HEDL-SA-1205

CONF-770611--25

CORE DESIGN METHODS FOR ADVANCED LMFBRs

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May 1977

This paper will be presented as a contributed paper at the June 1977 meeting of the American Nuclear Society in New York.

This paper is based on work performed at the Hanford Engineering Development Laboratory, Richland, Washington, operated by Westinghouse Hanford Company, a subsidiary of Westinghouse Electric Corporation for the Energy Research and Development Administration under Contract No. EY-76-C-14-2170.

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1.0 INTRODUCTION

The design of an LMFBR core is a complex process which is strongly dependent upon design philosophy, design criteria, selection of material properties and the calculational procedure involved. The development of a core design with optimum characteristics, whether it be doubling time, power costs or safety characteristics, requires a close coupling of the disciplines of reactor physics, thermohydraulics, mechanical design and fuel pin performance. The reasons for this are:

- The breeding ratio, doubling time, neutron fluence and reactivity lifetime of a reactor are all strongly dependent upon the volume fraction of fuel, steel and sodium in the core--and, hence, upon the thermo-hydraulic and mechanical design of the core.
- The mechanical design of the core, on the other hand, is strongly dependent upon the material irradiation swelling and creep rates--which are determined by the neutron fluence and temperatures in the core.

Thus, the mechanical design of the core of an LMFBR is strongly influenced by the reactor physics, and conversely, the reactor physics is strongly influenced by the mechanical design. This, by necessity, forces the development of a closely-coupled multidiscipline

approach. This is true regardless of whether oxide, carbide, nitride or metal fuels are utilized or whether the Pu/U or U/Th system is utilized.

2.0 DESIGN PROCEDURE

The multidiscipline approach requires an iterative design procedure to obtain a closely-coupled design. HEDL's philosophy requires that the designs should be coupled to the extent that the design limiting fuel pin, the design limiting duct and the core reactivity lifetime should all be equal and should equal the fuel residence time. This is accomplished at HEDL using the design procedure illustrated in Figure 1. It consists of an iterative loop involving three stages of the design sequence. Stage 1 consists of general mechanical design and reactor physics scoping calculations to arrive at an initial core layout. Stage 2 consists of detailed reactor physics calculations for the core configuration arrived at in Stage 1. Based upon the detailed reactor physics results, a decision is made either to alter the design (Stage 1) or go to Stage 3. Stage 3 consists of core orificing and detailed component 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 initial core configuration is arrived at by whatever means are expedient, usually taking advantage of past experience. Often a quick-running, scoping code called HAREM (Hanford Advanced Reactor Evaluation Model) is utilized. A flowchart of this code is shown in Figure 2. Input consists of design characteristics such as core temperature rise, reactor thermal power, fuel residence time, average

pin power, pin bundle pressure drop, and pin size. Output of the HAREM code includes number of subassemblies (S/A's), S/A spacing, duct geometry, and expected physics performance characteristics. A notable feature of HAREM is that the combination of duct pitch and wall thickness can be determined to minimize doubling time while matching duct lifetime to fuel residence time.

The detailed reactor physics calculations in Stage 2 are performed using 2DB[1], which is a two-dimensional multi-group diffusion code with an isotope depletion module. The calculational flow which is utilized is illustrated in Figure 3. The goal of these calculations in the iterative loop is to provide fluxes and linear power as a function of position for use in the thermohydraulics and fuel pin and duct lifetime calculations. In the reactor physics calculations, the core layout and subassembly designs for both fuel and blanket may be changed to meet the following non-mechanical design criteria:

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

An iterative technique is employed to determine the enrichment corresponding to an end-of-cycle multiplication factor of 1.000 and to determine the enrichment distribution corresponding to an acceptable power distribution. The multiplication factor is affected by varying the total fissile mass. The power distribution is affected by varying the relative cross sectional areas and fissile enrichments of the two core enrichment zones. The iteration consists of two initial depletion calculations selected to bracket the required enrichment. A plot of effective multiplication factor at end-of-cycle versus beginning-of-cycle enrichment is constructed, and a linear interpolation used to select a third enrichment estimate. If the third estimate does not meet the k_{eff} criterion, a new interpolation is performed to establish the correct fissile content. The power distribution is then examined by zone to determine if the peak linear powers are acceptable. If the peak linear powers do not coincide to within 10 percent, a decision is made to vary either the ratio of the enrichments of the core zones or the ratio of the cross sectional area of the two zones. In either case, some change in absolute magnitude of the enrichment is induced by any variation; if the power-balanced core does not meet the equilibrium k_{eff} criterion, the initial enrichment search is repeated.

The next step of the design procedure is to orifice the core using the orificing scheme shown in Figure 4. This is facilitated with the core orificing code ORIFIS. This code distributes a specified coolant flow to obtain a desired subassembly outlet temperature distribution across the core. Generally, the desired distribution

is related to lifetime considerations and is arrived at using trial and error methods and iterating between the ORIFIS code and the lifetime codes.

Fuel pin lifetimes are calculated using the computer code SIFAIL which uses the SIEX[2] fuel pin model illustrated in Figure 5. The code calculates fuel and cladding temperature, gas release rate, cladding stresses due to gas pressure loading, and cladding changes due to wastage, swelling, thermal creep, and irradiation creep. SIFAIL also calculates the cladding cumulative damage fraction based on stress rupture properties. This latter parameter is often used as the fuel pin life limiting parameter.

Figure 6 schematically illustrates the deflection model used in the code DEFLECT to calculate duct lifetime. The model uses the thin plate elastic deflection equations in conjunction with the method of Wire and Straalsund[3] for calculating irradiation creep.

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.

3.0 DESIGN CRITERIA AND MATERIAL PROPERTIES

Characteristics of the particular designs which emerge from this design procedure are strongly dependent upon the material correlations employed and upon the design criteria. Generally, HEDL uses nominal values of the most recently recommended NSMH* material

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*Nuclear Systems Material Handbook

property correlations. As these recommended equations change so do the characteristics of the emerging designs. Changes in design criteria have a similar effect. Currently, HEDL designs to separate criteria for fuel pin peak linear power, fuel pin lifetime, duct lifetime and duct/bundle interaction. Design conservatism is introduced by using hot channel uncertainty factors. The maximum fuel pin linear power is specified to avoid fuel melting with 3σ uncertainties and 15% overpower, and fuel pin performance is calculated using 2σ uncertainties on cladding and plenum temperatures. The fuel pin is designed to a "no failure" criterion. The response parameter currently being employed for oxide fuel pins is the cumulative damage fraction (CDF) based on cladding stress rupture properties; the limiting value of CDF for steady state design is usually taken to be 0.5. Fuel pin cladding strains are only limited in terms of bundle/duct interaction. The allowable extent of interaction is specified to prevent the fuel pins from contacting the duct wall using 0σ operating temperatures. The method of calculation was previously described. Duct lifetimes are limited by contact of adjacent ducts due to irradiation-induced swelling and creep dilation calculated using 2σ uncertainties on temperature.

4.0 ADVANCED CORE DESIGNS

The preliminary characteristics of three advanced mixed oxide core designs developed using the described design procedure are summarized in Table I. These particular designs were developed using 20% C.W. 316 stainless steel with the NSMH recommended Revision 5 swelling, Revision 3 creep, and Revision 2 stress-rupture properties.

Characteristics of all three core designs are very similar with the exception of fuel pin diameter. The small pin design has a diameter of 0.230 inches with a 10 mil cladding wall thickness. This particular design was selected to coincide with the design of the HEDL-P-40 fuel pins irradiated in EBR-II. It is noted that this particular subassembly recently achieved a burnup of 128 MWD/kg, which is 45% higher than the discharge exposure for this design. The large pin designs utilize a fuel pin diameter of 0.300 inches with a cladding thickness-to-diameter ratio equal to that of the small pin design. This diameter was selected as being near the probable upper limit for an oxide fuel pin. The duct dimensions in each case, although different, were each determined to accommodate 271 pins per subassembly for the indicated residence time with a coolant pressure drop across the bundle of 75 psi. The large pin design and the advanced large pin design are distinguished by the pin lifetime criteria used. The large pin design used a CDF = 0.5, while the advanced large pin design used a CDF = 1.0.

The performance parameters for the small and large pin designs are very similar. The large pin design, however, does have a slightly lower doubling time and fuel cycle cost. The lower doubling time is attributed to a slightly larger breeding gain and higher specific power. The linear power for this design does, however, exceed the maximum allowable linear power according to the design criterion for fuel melting. Redesign to correct this violation would probably increase both the doubling time and fuel cycle cost and result in closer comparison with the small pin design.

The effect of doubling the fuel pin lifetime criterion can be seen by comparing the large pin design with the advanced large pin design. The impact on doubling time is disproportionately small. This is due to the non-linear dependence of CDF on fuel pin residence time.

5.0 SUMMARY

In summary, HEDL's core design procedure closely couples the disciplines of reactor physics, thermohydraulics, mechanical design and fuel pin performance. The procedure uses detailed codes from each discipline such that the designs are converged in only a few iterations. The procedure is completely general and can be adopted to any LMFBR fuel system with only minor modifications, most notably in the fuel pin performance models.

Designs which have been developed using the procedure exhibit good performance characteristics and appear to be conservative relative to irradiation experience.

6.0 REFERENCES

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

2. 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.

3. 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.

4. Letter, P. A. Bohm (GE) to R. D. DeWitt (ERDA/SFO), "Transmittal of Report on ~~Phase~~ I Mechanical Test Results, Contract E(04-3)-893, ~~Task 11~~, ~~189 No.~~ SG010, 'Wire Wrap Assembly Engineering'," Wrote SG010-MEA-037, April 9, 1976.

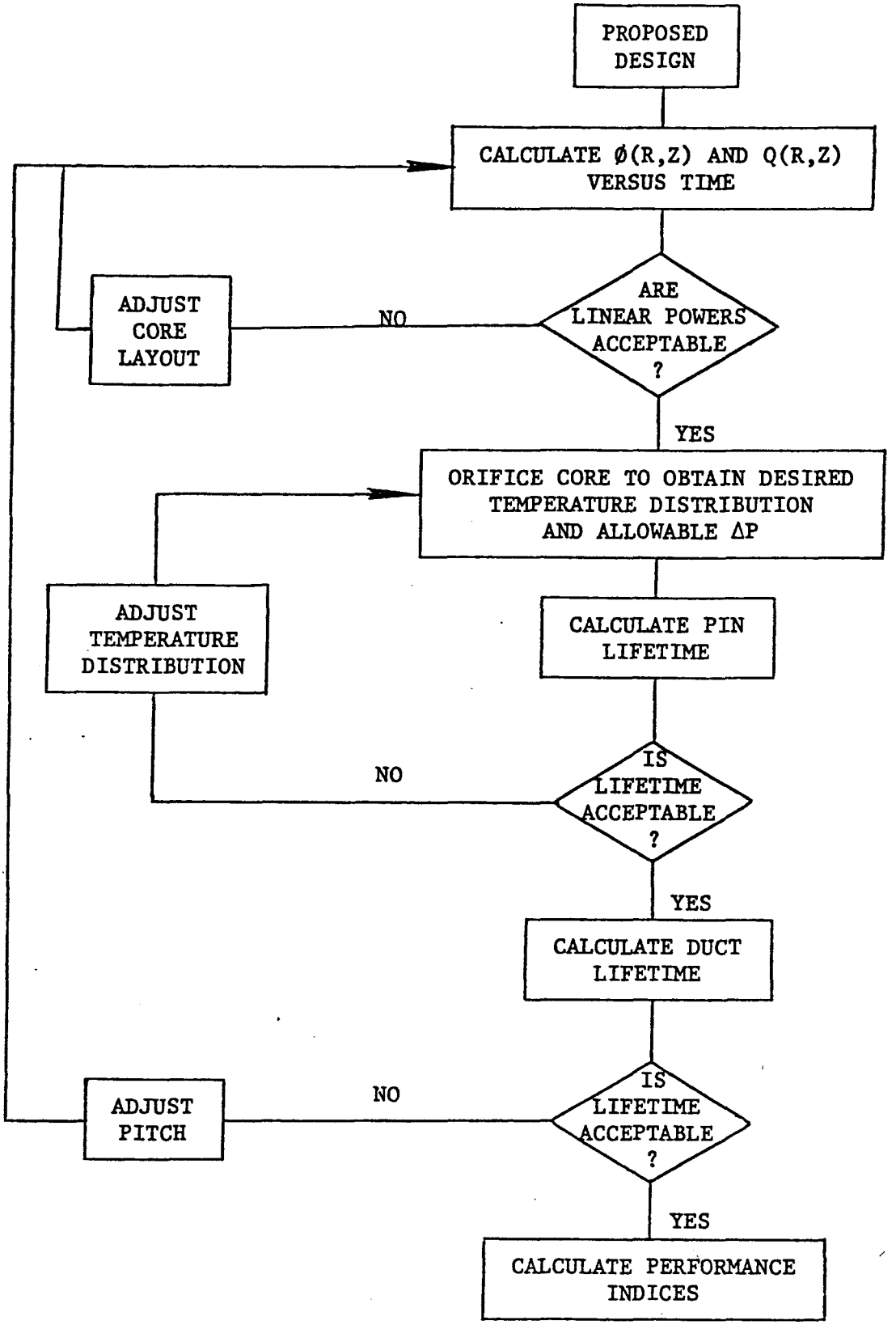

FIGURE 1. HEDL Core Design Procedure.

HAREM (HANFORD ADVANCED REACTOR EVALUATION MODEL)

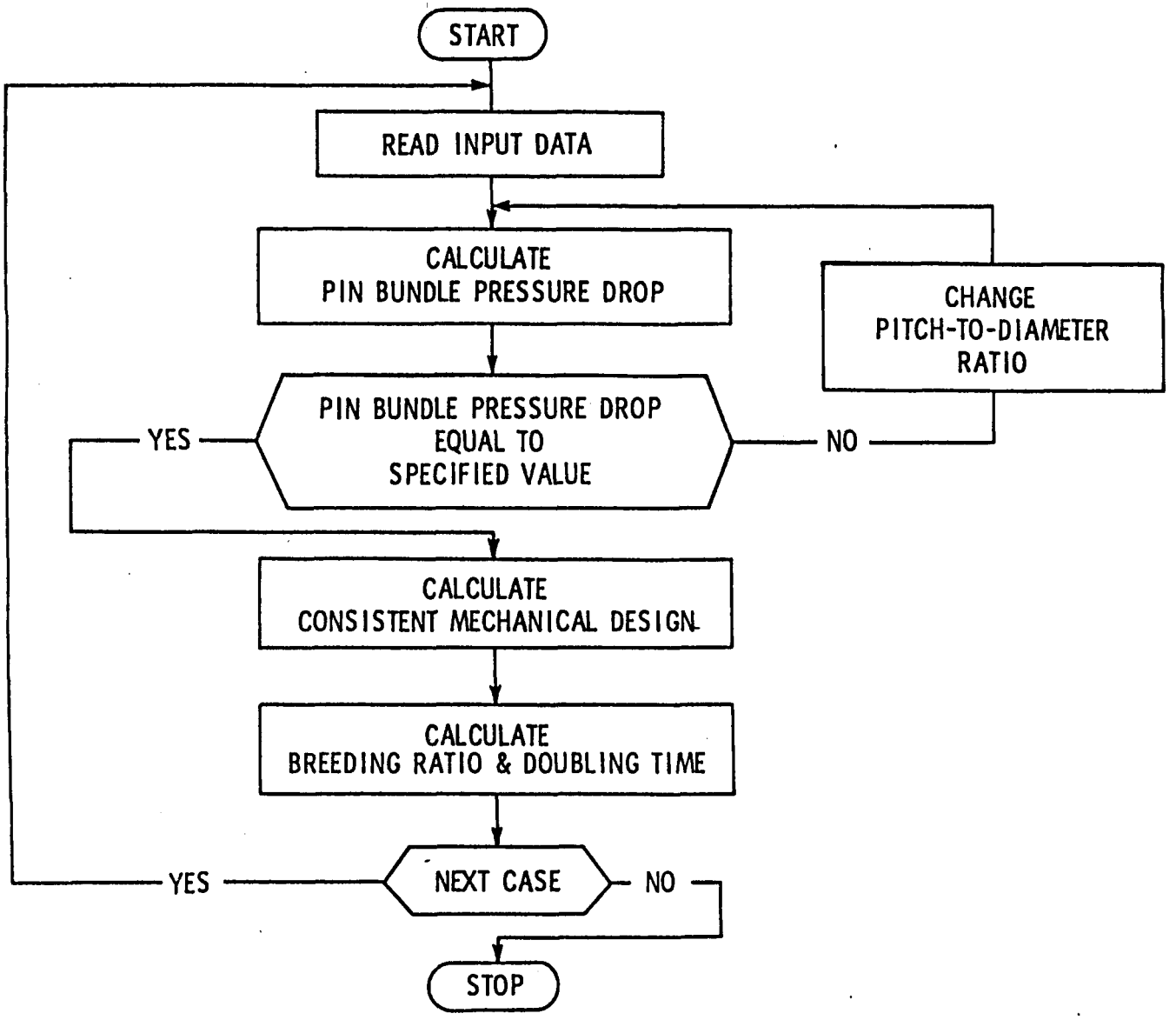

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FIGURE 2. HAREM Calculational Flow.

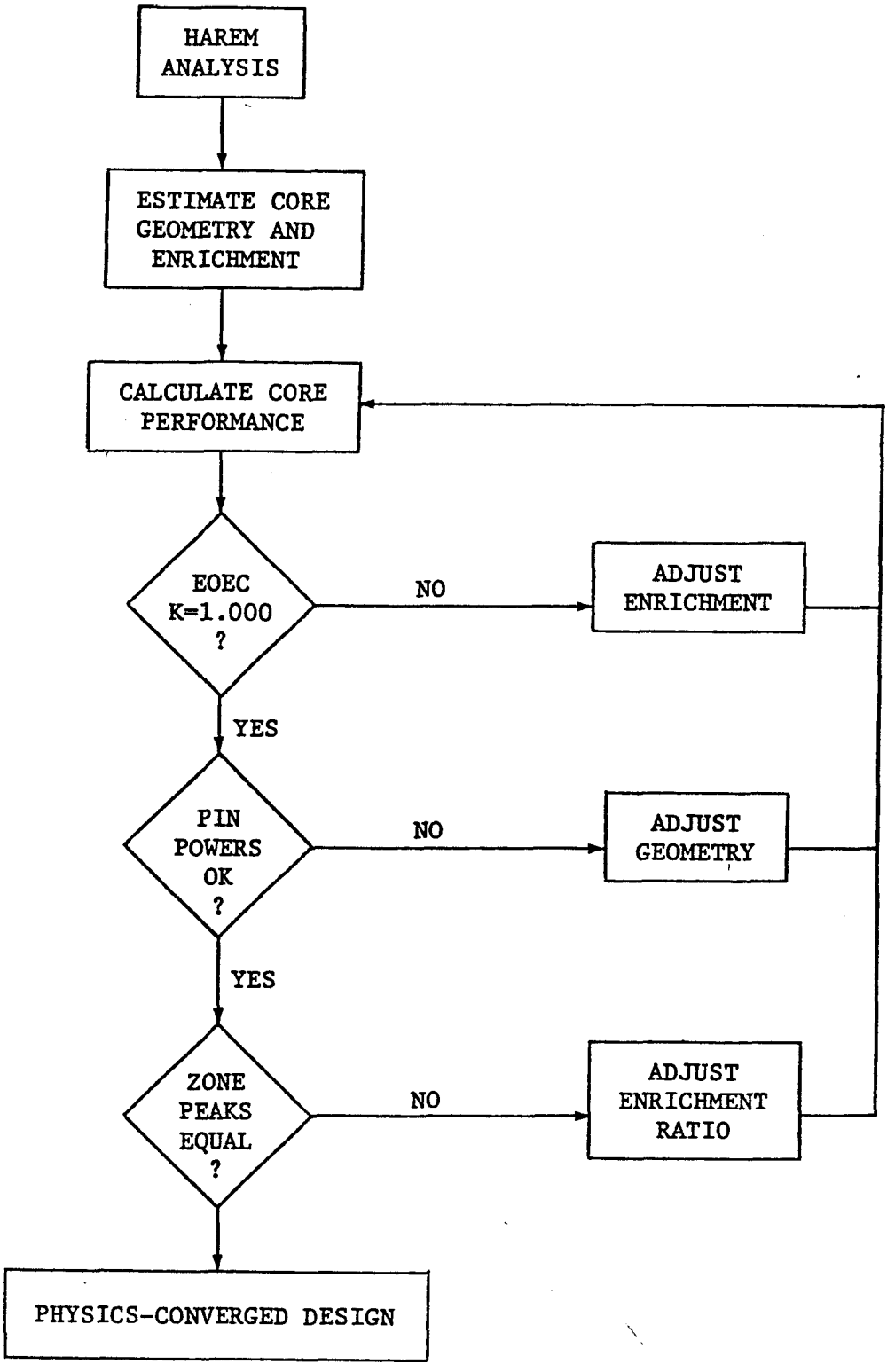


FIGURE 3. Physics Calculational Flow.

ORIFICING SCHEME

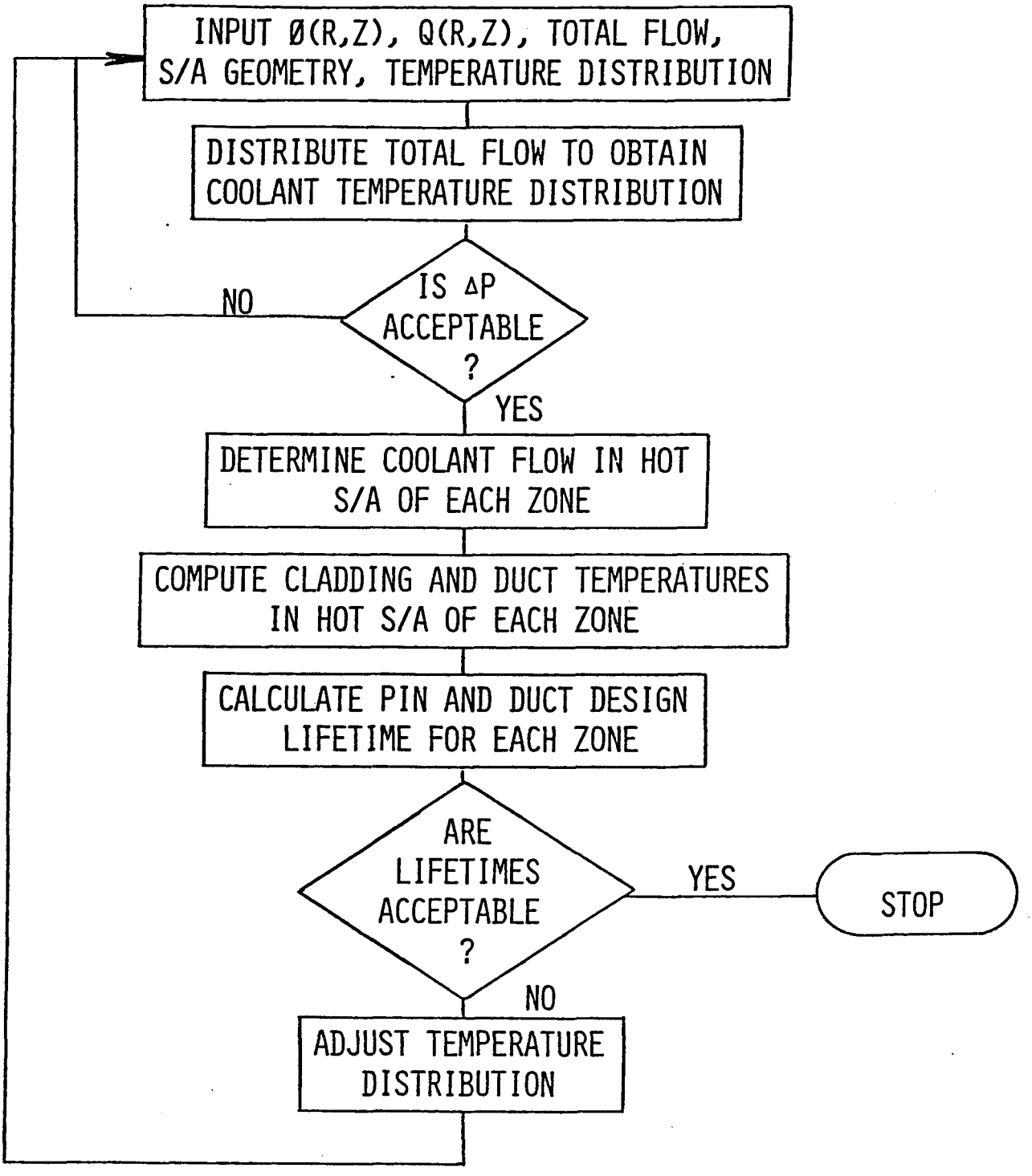
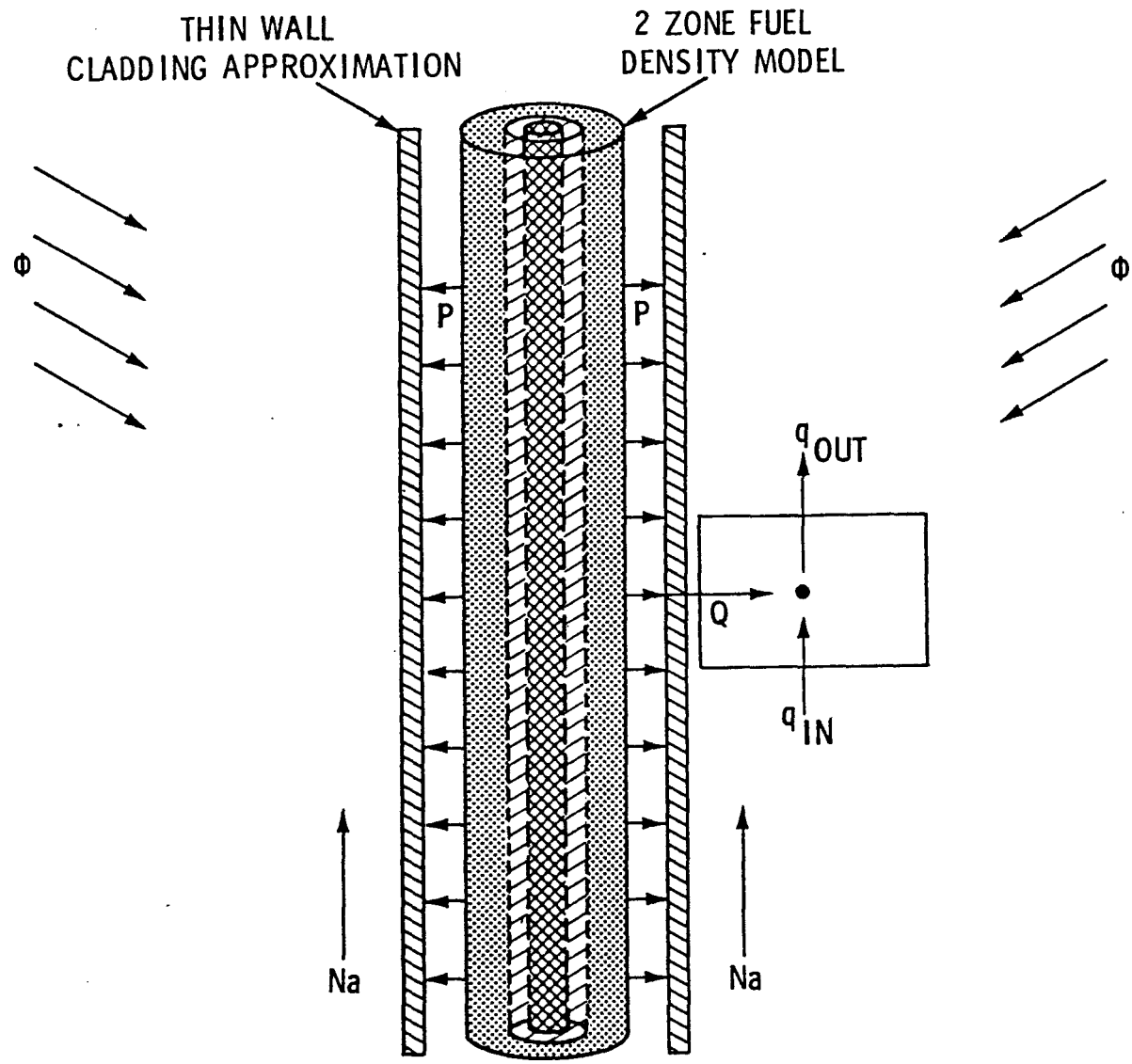


FIGURE 4. Calculational Flow for Establishing the Orificing Scheme.



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, THERMAL CREEP, AND CUMULATIVE DAMAGE FRACTION

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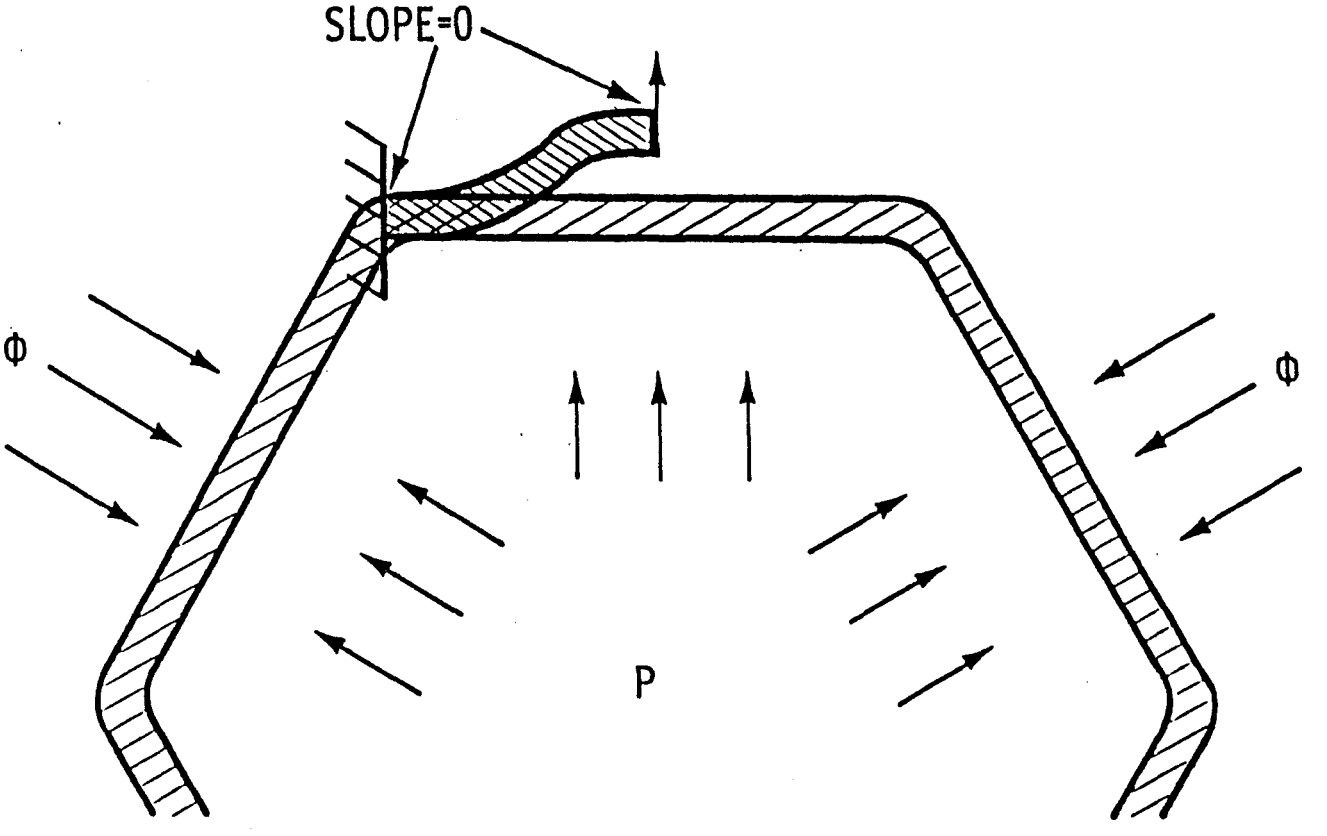
FIGURE 5. SIFAIL Fuel Pin Model.

THE DUCT MODEL - DEFLECT



INPUT: COOLANT PRESSURE, DUCT WALL TEMPERATURE, NEUTRON FLUX

CALCULATE: STRESS, IRRADIATION SWELLING, IRRADIATION CREEP, DEFLECTION

HEDL 7610-163.1

FIGURE 6. HEDL Duct Dilation Model.

TABLE I

HEDL ADVANCED DESIGNS

	Small Pin Design	Large Pin Design	Advanced Large Pin Design
Design Characteristics			
Electrical Power (MWe)	800	800	800
Thermal Power (MWt)	2500	2500	2500
Coolant Inlet Temperature (°F)	600	600	600
Coolant Outlet Temperature (°F)	900	900	900
Pin Lifetime Criteria	CDF=0.5	CDF=0.5	CDF=1.0
Duct Lifetime Criteria	Midplane Contact	Midplane Contact	Midplane Contact
Total Pin Length (ft)	9.5	9.5	9.5
Active Fuel (ft)	3.0	3.0	3.0
Axial Blanket (ft)	3.0	3.0	3.0
Plenum (ft)*	3.0	3.0	3.0
Pin Outer Diameter (in.)	0.230	0.300	0.300
Cladding Thickness (in.)	0.010	0.013	0.013
Pins per Subassembly	271	271	271
Duct Thickness (in.)	0.087	0.114	0.114
Duct OD (flat-to-flat) (in.)	4.785	6.139	5.976
Subassembly Pitch (in.)	5.001	6.441	6.322
Bundle Pressure Drop (psi)	75	75	75
Performance Parameters			
Average Linear Heat Rate (kW/ft)	6.44	11.3	9.0
Peak Linear Heat Rate (kW/ft)	10.0	17.5	13.4
Ave. Discharge Exposure (MWD/kg)	59.0	61.0	69.0
Peak Discharge Exposure (MWD/kg)	88.0	90.0	98.0
Peak Flux >0.1 MeV (n/cm^2-sec)	4.13×10^{15}	4.35×10^{15}	3.39×10^{15}
Core Enrichment (Pu/Pu+U) (%)	16.6	16.2	15.5
Fuel Residence Time (yrs) @72% LF	2	2	3
Core Conversion Ratio	0.929	0.941	0.986
Breeding Ratio	1.38	1.39	1.42
Compound Sys. Dbl. Time** (yrs)	13.1	12.2	11.6
Total Fuel Cycle Cost (mills/kwh)	4.57	3.41	--

*Bottom plenum

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