CONF-750804--11

PRELIMINARY THERMAL-HYDRAULIC DESIGN AND PREDICTED PERFORMANCE OF THE CLINCH RIVER BREEDER REACTOR CORE

Mario D. Carelli

Robert A. Markley

Westinghouse Advanced Reactors Division

This work was performed under AEC Contract AT (11-1)-2395

Preliminary Thermal-Hydraulic Design and Predicted Performance of the CRBR Core

Conference Paper M.D. Carelli R.A. Markley ASME

San Fran., Cal 8/11-13/75

PRELIMINARY THERMAL-HYDRAULIC DESIGN AND PREDICTED PERFORMANCE OF THE CLINCH RIVER BREEDER REACTOR CORE

Mario D. Carelli and Robert A. Markley
Westinghouse Advanced Reactors Division

SUMMARY

The preliminary thermofluids design of the core assemblies of the Clinch River Breeder Reactor Plant (CRBRP) is presented along with the predicted performance for various plant operating conditions. The selected radial blanket assemblies shuffling scheme and the new approach adopted for fuel and blanket assemblies orificing is discussed. Relevant thermofluids parameters (assembly flow rate and mixed mean outlet temperature, fuel rod temperatures, fission gas plenum pressure, etc.) are presented. Highlights of a detailed uncertainties study performed are summarized. This preliminary analysis has shown that the CRBRP core behavior is compatable with design limits and requirements; future developments for a final analysis are outlined.

1. OVERALL CONSIDERATIONS

A major step toward a viable and competitive commercial Liquid Metal Fast Breeder Reactor industry in the U.S. is the country's first Demonstration Plant, the Clinch River Breeder Reactor Plant (CRBRP).

Due to the plant first-of-a-kind nature and operating characteristics, the CRBRP core thermofluids design has to satisfy stringent design constraints such as: reactor assemblies maximum cladding temperature must be compatable with burnup (80,000 MWd/MT initial, 150,000 MWd/MT ultimate goal) and lifetime (3 years fuel, 6 years blanket, 1 year control assemblies) objectives; maximum fuel (or absorber) temperature must be below the melting point; assemblies outlet temperature must be compatable with upper internals design requirements; operating conditions must be consistent with design limits for transient and faulted conditions.

The CRBRP is designed to operate at a rated power level of 975 MWt. Two different sets of Plant conditions are considered in design and performance evaluations: a) Plant T&H Design; and b) Plant Expected Operating Conditions. The first set (730/995°F reactor inlet/outlet temperature; 41.5 x 10^6 lb/hr total reactor flow) corresponds to rated design conditions and is used in performance analyses of permanent plant components, like heat exchangers, internals, vessel, etc. Core assemblies performance calculated for this set of conditions represents the upper limit of steady state operation. The second set (716/965°F reactor inlet/outlet temperature; 44.0 x 10^6 lb/hr total reactor flow) was evaluated through a combined probabilistic analysis of reactor and balance of primary system uncertainties and is adopted in evaluating the expected performance of replaceable components, such as the core assemblies. Thus, the nominal design of fuel and blanket assemblies is based on Plant Expected Operating conditions, but is such that limiting conditions are not exceeded under the more stringent Plant T&H Design conditions; thereby, a built-in margin is factored into the core assemblies design.

Equilibrium (which is reached approximately after 5 years of operation) and first cycle conditions were considered. Analyses and predictions of thermal performance were mostly concentrated on equilibrium conditions, since the CRBRP will operate at equilibrium for more than 80% of its 30 years lifetime.

A summary of the principal thermal-hydraulic parameters of the CRBRP core at equilibrium conditions is reported in Table I.

2. CORE ASSEMBLIES DESIGN FEATURES

Major features of the thermofluids design of CRBRP core assemblies are briefly discussed in this section; for an overall description and details of assemblies geometry and mechanical design see, for example, Reference 1.

2.1 Radial Blanket Assemblies Fuel Management Scheme

The CRBRP radial blanket fuel management scheme resulted from trade-off studies involving nuclear, thermal, mechanical and economic considerations.

The principal requirements to be satisfied were the following:

- Six years assemblies design lifetime
- Assemblies shuffling of the in-out type
- Maximum(*) linear power rating not to exceed 20 Kw/Ft, to avoid incipient fuel melting
- Maximum cladding temperature compatable with lifetime objectives.

The reference shuffling scheme selected to meet the aforementioned requirements is shown in Figure 1, which represents a 1/12 symmetrical sector of core. Three types of assemblies (A, B, C) go through a double shuffle with two years successive residence in the inner (Suffix 1), middle (Suffix 2) and outer (Suffix 3) row; assemblies belonging to sequences D and E undergo a single shuffle with three years residence in each position, while assemblies F remain in the original position during the entire lifetime. The effect of the shuffling on the radial blanket assemblies thermofluids behavior is examined in Section 4.

(*) Including uncertainty factors at 3σ level of confidence plus short term (115% of rated power) overpower.

2.2 Fuel and Blanket Assemblies Flow Orificing Scheme

The following principal constraints had to be satisfied in selecting the flow orificing scheme for the CRBRP fuel and blanket assemblies:

- Maximum cladding temperature compatable with burnup objective (80,000 MWd/MT initial, 150,000 MWd/MT ultimate goal) for fuel assemblies and lifetime objective (6 years) for blanket assemblies.
- Minimum number of discriminating zones for economic reasons. It should be noted that the number of required discriminators depends on the combination of flow orificing and fuel enrichment zones. Two fuel enrichment zones (called inner and outer zone) are adopted in the CRBRP.
- Assemblies outlet temperature compatable with upper internals requirements, i.e., minimum temperature level and temperature gradient of the core assemblies mixed mean outlet temperatures.
- Flow allocation to the fuel and blanket assemblies compatable with cooling requirements of other components (8% of the CRBRP total reactor flow is needed for cooling of control, radial shielding assemblies, vessel, barrel, thermal liners, etc., thus leaving 92% of total reactor flow for fuel and blanket assemblies).

Burnup and lifetime objectives are satisfied if the total cumulative cladding strain and/or cumulative cladding damage function (including transient operation) are within the specified allowable limits. Cladding temperatures, fission gas pressure and burnup are the principal contributors to the cladding cumulative strain. Since the fission gas pressure increases during life and the strain burnup relationship is not linear (i.e., the strain increases rapidly as the burnup approaches end-of-life conditions), it follows that end-of-life temperatures are a close approximation of the effective temperature which determines the cladding strain integrated over the assembly life. The criterion adopted for CRBRP fuel and blanket assemblies orificing has therefore been to equalize the equilibrium end-of-life maximum cladding temperature at an allowable limit determined through analysis of the actual temperature/pressure history during the assemblies lifetime. This represents a new approach with respect to the past practice, where equalization of the maximum cladding temperature during the assemblies lifetime (which in the fuel assemblies case generally occurs at beginning-of-life) was sought.

Due to the opposite lifetime temperature behavior (fuel assemblies temperatures decrease due to burnup, while blanket assemblies temperatures increase with life due to the progressive production of plutonium) and the different residence time projected, the maximum end-of-life allowable cladding temperature in fuel and blanket assemblies was set at different values. The reference CRBRP orificing scheme shown in Figure 1, satisfies the requirements mentioned at the beginning of this section and was selected after detailed examination of the relative merit of alternate configurations. Following are the major features of the CRBRP reference core orificing scheme:

- Separate orificing zones for fuel and blanket assemblies
- Maximum number of discriminators in the fuel assemblies = 8
- Maximum number of flow orificing zones in the radial blanket assemblies = 4
- Preferential assignment of flow to the fuel assemblies in the inner fuel enrichment zone.

The rationale for the last feature was two-fold: 1) fuel assemblies located in the inner enrichment zone generally reach a comparatively higher burnup than outer zone assemblies; and 2) due to the insertion pattern of the control rods, the assembly power (hence the rod temperature) during a single cycle generally decreases in the inner assemblies, and increases in the outer assemblies (see Figure 4). Thus, if flow is allocated strictly on the basis of end-of-life temperature, fuel assemblies in the inner zone will experience a higher cumulative cladding strain than outer zone assemblies. By allocating comparatively more flow to the inner assemblies, not only the core-wide cladding strain will be more uniform, but also the values of the inner assemblies mixed mean temperature and of the assemblies exit temperature radial thermal gradient will be lower with beneficial effect on the upper internals structure. Therefore, assemblies in both the inner and outer zone were selected to belong to the same orificing zone (with the exception of zones 4 and 5 which comprise a few very low power assemblies) and the driver assembly in each orificing zone, i.e., the one determining the flow allocation to all assemblies belonging to the same zone, was generally located in the outer zone (the only exception is orificing zone 2), where the cladding temperature is higher at the end of the cycle. An alternate scheme featuring all driver assemblies in the outer zone would have resulted in approximately a 15°F reduction in the maximum cladding midwall temperature from 1350°F to 1335°F, but in an increase of the number of required discriminators from 8 to 9.

The maximum (at the 2σ confidence level) end-of-life cladding midwall temperature in the fuel and blanket rods was separately evaluated as a function of the assigned flow to the fuel and blanket assemblies. The results of this analysis are reported in Figure 2. Evaluation of the dependence of the cladding cumulative strain (and ultimate burnup and lifetime) with maximum end-of-life temperature indicated that the best trade-off between the requirements of the fuel and blanket assemblies was obtained by assigning, out of 92% total reactor flow allocated to fuel and blanket, 80% of total reactor flow to the fuel assemblies and the remaining 12% to the radial blanket assemblies. The individual assemblies flow rates (for Plant T&H Design conditions) based on this allocation are reported in Figure 1.

The CRBRP new orificing scheme approach resulted in a decrease of $\sim$50°F in end-of-life temperatures, compared with the previous approach of equalizing beginning-of-life temperatures. Such a decrease in the temperature of CW 316 SS cladding corresponds to an increase in attainable burnup of the order of 25,000 MWd/MT, other limiting effects (e.g., duct dilation, swelling, transient operation) being the same.

Work is in progress to refine the CRBRP orificing scheme toward the ultimate step of equalizing the mechanical strain. A "strain equivalent" temperature will be evaluated for each fuel and blanket assembly, such that by accounting for the assembly temperature/pressure history, a more uniform cladding strain in the assemblies will result. A double criterion will be followed in the flow allocation: a) not to exceed the "strain equivalent" temperature;

b) equalize and minimize the assemblies coolant mixed mean exit temperature, to reduce both temperature level and thermal gradients in the upper internals structure.

2.3 Control Assemblies

The CRBRP control systems consist of a primary system (15 control rod assemblies) plus a secondary system (4 assemblies). The purpose of the latter is to provide the reactor with an independent and diverse shutdown capability.

The design of the control systems is based upon nuclear, structural, thermo-fluids and safety considerations, e.g., reactivity worths, speed of response, lifetime requirements, behavior under seismic conditions, off-normal occurrences, failure modes, etc.

The thermofluids studies supporting a comprehensive analysis of primary control assemblies requirements which led to the selection of the 37-pin configuration CRBRP reference design (FFTF primary control assemblies have 61 pins per assembly) are presented in Reference 4. The prime thermofluids considerations favoring the 37 pin design were: a) higher safety margin (1.36) to floatation (a design requirement of the primary control assemblies(*) is to prevent floatation at full flow even with the control rod driveline disconnected); b) faster insertion during scram; and still c) same maximum cladding midwall temperature in absorber pins. As indicated in Table I, the maximum cladding midwall temperature is close to the interim design limit of 1225°F, while the maximum absorber centerline temperature is considerably below the 4000°F melting point of B_4C. Analyses show that the CRBRP primary control assemblies well exceed the minimum insertion speed during scram required to assure safe shutdown under all design transients.

(*) The secondary control rods cannot float as an inherent design feature.

3. UNCERTAINTY ANALYSES

Detailed studies were performed to assess the impact of theoretical and experimental analyses uncertainties, instrumentation accuracy, manufacturing tolerances, physical properties and correlation uncertainties on the core thermal-hydraulic predicted performance. Hot channel/hot spot factors for fuel, radial blanket and primary control assemblies were determined to account quantitatively for the above uncertainties and semi-statistically combined. Separate groups of uncertainty factors were established in each type of assembly for calculation of: a) rod temperatures (coolant, cladding, fuel or absorber); b) coolant exit mixed mean temperature (assembly and upper collector exits); and c) rod fission gas plenum pressure (plenum temperature, rod burnup). An example of such analyses is reported in Table II which applies specifically to rod temperature uncertainties for the fuel assemblies. A detailed documentation of the uncertainty analyses performed for the CRBRP core is reported in Reference [2]. The hot channel factors calculated through these studies were applied to the prediction of core assemblies performance discussed in the next section.

4. PREDICTED THERMAL-HYDRAULIC ASSEMBLIES PERFORMANCE

As mentioned in Section 1, the thermal-hydraulic performance of CRBRP assemblies was predicted on a core-wide basis for a combination of various plant lifetime and operating conditions, i.e., first cycle and equilibrium core, Plant T&H Design and Expected Operating conditions. A complete documentation can be found in References [3] and [4]. Highlights of the most significant results of these analyses follow. The thermofluids behavior of the CRBRP assemblies was evaluated at beginning and end-of-life for the more conservative T&H Design conditions in order to evaluate the maximum value attained by relevant parameters such as rod temperatures, fission gas pressure, mixed mean exit temperature and to assure that specified limits (e.g., no fuel centerline melting) are not exceeded at any time during the reactor lifetime. Values thus calculated also represented the steady state starting point for transient and safety analyses.

A summary example of these analyses is shown in Figure 3 which reports the maximum value during life (at the 2σ level of confidence) of cladding midwall temperature, fission gas pressure and mixed mean exit temperature attained in each fuel and blanket assembly. While in the fuel assemblies the maximum cladding and mixed mean temperatures occur during the first cycle of assembly residence in the reactor (the maximum fission gas pressure obviously occurs at end-of-life), in the blanket assemblies all three parameters reach their peak value at end-of-life conditions. Of course, maximum conditions in the assemblies are not attained simultaneously since the blanket assemblies are shuffled with scattered pattern (assemblies of the B sequence are shuffled with one year lag in respect to other assemblies) and approximately one-third of the fuel assemblies are replaced during the yearly refuelings as shown in Figure 1. Typical examples of cladding lifetime temperature/pressure history are reported in Figure 4. The different lifetime trend between inner zone assemblies (of which assembly #6 is an example) and outer zone assemblies (exemplified by assembly #18) is evident: while in the inner assemblies the cladding temperature is steadily decreasing from beginning to end-of-life, in the outer assemblies it decreases from cycle to cycle (due to depletion effects), but increases during each cycle (due to shift in power from control rod movement). Consequently, the fission gas pressure in the outer zone does not increase as smoothly as in the inner assemblies.

The dramatic effect of the radial blanket assemblies shuffling (remember that the prime purpose of shuffling was to limit the power rating below the melting point) in curtailing the cladding temperature and pressure increase is also evident from Figure 4. In addition, shuffling has a very important effect in limiting the end-of-life pressure. In the case of assemblies of sequence A for example, the fission gas pressure at the end of the second, fourth and sixth years (end of the residence time in each position, respectively) is practically the same although the burnup is continually increasing. This effect is due to the fact that shuffling to a more peripheral position decreases: 1) the plenum temperature, hence the pressure of gas present at time of shuffling; and 2) the assembly power, hence the fuel temperature is reduced to a point below the restructuring threshold level. Additional fission gas release is therefore practically eliminated since the gas release from non-restructured fuel is orders of magnitude less than from the restructured fuel, especially at average assembly burnups of the order of 10,000 - 20,000 MWd/MT as is the case for the blanket assemblies. The lifetime behavior of assemblies F (which do not undergo shuffling) confirms this rationale: the fission gas pressure after the third year of residence increases more rapidly than the cladding (and plenum) temperature, due to the progressive enlargement of the restructured zone and consequent increase of the fission gas release fraction. Thus, the fission gas pressure is higher even though the maximum cladding (and plenum) temperature is less than for radial blanket assemblies of the A type.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

The preliminary thermofluids design and predicted performance of the CRBRP core assemblies has been presented. The behavior of the core assemblies has been found to be compatable with design limits and requirements; adoption of a simple shuffling scheme has provided satisfactory performance of the blanket assemblies; a new orificing criterion has proven to be a definite improvement over past practices and a significant step toward a truely optimized orificing scheme. This preliminary study will be followed by a final design and evaluation, when the CRBRP environment (e.g., nuclear physics data) will be completely finalized. Future thermal-hydraulic related analyses will include: a) improved orificing scheme, optimized on a caldding strain basis; b) improved radial blanket fuel management, optimized on strain and lifetime considerations; c) evaluation of startup cycles (from the second up to establishment of equilibrium conditions); d) modeling of fuel behavior during the entire assemblies lifetime; and 3) consideration of reducing temperature levels and gradients of the upper internals structure.

ACKNOWLEDGEMENTS

Many individuals participated in the studies presented in this paper. The continuous cooperation of C. W. Bach and the assistance of F. C. Engel, D. Y. Nee and D. R. Spencer should be singled out; their most valuable help is gratefully acknowledged.

REFERENCES

1. P. W. Dickson, "Reactor Systems", in Proceedings of Breeder Reactor Corporation, January, 1974 Information Sessions on the CRBRP, CONF-740116, pp. 86-92.

2. M. D. Carelli, D. R. Spencer, "CRBRP Assemblies Hot Channel Factors Preliminary Analysis", WARD-D-0050, October, 1974.

3. M. D. Carelli, C. W. Bach, F. C. Engel, D. R. Spencer, "Predicted Preliminary Thermal-Hydraulic Performance of CRBRP Fuel and Blanket Assemblies", WARD-D-0054, November, 1974.

4. D. Y. Nee, "T&H Evaluation in the Development of the CRBRP Primary Control System Design", WARD-D-0033, February, 1974.

TABLE I

PREDICTED THERMAL-HYDRAULIC PERFORMANCE OF CRBRP CORE AT EQUILIBRIUM CONDITIONS

PRIMARY SYSTEM	PLANT T&H DESIGN VALUES		PLANT EXPECTED OPERATING VALUES	
Reactor Power, MWt	975		975	
Inlet Temperature, °F	730		716	
Outlet Temperature, °F	995		965	
Flow, lbm/hr	41.446×10^6		44.044×10^6	
FUEL ASSEMBLIES	**BOL**	**EOL**	**BOL**	**EOL**
Maximum Midwall Cladding Temperature, °F (2σ)	1350	1200	1307	1165
Maximum Assembly Mixed Mean Outlet Temp., °F (Nominal)	1107	1016	1070	985
Maximum Fuel Centerline Temp. (3σ plus 15% overpower)	4780	NE	4760	NE
Peak Linear Power, Kw/Ft	11.1	8.7	11.1	8.7
Maximum (3σ plus 15% overpower) Linear Power, Kw/Ft	14.4	11.3	14.4	11.3
Maximum Fission Gas Pressure, Psia (2σ)	186	1790	182	1750
Maximum Assembly ΔP, Psia	111	111	126	126
Maximum Burnup, MWd/MT	---	150,000	---	150,000
RADIAL BLANKET ASSEMBLIES				
Maximum Midwall Cladding Temperature, °F (2σ)	964	1284	940	1244
Maximum Assembly Mixed Mean Outlet Temp., °F (Nominal)	842	1049	822	1016
Maximum Fuel Centerline Temp. (3σ plus overpower)	2267	4981	NE	NE
Peak Linear Power, Kw/Ft	4.7	14.5	4.7	14.5
Maximum (3σ plus overpower) Linear Power, Kw/Ft	7.1	19.6	7.1	19.6
Maximum Fission Gas Pressure, Psia (2σ)	191	379	186	377
CONTROL ASSEMBLIES, PRIMARY/SECONDARY				
Maximum(*) Midwall Cladding Temp., °F (2σ)	1206/1050	1195/NA	NE	NE
Maximum(*) Assembly Mixed Mean Outlet Temp., °F (Nominal)	988/805	982/NA	NE	NE
Maximum(*) Absorber Centerline Temp. °F (3σ plus overpower)	2187/2870	1963/NA	NE	NE
Maximum(*) Plenum Pressure, Psia	NE	4000/NA	NE	NE
Flow Split (Bundle/Total)	0.63/0.51	0.63/0.51	0.63/0.51	0.63/0.51

(*) Primary: fully inserted conditions. Secondary: parked conditions.
NA Not available.
NE Not evaluated.
BOL Beginning of life.
EOL End of life.

TABLE II

CRBRP FUEL ASSEMBLIES ROD TEMPERATURES HOT CHANNEL/SPOT FACTORS

		Coolant	Film	Cladding	Gap	Fuel	Heat Flux
DIRECT(+)							
Power Level Measurement and Control System Dead Band		1.03					1.03
Inlet Flow Maldistribution		1.05 }	1.035				
Subassembly Flow Maldistribution Calculational Uncertainties		1.08 }					
Cladding Circumferential Temperature Variation			1.0(◇) 1.7(*)	1.0(◇)			
STATISTICAL (3σ)(o)							
Inlet Temperature Variation		1.02(ϕ) 1.0(†)					
Reactor ΔT Variation		1.04(ϕ) 1.0(†)					
Nuclear Data		1.06					1.065
Fissile Fuel Maldistribution		1.01					1.035
Wire Wrap Orientation		1.01					
Subchannel Flow Area		1.028	1.0				
Film Heat Transfer Coefficient			1.12				
Pellet-Cladding Eccentricity			1.15	1.15			
Cladding Thickness & Conductivity				1.12			
Gap Conductance					1.48(1)		
Fuel Conductivity						1.10	
Coolant Properties		1.01					
TOTAL	2σ	1.232(ϕ) 1.221(†)	1.168 1.986(*)	1.128			1.081
	3σ	1.264(ϕ) 1.248(†)	1.234 2.101(*)	1.192	1.48	1.10	1.106

(+) Uncertainties due to physics analysis calculational methods and control rod effects (4% on coolant enthalpy rise and 5% on heat flux) are applied directly on nuclear radial peaking factors.

(*) For cladding midwall temperature calculations. Applies to nominal temperature drop between cladding midwall and bulk coolant.

(◇) For fuel temperature calculations.

(o) In addition, the assembly inlet temperature will be increased by 16°F, to account for primary loop temperature control uncertainties.

(1) Applies to BOL conditions.

(ϕ) Applies to Plant Expected Operating Conditions.

(†) Applies to Plant T&H Design Conditions.

6869-1

ZONE	FLOW (LB/HR)
①	184240
②	165355
③	155690
④	144800
⑤	126130
⑥	53590
⑦	49530
⑧	28860
⑨	15310

CONTROL ASS'Y	FLOW (LB/HR)
CENTRAL	40140
ROW 4 (Primary)	33915
ROW 4 (Secondary)	15700 (Upflow Only)
ROW 7 CORNER	33915
ROW 7 FLAT	40140

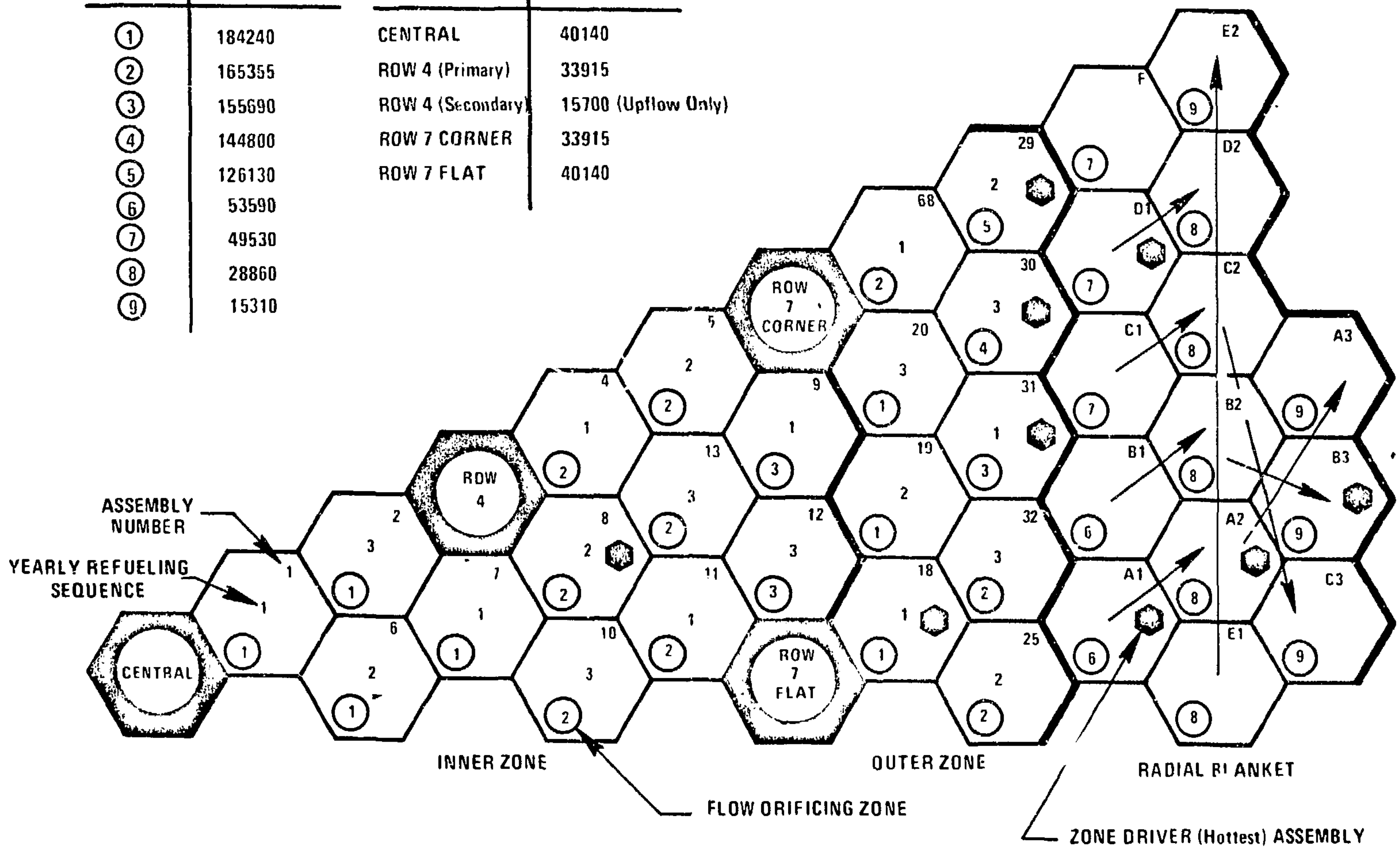

Figure 1. CRBRP Reference Assemblies Orificing, Fuel Refueling, and Radial Blanket Shuffling Schemes

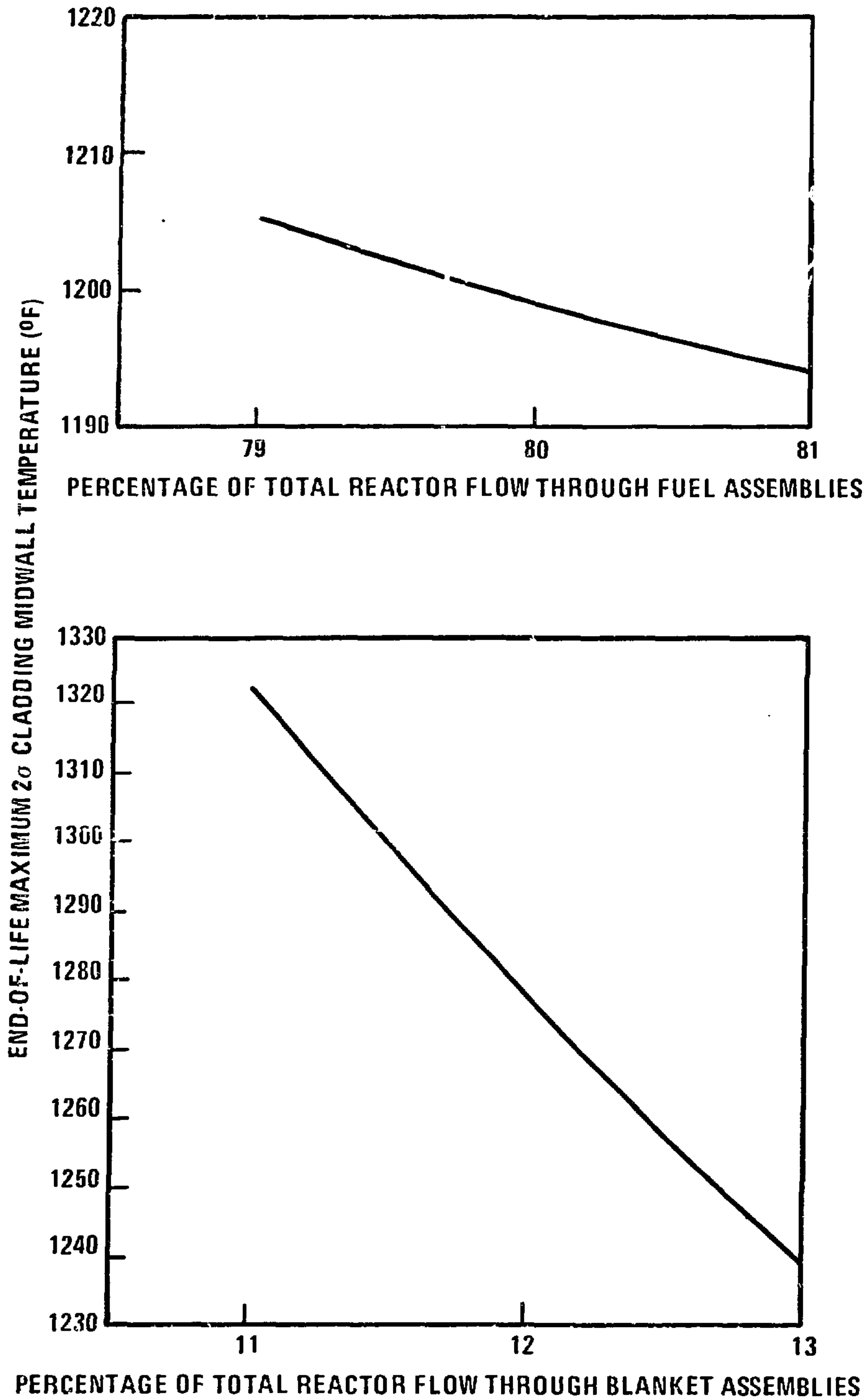

Figure 2 Maximum Cladding Midwall Temperature in Fuel and Blanket Assemblies as a Function of Assigned Flow (Plant Thermal Hydraulic Design Conditions)

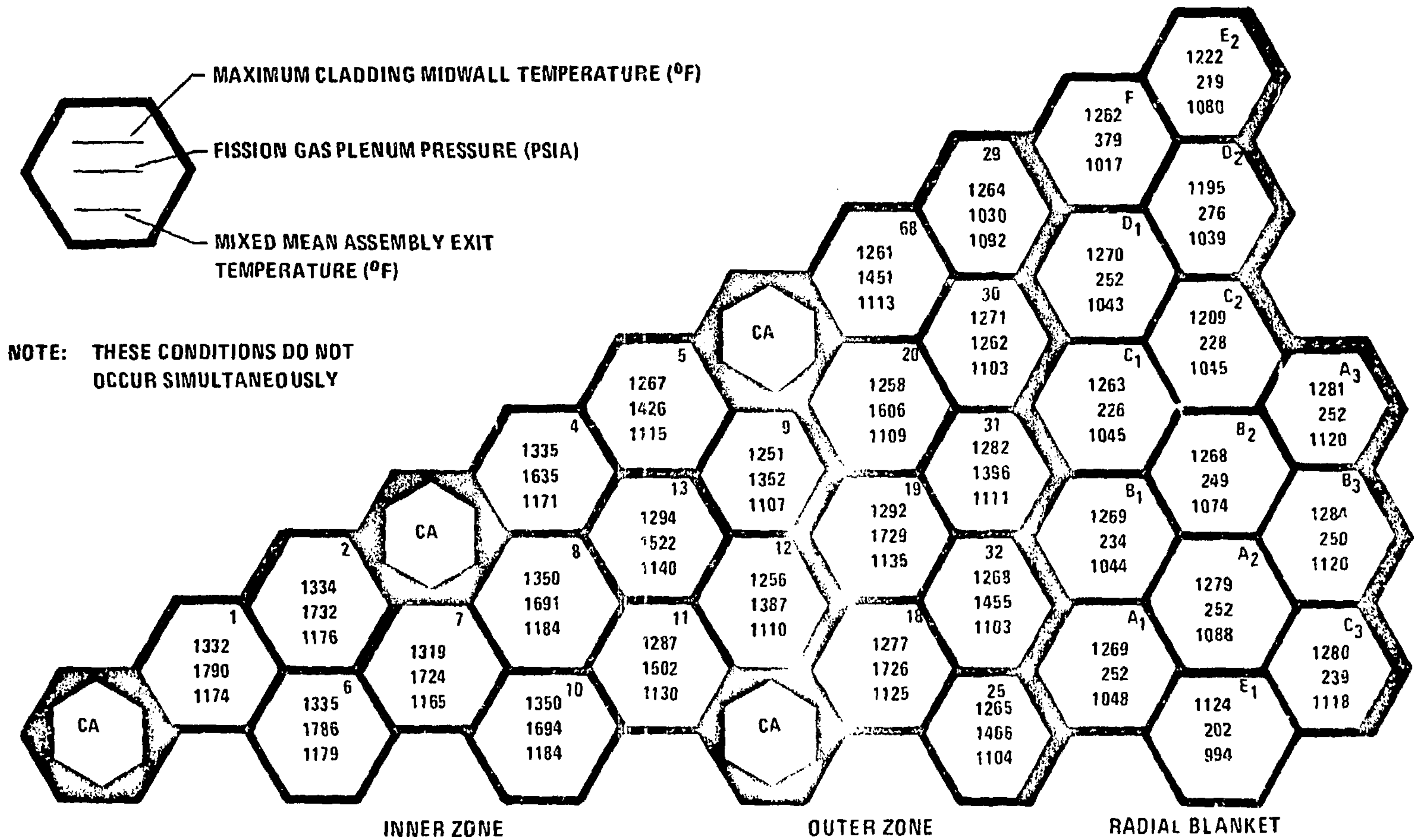

Figure 3. Envelope of Maximum Values (At 2σ Level of Confidence) of Significant Thermofluids Parameters for CRBRP Core Assemblies at Plant T&H Design Conditions

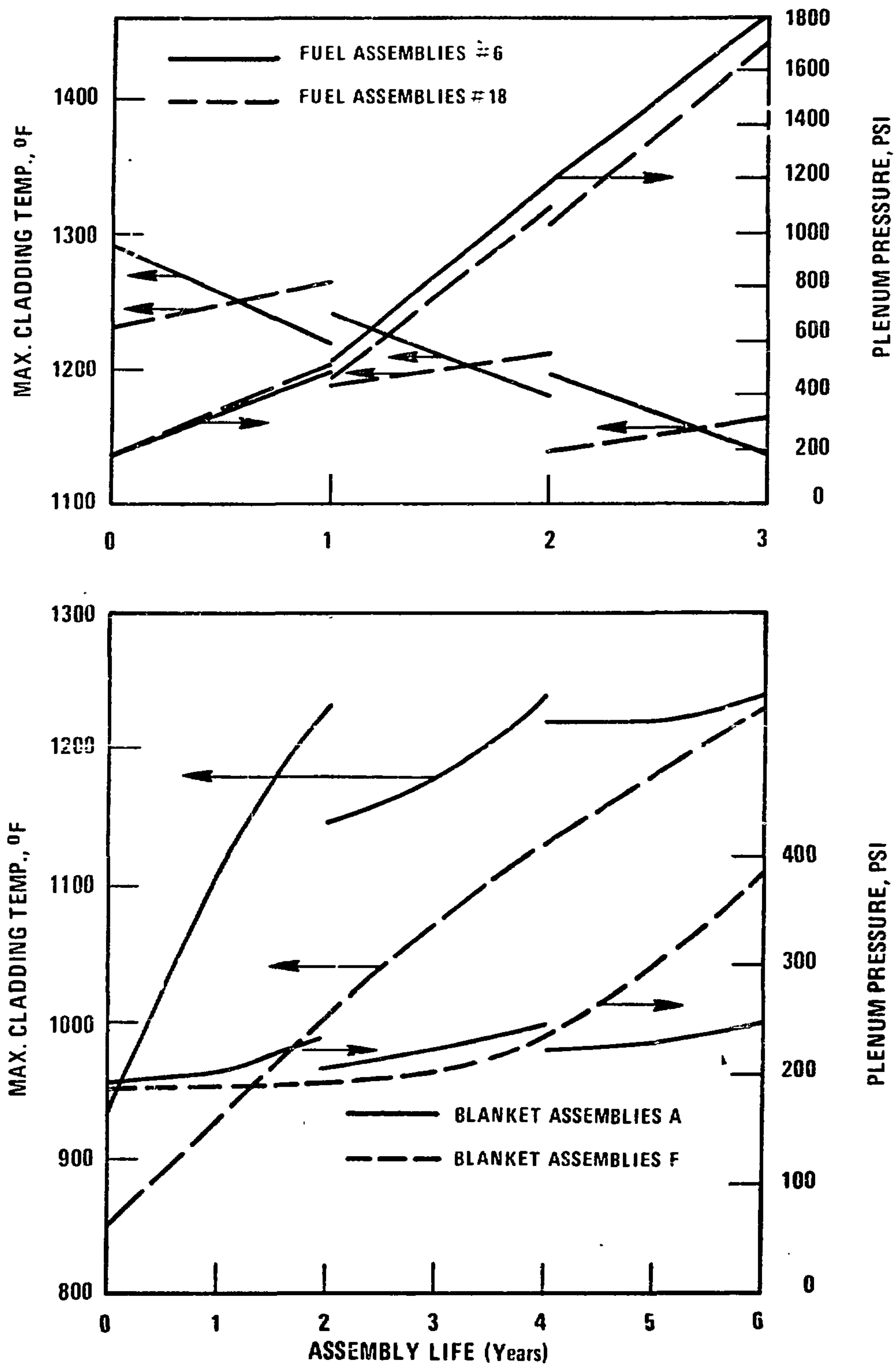

Figure 4. Typical Cladding Lifetime Temperature/Pressure History in CRBRP Fuel and Radial Blanket Assemblies

6869-2