

Core Design

Active Fuel Length (in/cm)	24/61
Plenum Length (in/cm)	26/66
Pin Outer Diameter (mils/mm)	230/5.84
Cladding Thickness (mils/mm)	15/0.381
Fuel Pin P/D	1.17
Pins per Assembly	271
Duct Wall Thickness (mils/mm)	101/2.56
Duct Spacing (mils/mm)	138/3.51
Duct Outside Flat-to-Flat (in/cm)	4.737/12.03
Subassembly Pitch (in/cm)	4.875/123.8
Nozzle-to-Nozzle ΔP (psi/kPa)	~100/~690
Maximum Mixed Mean Outlet Temperature (°F/°K)	974/796
Volume Fractions in Active Core	
Fuel	0.3895
Sodium	0.3581
Steel	0.2281
Control	0.0243

Performance Parameters

Fuel Linear Power (kW/ft/w/cm)	
Average	8.75/287
Nominal Peak	12.11/397
3σ + 15% Peak	15.9/522
Average Discharge Exposure (MWD/kg)	79
Peak Discharge Exposure (MWD/kg)	108
Maximum CDF	0.06
Peak Neutron Flux, $E > 0.1$ MeV ($n/cm^2/sec$)	4.57×10^{15}
Peak Fluence, $E > 0.1$ MeV (n/cm^2)	2.00×10^{23}
Peak Cladding Temperature, BOL (°F/°K)	
Nominal	1093/862
2σ	1279/966

Table V
(cont'd)

Fuel Residence Time (calendar yrs)	2
Number of Subassemblies	
Drivers - Zone 1	498
Drivers - Zone 2	270
Control	49
Radial Blanket	444
Core Enrichment (Pu/Pu+U) (%)	
Inner Zone	20.7
Outer Zone	26.7
Total Fissile Inventory (kg-BOEC)(1,2)	3665
Total Heavy Metal (kg-BOEC)(2)	58656
Breeding Ratio	1.29
Compound System Doubling Time (yrs)	17.2
Sodium Void Worth ($)	
Fresh Core	+1.27
EOEC	+3.16
Fuel Cycle Cost (mills/kwh)	4.4

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(1) U-235 + Pu-239 + Pu-241

(2) Driver fuel region including axial blankets

radial blanket assemblies. The large number of subassemblies in this design is a direct consequence of the 24 inch (61 cm) active fuel length, which was selected to minimize sodium void worth. The sodium void worth is 3.16$ at the end-of-equilibrium cycle, which is a significant decrease from that of the Level I Homogeneous design. The fuel cycle cost for this design is 4.43 mills/kwh, which is a significant increase over that of the Level I Homogeneous design. The primary reason for this increase is, of course, the reduction in active fuel length from 36 inches (91 cm) to 24 inches (61 cm). Thus, the sodium void worth was reduced by 26% while the fuel cycle cost increased by 38%.

The Level II Heterogeneous design, shown in Table VI, is a 1200 Mwe heterogeneous unit utilizing the CRBR fuel pin. The reactor inlet temperature is 595 °F (586 °K), the reactor outlet temperature is 895 °F (752 °K), the fuel pin pitch-to-diameter ratio is 1.21, and the active fuel length is 48 inches (122 cm). Again, the design differs considerably from the CRBR even though the fuel pin is identical. As shown on the core map, Fig. 8, the core consists of 378 driver assemblies, 36 control assemblies, 217 internal blanket assemblies, and 288 radial blanket assemblies. As can be seen in Fig. 8, the Level II Heterogeneous design has six single rows of interior blankets separated by either single or double rows of fuel. This configuration was chosen in order to establish a reasonable amount of incoherence without uncoupling the core. The sodium void worth of this design is 2.53$ at the end-of-equilibrium cycle, and the fuel cycle cost is 2.95 mills/kwh. The reason the Level II Heterogeneous design has a fuel cycle cost lower than that of the Level II Homogeneous design is due primarily to the 48 inch (122 cm) active fuel length of the heterogeneous design.

Table VI

HEDL LHRFDS Level II Heterogeneous Design

Plant Design

Electrical Power (MWe)	1200
Thermal Power (MWt)	3750
Reactor Inlet Temperature (°F/°K)	595/586
Reactor Outlet Temperature (°F/°K)	895/752
Number of Core Orifice Zones (Fuel/ Internal Blanket)	7/6

Core Design

Active Fuel Length (in/cm)	48/122
Plenum Length (in/cm)	54/137
Pin Outer Diameter (mils/mm)	230/5.84
Cladding Thickness (mils/mm)	15/0.381
Fuel Pin P/D	1.207
Pins per Assembly	271
Duct Wall Thickness (mils/mm)	102/2.59
Duct Spacing (mils/mm)	206/5.23
Duct Outside Flat-to-Flat (in/cm)	4.889/12.42
Subassembly Pitch (in/cm)	5.095/12.94
Nozzle-to-Nozzle ΔP (psi/kPa)	~170/~1173
Maximum Mixed Mean Outlet Temperature (EOL) (°F/°K)	961/789
Volume Fractions in Active Core	
Fuel (Band 1/Band 2/etc.)	.3786/.3245/.3786/ .3118/.3786/.3506
Steel	0.2188
Sodium	0.4025
Control (Band 1/Band 2/etc.)	0/.0541/0/.0668/0/.0280

Performance Parameters

Fuel Linear Power (kW/ft/w/cm)	
Average	6.9/226
Nominal Peak	12.0/394
3σ + 15% Peak	15.7/515
Average Discharge Exposure (MWD/kg)	86
Peak Discharge Exposure (MWD/kg)	122
Maximum CDF	0.25
Peak Neutron Flux, E > 0.1 MeV ($n/cm^2/sec$)	$3.5x10^{15}$
Peak Fluence, E > 0.1 MeV (n/cm^2)	$1.9x10^{23}$
Peak Cladding Temperature (BOL) (°F/°K)	
Nominal	1200/922
2σ	1401/1034

Table VI
(cont'd)

Fuel Residence Time (calendar yrs)	2.5
Number of Subassemblies	
Drivers - Zone 1	162
Drivers - Zone 2	216
Control	36
Radial Blanket	288
Internal Blanket	217
Core Enrichment (Pu/Pu+U) (%)	
Inner Zone	25.2
Outer Zone	29.3
Total Fissile Inventory (kg-BOEC)(1,2)	4319
Total Heavy Metal (kg-BOEC)(2)	60892
Breeding Ratio	1.31
Compound System Doubling Time (yrs)	19.0
Sodium Void Worth (EOEC) ($)	+2.53
Fuel Cycle Cost (mills/kwh)	3.0

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(1) U-235 + Pu-239 + Pu-241

(2) Driver fuel region including axial blankets, but not internal blankets

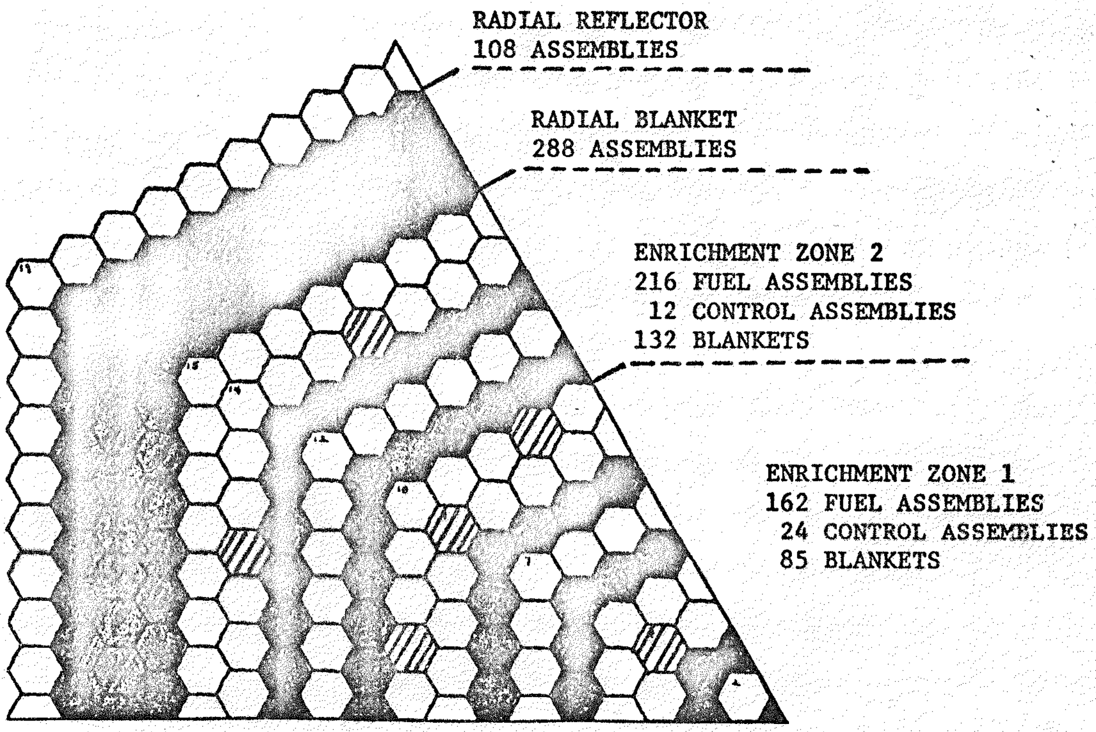

Fig. 8. Core Map for the Level II Heterogeneous Design

CONCLUSION

The performance characteristics of the six LMFBR core designs are summarized in Table VII. The Small Pin, Large Pin, and Advanced Large Pin designs have the highest breeding ratio and shortest compound system doubling time. This is because a deliberate attempt was made to minimize the amount of steel in the core during the development of these designs. The Level I and II designs have lower breeding ratios and longer compound system doubling times since they were constrained to use the CRBR fuel pin. A deliberate attempt was made during the development of these designs, however, to minimize the sodium void worth. As can be seen, the sodium void worth of the Level II designs is quite small--3.16$ and 2.53$ for the homogeneous and heterogeneous designs, respectively. The only advantage to the Level I Homogeneous design is that a minimum amount of development is required. The Level II Homogeneous design has the shortest compound system doubling time of the three designs utilizing the CRBR fuel pin. The fuel cycle cost, however, is quite high. The Level II Heterogeneous design has the lowest sodium void worth.

References

1. J. C. Chandler, D. R. Marr, D. C. McCurry, D. A. Cantley, and R. P. Omberg, "The Development of LMFBR Core Designs Using Reference and Advanced Oxide Fuel," International Meeting on Advanced LMFBR Fuels, October 1977, Tucson, Arizona.

2. W. W. Little and R. W. Hardie, "2DB Users' Manual - Revision 1," BNWL-831, Battelle Memorial Institute, August 1969.

3. D. S. Dutt and R. B. Baker, "SIEX - A Correlated Code for the Prediction of LMFBR Fuel Thermal Performance," HEDL-TME 74-55, Hanford Engineering Development Laboratory, June 1975.

4. G. L. Wire and J. L. Straalsund, "A Simple Method for Calculations of Steady-State Creep Rates in Nonconservative Plastic Deformation," Nuclear Technology, 30, 71, July 1976.

5. R. W. Hardie, W. W. Little, and R. P. Omberg, "A Comprehensive Expression for the Doubling Time of Fast Breeder Reactors," *Nuclear Technology*, *21*, 158 (1974).

6. D. R. Marr, R. W. Hardie, and R. P. Omberg, "An Expression for the Compound System Doubling Time Which Explicitly Includes the Approach to Equilibrium," Trans. Am. Nucl. Soc., *26*, 587 (June 1977).

Table VII

Summary of Performance Characteristics

	Small Pin	Large Pin	Advanced Large Pin	Level I Homogeneous	Level II Homogeneous	Level II Heterogeneous
Electrical Power (Mwe)	800	800	800	1200	1200	1200
Thermal Power (Mwt)	2500	2500	2500	3333	3750	3750
Fuel Pin Diameter (inch/mm)	0.230/ 5.84	0.300/ 7.62	0.300/ 7.62	0.230/ 5.84	0.230/ 5.84	0.230/ 5.84
Cladding Wall (mils/mm)	10/ 0.254	13/ 0.330	13/ 0.330	15/ 0.381	15/ 0.381	15/ 0.381
Active Fuel Length (inch/cm)	36/91	36/91	36/91	36/91	24/61	48/122
Fuel Residence Time (yrs)	2.0	2.0	3.0	2.0	2.0	2.5
Core Average Discharge Exposure, (MWD/kg)	59	61	69	69	79	86
Fissile Mass in Core(1) (kg-BOEC)	2549	2420	2906	3400	3387	4240

Table VII
(cont'd)

	Small Pin	Large Pin	Advanced Large Pin	Level I Homogeneous	Level II Homogeneous	Level II Heterogeneous
Specific Power (Mwt/kg fis)	0.98	1.03	0.86	0.98	1.11	0.88
Breeding Ratio	1.38	1.39	1.42	1.17	1.29	1.31
Compound System Doubling Time (yrs)	13.1	12.2	11.6	36.7	17.2	19.0
Sodium Void Worth,(2) EOEC ($)	-	-	-	4.28	3.16	2.53
Fuel Cycle Costs, (mills/kW-hr)	5.0	3.5	2.2	3.2	4.4(3)	3.0(3)

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(1) U-235 + Pu-239 + Pu-241 in active fuel region--not including axial, radial, or internal blankets.

(2) This is the worth of flowing sodium in the active core region. It does not include sodium in the control rods, in the gaps between subassemblies, in the axial or radial blankets, nor in the internal blankets.

(3) The homogeneous design has a higher fuel cycle cost than the heterogeneous design because of the shorter core height.