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REACTOR FLOW AND PRESSURE DROP STUDY

By

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ABSTRACT

A study was made to determine the flow rates and pressure drops for all primary system flow paths through the FTR. The main data and results are in tables, diagrams and curves. The results are intended to provide a common basis for evaluation of parametric changes in the system.

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ERRATA

On page C-2 of Reactor Flow and Pressure Drop Study, change the equation for the Reynolds number to read:

$$Re = \frac{MDe}{\mu A_f} \times \frac{3600}{12} = \frac{WDe}{\mu A_f 12}$$

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NOMENCLATURE

- N = number of pins in bundle
 N_D = number of pins in long hex dimension
 d_p = pin diameter, inches
 d_w = wire diameter, inches
 D_F' = hex dimension across flat for snug-fit bundle, inches
 D_F = hex dimension across flat including fit allowance, inches
 D_T' = hex dimension across corners for snug-fit bundle, inches
 D_T = hex dimension across corners including fit allowance, inches
 L = length, inches
 B = wetted perimeter, inches
 D_e = equivalent diameter, inches
 A = flow area, inches²
 P = triangular pitch ratio, $(d_p + d_w)/d_p$
 F = allowance factor, D_F/D_F' or D_T/D_T'
 ΔP = pressure drop, psi
 ΔT = temperature rise, °F
 K = dimensionless resistance coefficient
 f = dimensionless friction factor, Moody's
 M = flow, lb/sec
 W = flow, lb/hr
 g = gravitational constant, 32.2 ft/sec²
 ρ = density, lb/ft³
 μ = viscosity, lb/hr-ft
 Re = Reynold's Number

It is expected that the HTS supply pressure will exceed the minimum reactor-head demand. This study seeks an estimate of this head difference; which is called available pressure.

II. PURPOSE

The purpose of this study is:

- . To identify all flow paths through the reactor.
- . To prepare demand,¹ power, and other curves of importance for characterizing reactor power, flow and pressure drop.
- . To disclose uncertainties (as curves bounding a standard curve, or as otherwise stated). Assumptions are to be stated.

1 "Demand" curves in this study mean pressure drop versus flow curves. Some engineers customarily use "characteristic" or "operating" curves.

III. SUMMARY

This study is best summarized by the diagrams, Figure 2 and 3, and in the three tables of results as follows:

- . Table III, page 41, shows the reactor flow in-toto and component by component.
- . Table I, page 28, shows the basic pressure drop through the reactor.
- . Table IV, page 46, shows the pressure drop available between the HTS delivery capability and the reactor basic pressure drop.

The available pressure drop can be applied to the following:

- . Closer packing of drivers and open loop bundles.
- . Use of grid-spaces in lieu of wire wrap for the support of driver and open loop test bundles. One study indicates a minimum of 45 psi.
- . Use of all left over pressure drop for orificing of drivers.

IV. CONCLUSION

On the basis of this study it is concluded that the Reactor flow and pressure head demand are within the HTS normal delivery capability. The available head between the HTS normal and the reactor needs is estimated as 64 to 83 psi depending on the flow used. See Table IV.

V. DESCRIPTION

FTR heat removal is complicated by the multiplicity of heat sources and coolant flow paths. While most of the heat is generated in the core, significant amounts also are generated in the control rods, reflectors, surrounding shields and in the in-vessel fuel storage (decay heat). The differing heat removal requirements for each group of sub-assemblies, including the core, must be satisfied for proper and safe reactor operation. The core map, Figure 1, shows the reactor groups and the subassembly positions in the matrix arrangement. Outside the matrix, temperature limitations of the reactor vessel wall present an additional coolant flow requirement. This flow removes no reactor generated heat. It merely quenches the exit coolant. Leakage flow occurs through the fitting from the grid plate to inlet plenum joint. Some leakage is necessary for providing driver and open-loop subassembly holddown forces. Primary coolant flow must be coupled suitably to remove all the heat generated with due allowance made for the leakage flows. The flow paths are illustrated in Figures 2 and 3. Figure 2 assumes that all cooling is accomplished by parallel paths through the reactor. Figure 3 assumes that cooling is accomplished by parallel paths except for the reflector, shields and the in-vessel fuel storage which assumes that natural convection cooling within reactor pool. To ascertain the total reactor flow each flow path must be independently analyzed for its contribution and the individual contributions integrated.

Coupled with the flow problem is the pressure drop problem. The flow path having the highest pressure drop establishes a basis for the overall pressure to which all parallel paths must be made equal.

FIGURE NO.1
CORE MAP

- OPEN TEST ASSEMBLY WITH PROX. INSTR. - 1
- OPEN TEST ASSEMBLIES - 2
- CLOSED LOOPS - 6
- SAFETY RODS - 3
- REFLECTOR/RESTRAINT POSITIONS - 42
- PERIPHERAL CONTROL RODS - 15
- REFLECTORS - 66
- DRIVERS - 76
- FLUX MONITOR POSITIONS - 2
- IN-CORE SHIM/SCRAM RODS - 3
- COMBINATION STIFF AND FLUX MONITOR POSITION - 1

FIGURE 2

HIGH FLOW DIAGRAM

FIGURE 3.

LOW FLOW DIAGRAM

The maximum-flow driver assembly is the key pressure drop path. All other paths, including the lesser flow drivers, have a lower basic pressure drop than the maximum-flow driver without orificing because of the lower flow requirements.

For this initial study the driver dimensions are as follows:¹

- . 0.230 inch fuel pin diameter
- . 0.056 inch wire wrap diameter
- . 12 inch wire wrap pitch
- . 93 inch long fuel assembly not including inlet shield

While these dimensions and the spacing scheme are the BNWL choice for now, they do not exclude other possible future choices. The wire wrap diameter being relatively large compared with the pin diameter, $P = 1.243$, and being wrapped at the 12 inch pitch, is a low pressure drop arrangement. Other dimensions could and other support schemes such as grid spacers would probably demand greater pressure drop capability. Such prospects as these will probably apply to open loop (OL) tests where all manner of test bundle sizes and support schemes could require a higher range of pressure drop capability. As an example, one study,² indicates a minimum of 45 psi additional pressure drop needed. Available pressure drop over and above the minimum core needs is valuable for orificing of all fuel assemblies. Orifices can be made so precise that demand characteristics can be established with reduced uncertainty. It can be shown that the tolerance band on flow through similarly orificed bundles can be reduced.

1 See Appendix A for additional derived data

2 Based on verbal information from WARD; honeycomb spacers to be at 6 inches below core, 4 inches through core and at 7 inches above core

The pressure drop available for the aforementioned needs is dependent upon the difference between normal delivery capability of the HTS and the minimum reactor pressure drop. The HTS capability has been defined in the introduction as a point on the HTS pump normal characteristic curve. The reactor flow demand is expected to be less than the 42,000 gal/min mentioned, but it could be more under certain circumstances, which will be made clear later. Flows below 42,000 gal/min must be accompanied by an increase in pressure head, and flows greater, by a decrease. The pressure drop across the reactor, plenum-to-plenum is expected to be in the neighborhood of 145 psi. This is not a design requirement, but is expected to cover all pressure drop contingencies and still leave something over to orifice.

VI. DISCUSSION

A. GENERAL

The characteristic performance curves for the reactor, the reactor sub-groups, the subassemblies and the components thereof, are presented as best estimates. Each figure is qualified by notations on the curves and by the text as to basis and limitation. Comments are invited and verified material will be incorporated into this study.

B. EFFECT OF COOLANT TEMPERATURE ON PRESSURE DROP

The sodium coolant temperature effect on the pressure drop was found small enough to be disregarded. Demand curves in the accompanying figures are applicable for any temperature rise, even zero degrees, for temperatures between 500 °F and 900 °F provided that the core mean temperature is used as a basis for properties. Appendix B is an analysis comparing the influence of temperature upon pressure drop. As an extreme case, for isothermal flows at 500 °F and 900 °F, the difference in ΔP is about 2.2%.

C. CORE DRIVERS

The most important coolant flow path is that through the core drivers. Here the bulk of the heat is generated and most of the coolant flow occurs. The core driver flow is complex. The diagrammatic representation of Figures 2 and 3 is an over simplification. There are 76 parallel driver flow paths, each as diagrammed in the two figures. The energy generated in a driver decreases with distance from the core center. If no flow restrictions are incorporated in the drivers, each would have essentially the same flow but a coolant temperature rise proportional to the energy generated. Fuel pin temperature levels would be affected, central being high and fringe low. Flow adjustments between drivers to flatten fuel temperatures can be accomplished by adding suitable restrictions to the drivers. The temperature criteria for making this flow adjustment is covered next.

D. ORIFICING¹

Orificing schemes for uniform average temperature rise and uniform peak cladding temperature were considered. For both schemes, the orifice pattern used was one in which all subassemblies in a given "ring" or "hexagonal row" have the same orifice size. This pattern was chosen because it is impractical to orifice individual subassemblies and to change orifice requirements as burnup progresses or when different experiments are inserted.

The ring flow rate for the criteria of uniform average temperature rise was determined using the average power of each ring and the requirement that the ring bulk mean coolant temperature rise be 300 °F. This scheme is not amenable to hot channel analysis because the slope of the power curve and the effect of intra-subassembly energy transport are neglected. Thus, there is no guarantee that the peak clad temperature is less than some specified value.

For the criteria of uniform peak cladding temperature the ring flow rates are determined by an iterative procedure in which the flow in each ring is varied until the peak cladding temperatures of all rings are equal. The peak cladding temperature is defined as:

$$T_{\text{peak}} = (\Delta T_c \cdot \text{HCF}_c) + (\Delta T_{\text{film}} \cdot \text{HCF}_{\text{film}}) + (\Delta T_{\text{clad}} \cdot \text{HCF}_{\text{clad}}) + T_o$$

Where:

ΔT_c = coolant ΔT for coolant associated with the peak pin in the ring.

HCF_c = coolant hot channel factor (including energy transport)

1 Based on memo, C. Wheeler to R. Keyes, 4/18/69, subject: Core Orificing; also later memo, same subject, 5/26/69

$$\Delta T_f = \text{film } \Delta T$$

$$HCF_{\text{film}} = \text{film hot channel factor}$$

$$\Delta T_{\text{clad}} = \text{clad } \Delta T, \text{ function of peak pin power}$$

$$HCF_{\text{clad}} = \text{clad hot channel factor}$$

$$T_o = \text{inlet temperature}$$

The required flow rates for each of the six orificing rings for both criteria are shown in the accompanying Figure 4. The flow rates are based on currently available power data and are subject to change, depending upon the selected fuel management scheme and test loading results.

The available pressure drop for orificing is dependent upon the difference between the HTS delivery capability and the driver minimum pressure drop demand. Discussion of this subject will come later in its logical place.

The discontinuity at 20 cm radius is accountable to the difference in fuel formulation between the two core zones. It is worth noting that, at the outermost row, there is a flop-over in the flow relationship. A rough estimate discloses the maximum cladding temperature to be 50 °F higher for the constant temperature rise criterion than for flow based on the uniform peak cladding temperature criterion. The uniform peak cladding temperature criterion is the conservative choice. A lower pressure drop through the maximum flow driver is gained because the flow is lower.

The 2.073×10^5 lb/hr rate of the maximum flow driver is the reference value chosen for this study. It, along with other driver flows

FIGURE 4
DRIVER FLOW VERSUS RADIAL DISTANCE FROM CORE CENTER

per Figure 4, happens to suit a temperature rise through the core of slightly above 300 °F for a reactor power of about 400 MW.

E. CORE COMPONENTS

1. Driver Flow Path

A typical driver flow path through the core involves a number of components. Figure 5 is a diagrammatic of both the flow through a driver assembly and flow through open loop test assembly. The open loop test assembly detail will be the experimenter's choice. We can derive no demand curves. The driver assemblies will have the same demand curve before incorporation of the orifices. So we commence with deriving the unorificed demand curve for a typical driver assembly. Component demand curves to follow are discussed in order of their position in the flow path, except for the orifice which will be discussed later. From the component characteristic it will be possible to develop the overall core characteristic curve.

FIGURE 5

TYPICAL DIAGRAMS OF DRIVER AND OPEN LOOP

2. Inlet Receptacle and Hold-Down Leakage

An inlet receptacle conducts coolant from the inlet plenum to the driver assembly. The leakage flow that occurs at the receptacle-driver assembly interface is necessary for providing a hold-down force to overcome the pressure uplift force. A calculation based on an assumed diametral clearance of 0.020 inches result in 2.1% of driver flow required for hold-down leakage. If the nose piece of the fuel assembly were to fit eccentrically or if a greater clearance is needed, the leakage flow would be higher. There seems to be a great deal of uncertainty expressed regarding hold-down leakage. Undoubtedly more study is necessary and additionally some testing is planned in order to reduce the uncertainty. Our selection for now is 1.00×10^6 lb/hr for normal reactor operation total hold-down leakage. The pressure drop through the receptacle is small and not greatly affected by the uncertainty of the leakage flow. The demand curve for the receptacle is shown in Figure 6.

3. Driver (Fuel) Assembly

The driver fuel assembly for pressure drop purpose is considered to be from the top of the receptacle to the instrument probe inlet. The parts included are the fuel bundle and the shroud tube before and after the fuel bundle. Figure 7 is the demand curve for the bundle friction. Figure 8 is the demand curve for the fuel bundle inlet and exit pressure drop plus the friction of the shroud tube before and after the bundle. The alignment structure at the inlet and outlet of the bundle was not especially considered. The pin length carried over this structure length was allowed to account for this pressure drop. Refer to Appendix C for details for calculating these and other pressure

NOTES:

1. REF. DWG. SK-3-14 400
2. BASED ON SLOTS IN NOSE PIECE TO MATCH RECEPTACLE SLOTS.
3. ASSUMED 0.020 DIAMETRAL CLEARANCE FOR HOLD-DOWN LEAKAGE OF 2.1%.

FIGURE 6

INLET RECEPTACLE ΔP VS FLOW

NOTES:

1. REF. DWG. SK-3-14581
2. METHOD OF ΔP CALCULATION SEE APPENDIX C
3. FOR SHIELD AT BUNDLE INLET ADD 12 INCHES.
4. $\Delta P_{\text{SHIELD}} = 12/93 \times \Delta P$

FIG. 7 FUEL BUNDLE FRICTION ΔP VS FLOW

drops. Pressure differences due to elevation differences are not included. From Figure 7 and 8 the demand curve for the driver assembly is derived and disclosed in Figure 9.

Figure 10 is a power curve suitable for determining driver power generation.

4. Inlet Shield

Appropriate allowance for the inlet shield, a 12-inch extension of the driver fuel bundle at the entrance, can be ratioed from Figure 7.

FIGURE 8

OTHER ΔP LOSSES IN THE
FUEL ASSEMBLY vs FLOW

FIGURE 9 DRIVER ASSEMBLY UNORIFICED
 ΔP vs FLOW

FIGURE 10
POWER CURVES FOR FUEL ASSEMBLY
AND OPEN LOOP

5. Instrument Probe

An instrument probe is provided for each driver assembly. Groups of instrument probes are lowered into mating groups of driver assemblies and secured there for reactor operation. The diametral clearance between the tube enclosing the instrument probe and the top fitting of the fuel assembly serves as a leakage path. The coolant flow from the driver assembly is divided between the instrument probe and the leakage.

The FEDAL system is under study at this time. Consequently the instrument probe details are not fully determined. For now the instrument probe pressure drop is assumed to be 15 psi,¹ and Figure 11 demand curve is so based. Some leakage flow must be accepted through the annular clearance channel at the probe-driver assembly interface. If minor this leakage may not interfere with the required performance of the probe instrumentation. Figure 12 is a demand curve for the leakage path noted thereon. It is expected that a large tolerance band apply to the leakage flow due to the likelihood of eccentric fit and to dimensional tolerances of the parts. If necessary to reduce leakage more resistance can be designed into the leakage path. Figures 11 and 12 are incorporated into Figure 13 to make a combined probe and leakage demand curve. The maximum leakage is less than 10%, which is probably acceptable.

Revisions of these figures should be expected and final characteristics determined from testing.

1 FEDAL Review Meeting at BNW, May 16 and 17, 1969, Agreements and Commitments, RR Derousseau memo June 4, 1969

FIGURE II INSTRUMENT PROBE
 ΔP vs FLOW

FIGURE 12
INSTRUMENT PROBE LEAKAGE
 ΔP VS FLOW

FIGURE 13 INSTRUMENT PROBE & LEAKAGE
 ΔP 's vs FLOW

F. CORE

The coolant path through the core, plenum-to-plenum, is the integrated sum of all driver flow paths.¹ The core flow demand curve and the applicable flow diagram are shown in Figure 14. All but the maximum flow driver are assumed to be orificed to give the Figure 4 driver flow rates at the pressure drop of the maximum flow driver at its flow rate unorificed.

Based upon the information generated thus far, it is possible to set a basic pressure drop for the reactor. By this is meant the required pressure drop before orificing the maximum flow driver assembly and for the core operating at some nominal flow. For now we say the flow rates of Figure 4 apply. Component by component the pressure drops through the maximum flow driver are summarized in Table I. This pressure drop is not to be construed as a requirement nor are the component pressure drops to be so construed. They only represent the best estimates that can be made at this time.

1 In Figures 2 and 3 the OL's are lumped with the drivers to represent the core. For convenience the OL's are not included with the drivers.

FIGURE 14 CORE WITH UNORFICED MAXIMUM
FLOW DRIVER INLET TO OUTLET PLENUM
 ΔP vs FLOW

TABLE I - REACTOR PRESSURE DROP

ITEM	FIG. NO.	ΔP psi	$\pm \Delta P$ psi	Ref. Dwg. No. - Issue - Date	BASIS	REMARKS	NOTES
Inlet Plenum	-	-	-	SK-3-14585, 1st 2/18/69	2100-1 in. dia. Holes, 2 in. Long		
Receptacle	6	1.1	0.2	SK-3-1440, 1st 10/22/68	Nose Pc. Slotted to Match Receptacle slots; leak path P = 1/4; 0.02-in. dia. Cl	Leakage = 2.1% depend on design	(1)
Fuel Bundle							
Friction Inlet	7	52.0	8.3	SK-3-14581, 2nd, 2/19/69	217-pins/0.23 in. dia. pin/.056 in. D wire @ 12-in. pitch/93-in. Lg.	Temp effect within 1.3 psi band 500 to 900 °F	(1&2)
Inlet & Outlet & Shroud Tube	8	3.4	1.0				
	8	3.4	1.0				
Instrument Probe	13	15.0	2.0	SK-3-12896, 2nd 3/14/69 SK-3-14581, Mod.	4.12 in. dia. x 0.60 in. dia. Cl x 1-in Lg. Leak Path; Na at 900 °F	Leakage 7.9 to 9.6% of flow per note 1	(2)
Shield at Inlet	7	6.7	1.1		12-in extension of fuel bundle		(1)
Total	14	78.2	8.7				(4)
Elev ΔP		7.4	-	SK-3-14541, 1st	About 20.7 ft. @ 700 °F		(3)
Reactor Between Plenums		85.6	± 8.7				(3)

Notes:

1. Max flow bundle, $W = 2.073 \times 10^5$ lb/hr based on a uniform max. cladding temperature criterion.
2. Elevation ΔP , receptacle inlet to instrument package outlet, 600 °F in/700 °F core ave./900 °F out = 7.05 psi
3. Cumulative tolerance = $\pm \sqrt{\sum_{n=1}^n (Tol_n^2)}$
4. Called "basic pressure drop" later in the report.

G. CONTROL RODS

The control rods are composed of three groups. Each rod contains, for this study, 5924 grams of natural B_4C^1 . Table II contains data on the control rod assemblies based on the assumption of a 200 °F coolant temperature rise for rods fully inserted.

TABLE II - CONTROL ROD ASSEMBLY DATA

Type	No.	Radial Position cm (1)	Watts per Gram (2)	Power MW	Flow lb/hr	
					Per Assy.	Group
Safety	3	32	65	0.385	2.13×10^4	0.064×10^6
Control	3	48	52	0.308	1.70×10^4	0.051×10^6
Peri- pheral	15	62 & 67	38	0.225	1.25×10^4	0.188×10^6

Total Flow = 0.303×10^6

(1) CCDD No. 33, Figure 7

(2) CCDD No. 33, Figure 9

Figure 15 is the demand curve for an unorificed control rod assembly. The orificing needed to match pressure drop to the required flow the plenum-to-plenum will necessarily take up the bulk of the total pressure drop. Figure 16 is a power curve for a single assembly showing the temperature rise as parameter. Figure 17 is the overall power curve for all rods for total control rod flow. The total power is generated by the insertion of some rods, while others are totally withdrawn and some partly inserted. The same flow is intended for each rod in a single group, as in Table II regardless of the rod's position.

1 CCDD for the Reactor Nuclear Control Component No. 33

FIGURE 15
CONTROL ROD ASSEMBLY
 ΔP VS FLOW

FIGURE 16

POWER CURVES
FOR
CONTROL ROD

FIGURE 17

POWER CURVES
FOR
CONTROL RODS

The design concept does not consider any flow control to suit rod position.

The control rods will need to be studied in detail to check the suitability of the 200 °F temperature rise assumption.

H. REFLECTORS AND CORE SHIELDS

The reflector and core shield assemblies cooling requirements are so minor that pressure drop through an unorificed assembly is almost nil. Orificing is necessary to make up the total plenum-to-plenum pressure difference. An alternative to cooling by parallel plenum-to-plenum flow paths is the use of natural convection circulation within the reactor pool. This alternative is considered as a means to achieve low HTS flow. Figure 18 and 19 show the power curves with temperature rise as a parameter for a reflector assembly and a core shield assembly respectively.

The power generated in the reflector and shield is about 19 MW when the reactor is operating at 400 MW.¹ This can be divided as about 15 MW approximately in the reflector and 4 MW in the shield. At an assumed coolant temperature rise of 250 °F the flow rates are respectively 0.665×10^6 lb/hr and 0.177×10^6 lb/hr.

1 W. L. Bunch, Energy Deposition Distribution in the FTR, BNWL-563, October, 1968

FIGURE 18

POWER CURVES
FOR
REFLECTOR

FIGURE 19

POWER CURVES
FOR
SHIELD

I. REACTOR VESSEL WALL COOLING

A concept related requirement is that the reactor vessel wall and outlet nozzles be cooled to a temperature less than 1000 °F by means of by-pass cooling.¹ The vessels conceptual design is suitable for a mixed mean coolant discharge temperature of 1200 °F. The major advantage of wall cooling is the reduction in wall and nozzle thermal gradients in response to HTS transients. The reference design concept is to channel some primary coolant up an adjacent annular passage between the wall and an inboard thermal liner. Figure 20, based on an assumed reactor bulk temperature rise of 350 °F,² shows that a flow of 0.5×10^6 lb/hr for a cumulative liner thickness of 2.5 inches meets requirements. If a cumulative liner thickness of 3 inches is used, then the flow would be high on the conservative side. Figure 21, a non-dimensional representative of the temperature rise versus wall coolant flow, can be usefully applied to other design parameters.

1 CCDD for the Reactor Vessel and Shield Component No. 32, 3/25/69, P 1-8 and 2-12 to 2-24

2 350 °F is a good approximation of reactor ΔT for a core bulk $\Delta T = 400$ °F

FIGURE 20 WALL COOLING
TEMPERATURE RISE vs FLOW

REF: MEMO., J. MURAOKA TO D.P. SCHIVELY, 3-3-69
 SUBJECT: HEAT LOAD ON VESSEL
 WALL COOLANT STREAM

FIGURE 21 WALL COOLING
 NORMALIZED TEMPERATURE RISE vs FLOW

J. REACTOR POWER AND FLOW

It is now possible to estimate an overall reactor flow rate. Flow through most of the reactor flow paths has already been mentioned. Additional items not yet covered are as follows:

- . 3 open loops are assumed to operate at 75% of a driver assembly in the same row.
- . Grid plate leakage is estimated as 0.200×10^6 lb/hr approximately; this could change with any design change and should be watched.
- . In-vessel fuel storage decay heat is assumed to be 1 MW and the corresponding coolant flow rate to be 0.090×10^6 lb/hr.

The power and the flow rates are summarized in Table III to give what we call a nominal and a maximum reactor condition. The power is set at 400 MW and the flow rates are set to suit an average core temperature rise of 301°F and other temperature rises as shown in the table. There is sufficient uncertainty to all the calculation that the core temperature rise could equally well be called 300°F . The flow rate summaries are stated for a High Flow and a Low Flow prospects. The High rate is based on the assumption that all nuclear heat is removed by plenum-to-plenum flow through the core, control rods, reflectors, shields and in-vessel fuel storage. The Low rate is based on the assumption that the nuclear heat from the reflectors, shields and in-vessel fuel storage is removed via natural convection cooling within the reactor sodium pool.

There is the prospect that the FTR may operate without the six closed loops (CL's). In this event it is expected that driver assemblies would be substituted. In Table III the additional flow for

TABLE III - REACTOR POWER AND FLOW

Flow Path	Power			ΔT °F	High Flow		Remarks	Low Flow		
					Flow			Flow		
	MW	Tol [±]	%		10 ⁶ x Lb/hr	%		10 ⁶ X Lb/hr	%	Remarks
76-Drivers	365.8		91.4	301	13.577	80.28		13.577	84.92	
3-Open Loops	10.8		2.7	301	0.405	2.39	Assume 75% Driver	0.405	2.54	Same
Core	376.5	5.7	93.11		13.982	82.67		13.982	87.46	
Hold-down Leakage					1.000	5.91	For study & Test	1.000	6.26	Same
Control Rods	3.5	1.5	0.9	200	0.303	1.79	ΔT for in-rods only	0.303	1.90	
Reflectors	15.0	2.0	3.8	250	0.665	3.93				Use nat. conv. to reactor pool
Shields	4.0		1.0	250	0.177	1.04				
Grid Pl. Leakage					0.200	1.18		0.200	1.25	
Wall Cooling				100	0.500	2.95	2.5-in liner	0.500	3.13	
In-vessel fuel storage	1.0				0.090	0.53				Nat. conv. in pool
Nominal Total	400.0	6.3	100	264	16.917	100	$Tol = \pm \sqrt{\sum (Tol_n)^2}$	15.985	100	$\Delta T = 280^\circ F$
					40,300	gal/min @ 900°F		38,100	gal/min @ 900°F	
6-Closed Loops for Drivers					1.046	6.17	Flow/driver row added	1.046	6.54	
Maximum Total	400.0			249	17.963	106.17		17.031	106.54	$\Delta T = 263^\circ F$
					42,800	gal/min @ 900°F		40,600	gal/min @ 900°F	

the six substitute drivers is shown as 1.046×10^6 lb/hr. This has been figured by adding the driver flow rates of Figure 4 for the CL row location. This choice is arbitrary because there is no stated requirements.¹ The contents of Table III are intended as reference information and are not yet to be construed as strict requirements.

K. REACTOR DEMAND CHARACTERISTICS

1. Reactor and HTS

The objective of analyzing all the flow paths is to arrive at the overall reactor characteristic. The reactor pressure drop is keyed to the "basic" pressure drop value of Table I and the range of flow rates are from the Table III. The HTS characteristic is based on a 500 foot (182 psi) head at 42,000 gal/min total pumping capability and a corresponding system resistance loss assumed at 37 psi outlet plenum to inlet plenum.

The pressure difference between normal HTS delivery capability and the reactor "basic" demand value is called the "available" pressure drop or head. This is the pressure difference that can be used in the driver flow paths for orificing. Figure 22 illustrates the construction of the reactor overall demand curve. Figure 23 is the overall demand curves for the FTR based on the flow path studies of this report. Table IV summarizes the available pressure difference for the four flow rates of Table III. Figure 24 is a power curve for the overall reactor with parameter of temperature rise. It is applicable also to the core when entered with the core's flow rate.

1 CSDD No. 61, Appendix B, item B-5.

FIGURE 22 TYPICAL REACTOR
INLET PLENUM TO OUTLET PLENUM
 ΔP vs FLOW
LOG-LOG PLOT

FIGURE 23 REACTOR INLET PLENUM
TO OUTLET PLENUM
 ΔP vs FLOW

OUTLET TEMP. = 900°F

FIGURE 24

TOTAL POWER CURVES
FOR REACTOR AND CORE

TABLE IV - AVAILABLE PRESSURE DROP

Definition, Table III	Flow		Normal HTS Delivery ΔP , psi	Available ΔP psi
	10^6 Lb/hr	Gal/min		
Nominal-High	16.917	40,300	152	74
Nominal-Low	15.985	38,100	161	83
Maximum-High	17.963	42,800	142	64
Maximum-Low	17.031	40,600	151	73

2. Core Orificed

The core demand curve assuming an orifice absorbs all the "available" pressure drop can be constructed from the Figure 23 demand curve for the overall reactor. Figure 25 shows the core demand curves for the four flow rates parameters of Table III.

3. Orifice Pressure Drop

In order that each driver assembly have the flow rate prescribed for it according to its row position disclosed in Figure 4, the orifice pressure drop must be appropriately matched. For the maximum flow driver the orifice pressure drop can be the "available" pressure drops of Table IV. For the other drivers, because their flow rates are less, the orifice pressure drops must be greater. They can be derived from the difference between the four overall pressure drops on the HTS

FIGURE 25 CORE ORIFICED
INLET PLENUM TO OUTLET PLENUM
 ΔP vs FLOW

normal curve of Figure 23 and the pressure drop of the unorificed driver plenum-to-plenum. Figure 26 shows the available pressure drop for driver assembly orificing for the four overall flow rates of Table III.

L. REACTOR OUTLET NOZZLES

The concept related requirement¹ that the outlet nozzles, like the vessel wall, must be cooled to a temperature less than 1000 °F, is essentially satisfied by the wall cooling arrangement. By definition the nozzles extend some short distance from the vessel wall and accordingly must be cooled. For each nozzle a cylindrical baffle structure which is fixed to the reactor thermal liner mates concentrically into the nozzle for approximately 12 to 24-in. The baffle is not secured to the nozzle. To cool the nozzle, some of the wall coolant is channeled through the annular clearance space between baffle and nozzle and mixes with the reactor outlet coolant. It is desirable that not too much of the wall coolant be stripped. While not meant to set the nozzle design concept, Figure 27 is an exploration of the amount of nozzle leakage for an assumed 26-inch pipe outlet with a 1/8 inch annular gap 12 inches long. The calculated leakage is about 11.5% of the wall coolant flow. The outlet nozzle may be 30-inch diameter. Conceivably the nozzle leakage flow could still be held to a minor percentage of the wall coolant flow. There is not an unsurmountable problem.

1 CCDD for the Reactor Vessel and Shield Component No. 32, 3/5/69, P 1-8

FIGURE 26 DRIVER ASSEMBLY
AVAILABLE ΔP CURVES

FIGURE 27

REACTOR OUTLET
NOZZLE AND LEAKAGE
 ΔP vs FLOW

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APPENDIX A

USEFUL RELATIONS

APPENDIX A

FIGURE A-1 OVERALL HEX. DIMENSION
OF PIN BUNDLE

FIGURE A-2 HEX. CORNER DETAILS

EQUATIONSSnug-Fit Dimensions

$$\begin{aligned}
 D_t' &= (N_d - 1) (d_p + d_w) + \frac{2}{\sin 60^\circ} \left(\frac{d_p}{2} + d_w \right) \\
 &= (N_d + 0.1547) d_p + (N_d + 1.3094) d_w \\
 &= (N_d P + 1.3094 P - 1.1547) d_p
 \end{aligned}$$

$$D_f' = D_t' \sin 60^\circ = 0.86603 D_t'$$

Shroud Dimensions, Inside

$$D_f = D_f' + \text{allowance}$$

$$D_t = D_f / \sin 60^\circ = 1.1547 D_f$$

FIT - Factor, F

$$F = D_f / D_f'$$

Cross-Section

$$\begin{aligned}
 A &= d_p^2 \left\{ 0.6495 [F(N_d P + 1.0394 P - 1.1547)]^2 \right. \\
 &\quad \left. - 0.7856 N (P^2 - 2 P + 2) \right\}
 \end{aligned}$$

Perimeter

$$B = 3 D_t + N P d_p$$

Equivalent Diameter

$$D_e = 4 A / B$$

VALUES

Ref: SK-3-14581, Driver Fuel Assembly, 2nd Issue, 2/19/69

Data

$$N = 217$$

$$N_D = 17$$

$$d_p = 0.23 \text{ inch}$$

$$d_w = 0.056 \text{ inch}$$

$$P = 1.243$$

$$D_f = 4.335 \text{ inch}$$

$$D_f' = 4.305 \text{ inch}$$

$$\text{Allowance} = 0.030 \text{ inch}$$

$$F = 1.007$$

Results

$$\text{Cross-section} \quad A = 6.74 \text{ in}^2$$

$$\text{Perimeter} \quad B = 210 \text{ inches}$$

$$\text{Equiv. Diam.} \quad D_e = 0.128 \text{ inch}$$

APPENDIX B

COMPARISON OF CALCULATED FRICTION ΔP 'S
FOR ISOTHERMAL FLOW WITH CORE TEMPERATURE
RISE FLOW THROUGH A FUEL PIN BUNDLE

APPENDIX B

<u>Data:</u>	Number of pins per bundle	217
	Pin diameter	0.23 inches
	Wire diameter, 12-in. wrap pitch	0.056 inches
	Length of temperature regions	
	Before core, L_1	8.75 inches
	Thru core, L_2	36.00 inches
	After core, L_3	<u>48.25 inches</u>
	Total length of fuel bundle, ΣL	93.00 inches
	Flow maximum, W	2.24×10^5 lb/hr
	Cross sectional flow area, S	6.7 inches ²
	Equivalent diameter, D_e	0.127 inches
	Density, at 900 °F, P_3	52.3 lb/feet ³

Equations for ΔP

The frictional pressure drop equations that follow use subscripts to indicate the temperature regions for which the appropriate temperature dependent variables are used. For the core temperature rise cases the pressure drop equation is:

$$\Delta P = \frac{.0016 \Sigma L W^2}{288 D_e g \rho_3 A^2} \left[f_1 \frac{L}{\Sigma L} \frac{P_3}{P_1} + f_2 \frac{L_2}{\Sigma L} \frac{P_3}{P_2} + f_3 \frac{L_3}{\Sigma L} \right. \\ \left. + \frac{.0016 W^2}{288 g \rho_3 A^2} \left[1 - \frac{\rho_3}{\rho_1} \right] \right] \quad (1)$$

The second term in the above allows for the increase in velocity head pressure. For the isothermal cases the pressure drop equation is:

$$\Delta P = \frac{.0016 \Sigma L W^2}{288 D_e g \rho_3 A^2} \left[f_n \frac{L_n}{\Sigma L} \frac{\rho_3}{\rho_n} \right] \frac{\Sigma L}{L_n} \quad (2)$$

Results for a number of cases are tabulated:

<u>Core ΔT, °F</u>	<u>Average Core ΔT, °F</u>	<u>ΔP, Psi</u>
300	750	60.0 (a)
350	725	60.0 (a)
400	700	60.0 (a)

(a) Velocity head pressure difference included and = 0.2 psi

APPENDIX C

The methods used to calculate pressure drops in the FFTF driver fuel subassemblies are described in this appendix.

Regions

The driver fuel subassembly shown in Figure C-1 is divided into three sections:

1. Inlet region
2. Pin region
3. Open duct region

The following list describes the three sections.

1. Inlet Region

- a. Pipe 4.37 inches long with an I.D. of 2.54 inches.
- b. Pipe I.D. increased from 2.54 inches to 3.466 inches over 6.5 inches in length.
- c. Transition from a circular cross section with an I.D. of 3.46 inches to a hexagonal cross section with the distance across the flats equal to 4.25 inches. This occurs over a length of 5.5 inches.
- d. A hexagonal duct 18.4 inches long with the distance across the flats equal to 4.25 inches.
- e. Duct expansion from 4.25 inches across the flats to 4.355 inches.

2. Pin Region

- a. Contraction into fuel from 16.2 in^2 to 6.68 in^2 .
- b. Length of pin region 93 inches.
- c. Pin diameter 0.23 inches.
- d. Wire wrap diameter 0.056 inches.

- e. Number of pins 217.
- f. Expansion from 6.68 square inches of coolant flow area to 16.2 in².

3. Open Duct Region

- a. Distance across the flats of the duct 4.335 inches.
- b. Length of open duct, 30 inches.

Pressure Drop Calculations

The following two equations were used to calculate pressure drops in the driver fuel assembly.

$$\Delta P_c = \frac{KM^2}{288 \rho_g A_f^2}$$

$$\Delta P_f = \frac{LfM^2}{288 \rho_g A_f^2 De}$$

The Reynolds number used to determine the friction factor was calculated from equation.

$$Re = \frac{MDe}{\mu A} \times \frac{3600}{12} = \frac{W De}{\mu A 12}$$

where A_f = Flow area, ft² (See Appendix A for equation)

Frictional losses except in the fuel pin bundle were calculated using a smooth tube friction factor.

$$f = \frac{0.184}{Re^{0.2}}$$

This equation is valid for Reynolds numbers ranging from 1×10^4 to 2×10^6 .

FIGURE C-1
DRIVER FUEL ASSEMBLY

FIGURE 1. SECTION THROUGH A 100 MILE PER HOUR WIND

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