WSRC-TR-92-357

Type Q Septifoil Guide Tube Freeboard; Model Description and Results (U)

Task Number: 92-057-1

edited by

M. A. Shadday Jr.

contributions by

N. M. Askew
G. P. Flach
L. D. Koffman
M. A. Shadday Jr.

September 1992

Patent Status

This internal management report is being transmitted without DOE patent clearance, and no further dissemination or publication shall be made of the report without prior approval of the DOE patent counsel.

Westinghouse Savannah River Company
P. O. Box 616
Aiken, SC 29802

Prepared by the U. S. Department of Energy under Contract DE-AC09-89SR18035

NRTSC
NUCLEAR REACTOR TECHNOLOGY
AND SCIENTIFIC COMPUTATIONS

WSRC-TR-92-357

Keywords: Control Rods
Septifoils

Retention: Permanent

Type Q Septifoil Guide Tube Freeboard; Model Description and Results (U)

Task Number: 92-057-1

edited by

M. A. Shadday Jr.

contributions by

N. M. Askew
G. P. Flach
L. D. Koffman
M. A. Shadday Jr.

ISSUED: September 1992

SRTC **SAVANNAH RIVER TECHNOLOGY CENTER, AIKEN, SC 29808**
Westinghouse Savannah River Company
Prepared for the U. S. Department of Energy under
Contract DE-AC09-89SR18035

PROJECT:	**K Reactor Restart**
DOCUMENT:	**WSRC-TR-92-357**
TITLE:	**Type Q Septifoil Guide Tube Freeboard; Model Description and Results (U)**
TASK NUMBER:	**92-057-1**
TASK TITLE:	**Septifoil Leakage Verification and Resolution**

Table of Contents

Introduction and Summary

On May 25, 1992, a moderator leak was detected as partial length control rods in K Reactor were being positioned for reactor start up. The source of the leak was suspected to be overflow of the control rod guide tubes that are above the septifoils, though the cause was unknown. The control rods were re-inserted, and the process water pump AC drive motors were tripped. K Reactor start up was put on hold until the cause of the leak was understood, and rectified. Tests to determine the cause of the leak were initiated by the Heat Transfer Laboratory (HTL) that evening. On May 27, the cause of the overflow was identified from HTL tests. The overflow was caused by flow through the partial control rod extension tubes up into their guide tubes. When the top ends of the partial length control rod extension tubes are drawn up into the guide tubes, the guide tubes are pressurized by the flow diverted through the extension tubes, and the freeboard in those guide tubes is reduced.

This secondary flow path was not anticipated when the type Q septifoil was designed, and it was therefore not included in existing septifoil models. This report documents the development of a septifoil model that includes the various secondary flow paths, and predicts the freeboards in the guide tubes, as functions of the control rod positions, the blanket gas pressure, and the septifoil flow rate. The results of this model agree very well with HTL test results, and therefore reinforce confidence in the management decision to throttle septifoil flow to approximately 70 gpm, to prevent overflow of the septifoil guide tubes.

Septifoil Description

Reactor power is controlled by the motion of control rods that are grouped in clusters of seven. Each cluster is housed inside of a septifoil. There are 61 septifoils in K-reactor, and each is surrounded by six fuel assemblies. The septifoil sits on a supply pin, on the tank bottom, that provides coolant flow for the control rods. The coolant exits the septifoil through holes and slots near the top of the septifoil housing. Most of the septifoil flow discharges through twelve slots into the reactor tank between the poison plate and the top shield. The balance discharges through twelve .25 inch holes just below the poison plate.

Figure 1 is a schematic of a septifoil assembly. The assembly that the control rods travel in consists of three parts: the septifoil housing in the reactor tank, the muff that penetrates the top shield, plenum, and gas space; and the guide tube assembly that sits on top of the reactor. The guide tubes extend approximately fifteen feet above the reactor tank, and they are open at the top to the process room air. With 5 psig blanket gas pressure and no septifoil flow, the moderator rises in the guide tubes to the point where the free surface is approximately six feet from the top, or the freeboard is six feet. A web separates the septifoil housing into seven channels for the control rods, and they pass through holes in guide plates in the muff section. The web is perforated to allow passage of fluid between the channels, so the septifoil housing and muff can be treated as a single flow channel, when considering axial flow over the control rods. The guide tube assembly consists of seven separate guide tubes up into which the control rods are pulled. The fluid cannot move laterally between guide tubes, so pressurizing a single guide tube can result in reduced freeboard or overflow for the individual tube.

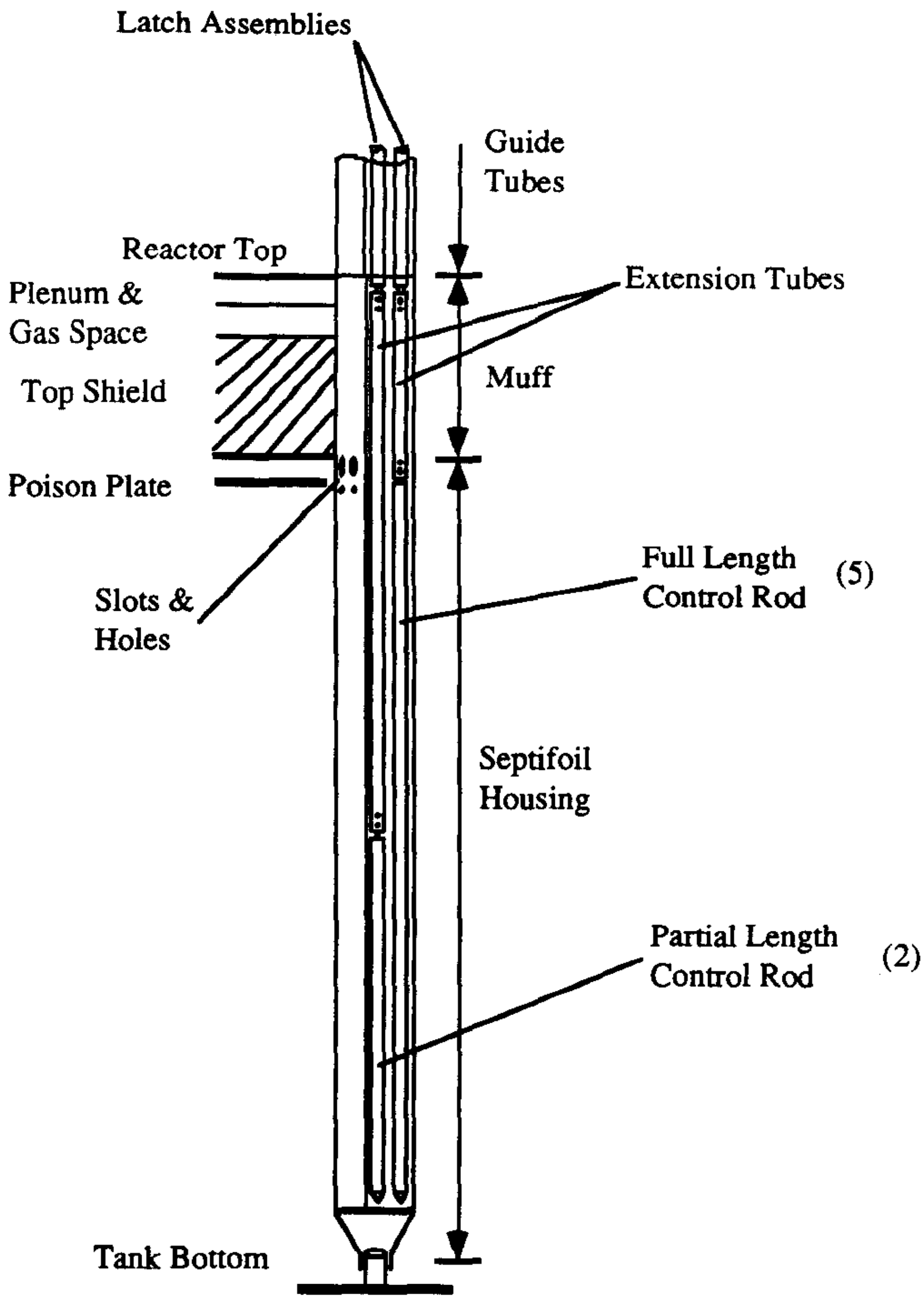

Figure 1. Schematic of a Type Q Septifoil Assembly

A septifoil contains five full length control rods and two partial length control rods. The full length control rods are used to control reactor power, and they are withdrawn sequentually. The two partial length control rods are moved in concert, and are used to modify the axial power profile in the reactor. These rods are not withdrawn from the reactor. There are two types of full length control rods, cadmium and lithium-aluminum. The two cadmium rods are used for shutting down the reactor. These rods are fully withdrawn during reactor operation. During a SCRAM, the withdrawn full length control rods are driven into the reactor together at the rate of 1.62 in/s. The partial length control rods are normally positioned at the point of maximum worth, so they are not moved during a SCRAM, (Olson, 1974).

Hollow extension tubes connect the control rods and the latch assemblies. There are eight drain holes at either end of each extension tube. When the control rods are fully inserted in the septifoil, the upper ends of the extension tubes are just below the guide tubes, and the lower ends of the full length rod extension tubes are level with the septifoil housing slots. The lower ends of the partial rod extension tubes are approximately half way up the septifoil. The hollow extension tubes are secondary flow paths through which some of the septifoil flow is diverted. The partial rod extension tubes allow fluid to flow to the upper end of the septifoil muff, and the full length rod extension tubes are flow paths for return flow to the septifoil slots. These secondary flow paths were not important in the previously used type J septifoil because the holes distributed along the length of the housing prevented the septifoil from being significantly pressurized with respect to the reactor tank. Because all of the septifoil flow is discharged at the top of the type Q septifoil, the region of the housing below the slots can be significantly pressurized, and this is the supply pressure for flow diverted through the partial rod extension tubes.

Figure 2 is a schematic of the cross-section of a septifoil, showing the control rods and the web. The control rods and extension tubes have an outside diameter of .94 in. The web divides the septifoil into seven channels, one for each control rod. It is heavily slotted, as shown in Figure 3, to allow the free exchange of fluid between channels. The web extends from the septifoil bottom end fitting orifice plate to 2.7 in. above the septifoil housing slots. Approximately 50% of the web is cut out to form the slots between channels.

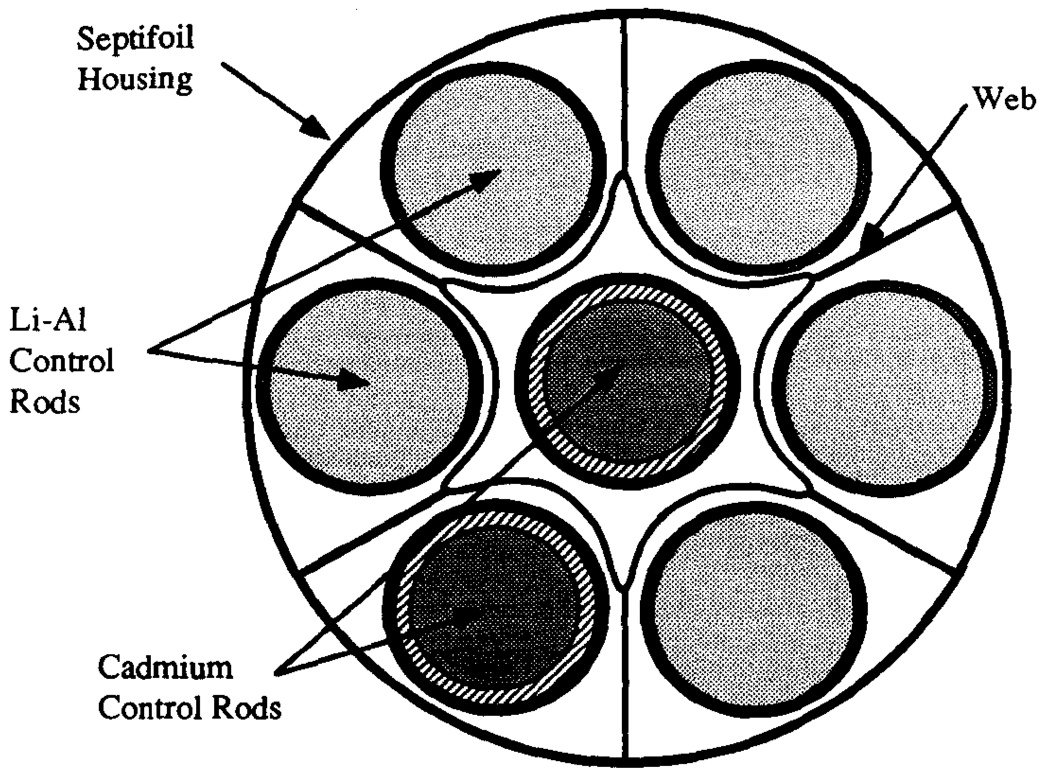

Figure 2. Septifoil Cross-Section with Control Rods

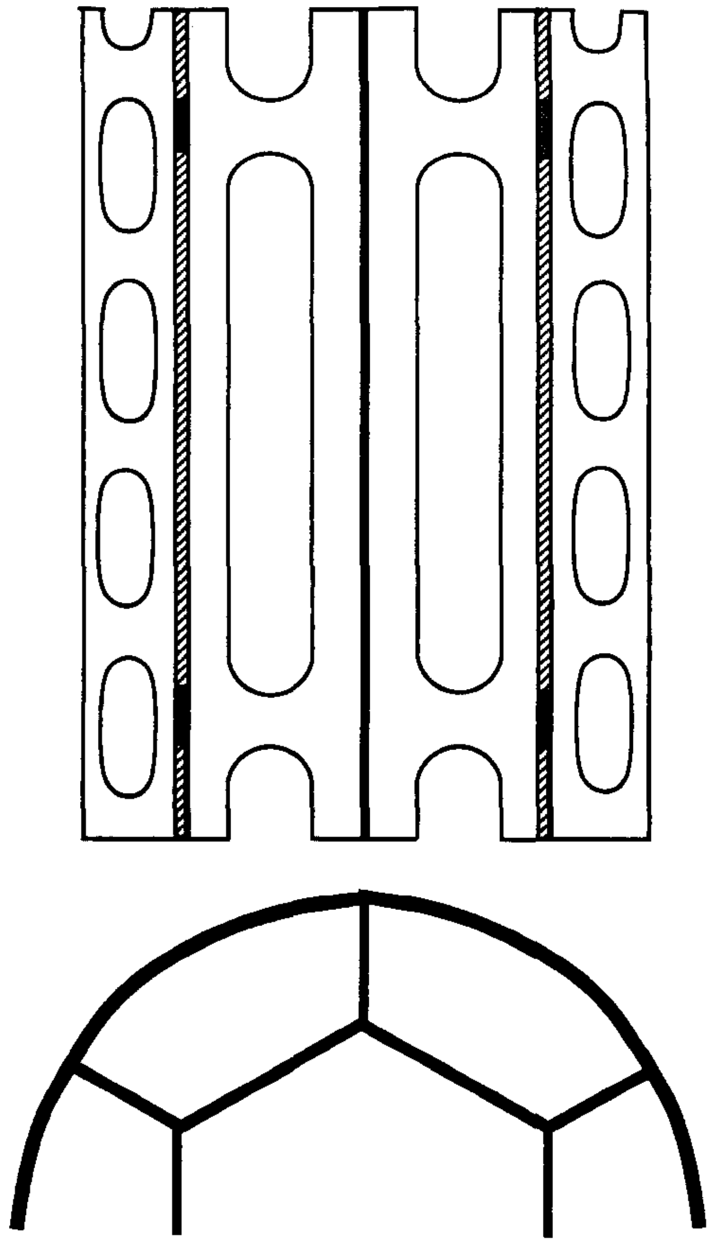

Figure 3. Schematic of the Web and Slots

The septifoil muff sits on top of the septifoil housing. This is the component that penetrates the upper part of the reactor: the plenum, gas space, and the top shield. Figure 4 is a schematic of the muff. It consists of a cylindrical housing and six guide plates that ensure the proper alignment of the control rods. The bottom four guide plates are 4.5 in. thick, and the top two are 1 in. thick. When the control rods are fully inserted, the upper extension tube holes are just below the top guide plate. The guide tube assembly sits on top of the septifoil muff. It consists of seven individual cylindrical passages for the axial movements of the control rods. The guide tubes serve as standpipes for the septifoil.

The thin annular gaps between the control rods and the guide plate restrict the downward axial flow through the muff. The extension tubes of fully inserted full length control rods are alternate flow paths for return flow to the septifoil effluent slots.

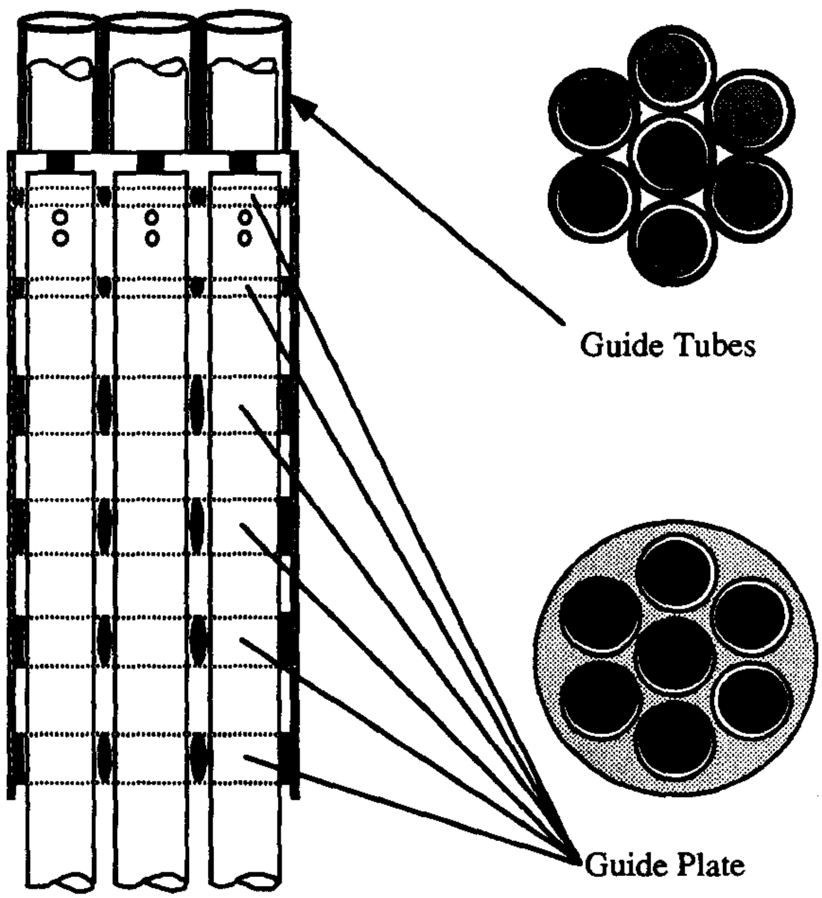

Figure 4. Schematic of the Septifoil Muff and Guide Tube Assembly

K-reactor has sixty-one septifoils. Figure 5 is a schematic of the septifoil coolant supply system. Some of the process water flow is diverted at the discharge side of the heat exchangers for septifoil cooling. There are two horizontal six inch diameter ring headers below the reactor vessel that supply coolant flow to the individual septifoils. Each ring header distributes the septifoil supply flow from three of the process water loops, and there are two three inch diameter lines that connect the two ring headers. The right side ring header supplies thirty-one septifoils, and the left side supplies thirty. During normal operation, the flows in the two sides of the system are essentially symmetric, and there is very little cross-flow between the ring headers, (Shadday, 1991). There is a four inch motor operated plug valve in each of the supply lines from a pair of heat exchangers. These valves can be used to throttle septifoil flow.

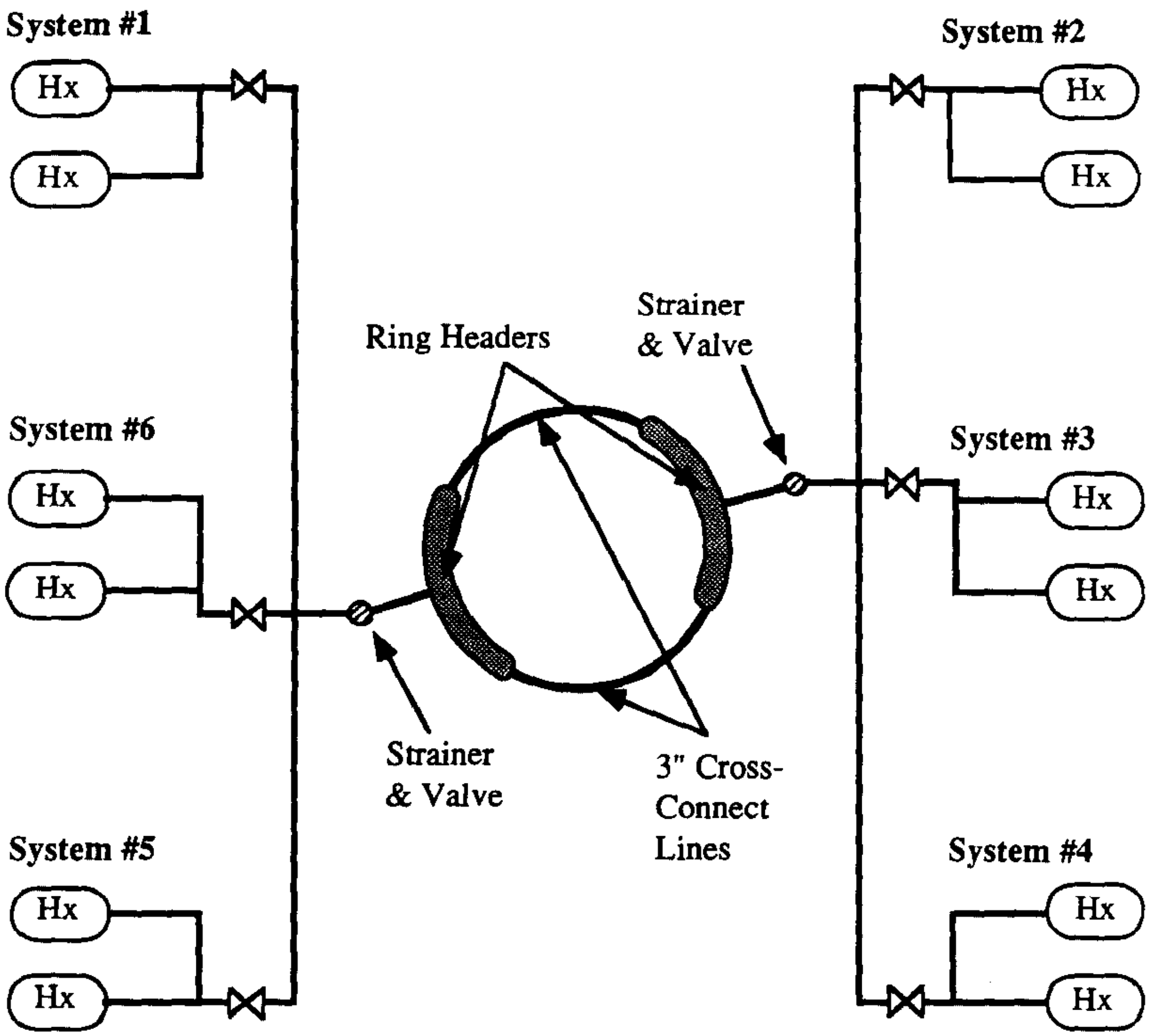

Figure 5. Schematic of the Septifoil Coolant Supply System

Figure 6 is a schematic of the individual septifoil supply lines coming off of the ring header. Lines come off of both the top and the side of the ring header, with most coming off of the top. In K-reactor, each ring header has eight lines coming off of the side, and the balance coming off of the top. The septifoil lines are 1.25 inch schedule 40 steel pipe. There is a pressure tap in the 180 degree elbow directly below each of the septifoil cooling water upflow pins, and these pressures are read in the reactor control room. The cooling water upflow pins are approximately four ft. long, 2.75 inch I.D. pipes with helical inserts. The flow exits the upflow pins through one inch I.D. pipes, that protrude through the tank bottom. The septifoils sit on top of the upflow pins.

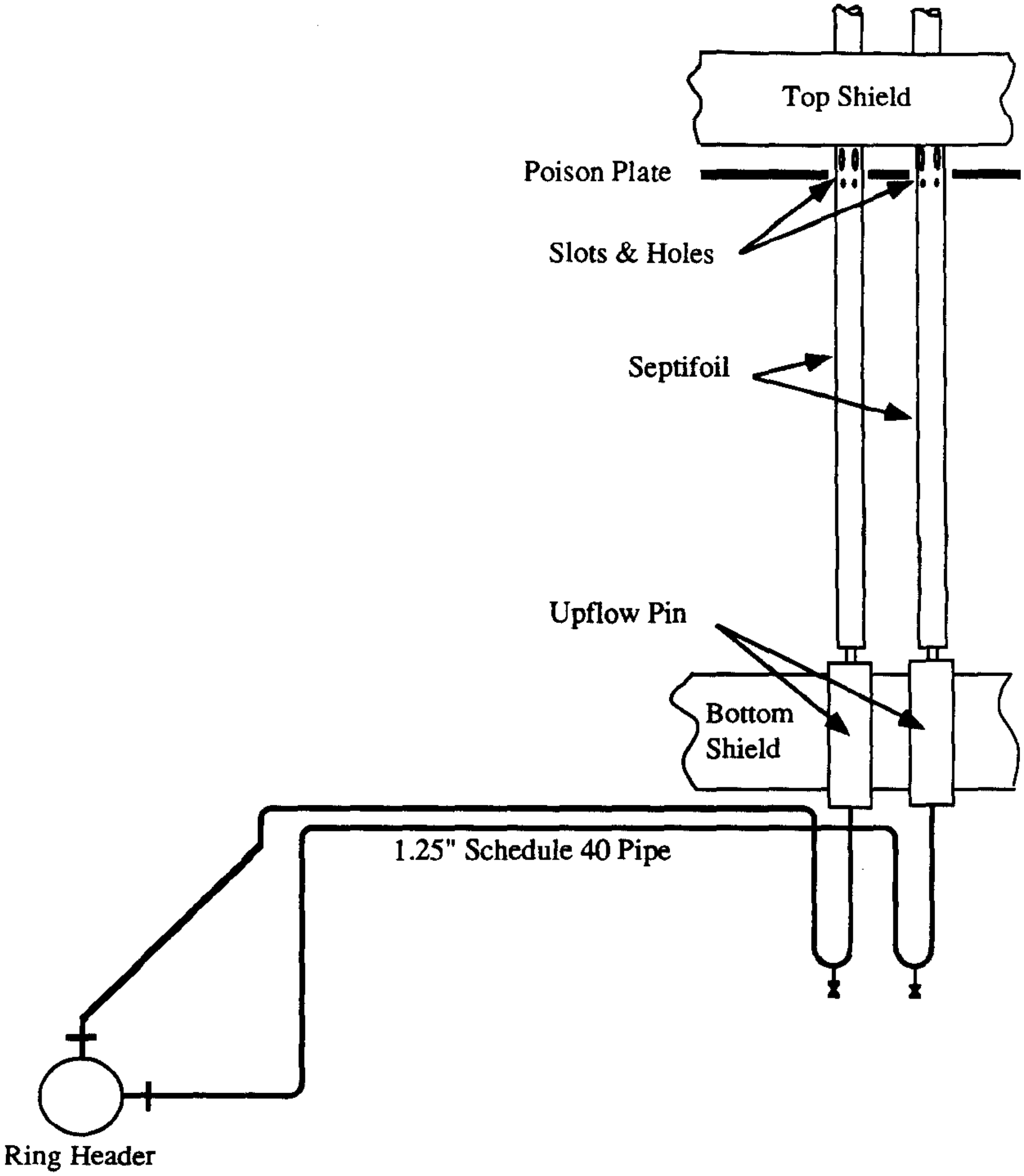

Figure 6. Schematic of Individual Septifoil Piping

Problem Description

The septifoil was designed to have a single flow path, up through the housing and out the slots. The region above the slots, the muff and guide tubes, was to be a standpipe with stagnant moderator, and the hydrostatic pressure of the column of fluid in the standpipe was to be the driving head for flow out through the slots. Because the hollow extension tubes are low resistance flow paths for axial flow, septifoil hydraulics are considerably more complicated than they were designed to be, and must be analyzed as a flow network with parallel legs.

Figure 7 is a schematic of a septifoil with all control rods fully inserted, that shows the flow paths. There is a single flow path from the upflow pin to the lower holes in the two partial length control rod extension tubes. At this point the flow splits, with some diverted up through the extension tubes and the balance continuing up through the septifoil housing to the level of the slots and holes. The flow diverted through the partial rod extension tubes discharges through the upper drain holes into the upper end of the septifoil muff, between the top two guide plates. The flow returns to the level of the slots by one of two paths: down the muff past the guide plates, or through the full length control rod extension tubes. The return flows down the septifoil muff join with the flow up the septifoil, and all of the flow exits through the septifoil slots and holes. With this rod configuration, the heights of the columns of moderator in the guide tubes are all the same. The column heights are determined by the pressure drops across the slots and for the return flows down the muff.

Figure 8 is a schematic of a septifoil with the two partial control rods moved up, and all five full length rods fully inserted. The partial rods are moved high enough for the upper extension tube holes to be in the guide tubes. There is a single flow path up to the level of the lower holes in the partial rod extension tubes. At this point the flow again splits, with part flowing up the extension tubes. The flow exits through the upper holes and travels down the two partial rod guide tubes and past the top guide plate of the muff. From this point the flow pattern is the same as for the case with all rods inserted. The flow path down the two guide tubes has a small cross-sectional area, and consequently a relatively high resistance. The heights of the columns of fluid in the two partial rod guide tubes is increased over the heights in the other guide tubes by the hydrostatic equivalent of the hydrodynamic pressure drop from the upper partial rod extension tube holes to the muff.

Figure 9 is a schematic of a septifoil with the two partial control rods moved up, some of the full length control rods partially withdrawn, and the balance fully inserted. The effect of withdrawing full length control rods is to close off return flow paths through the extension tubes for practical purposes. Again the highest columns of moderator will occur in the partial rod guide tubes.

These three cases cover the control rod configurations that can be expected in K-reactor. There are administrative constraints on control rod movements that alleviate the need to consider all possible rod configurations. The two partial control rods move together, and they are generally positioned before any full rods are pulled for startup. The two cadmium full length rods are fully withdrawn before the reactor goes critical. The remaining full length lithium rods are withdrawn sequentially, until the desired reactor power is achieved. During normal operation, the full length rods are either fully inserted or withdrawn, except for the one rod in an intermediate position that is the controlling rod. In a SCRAM, the full length rods are driven together, and the partial rods remain stationary. The worst rod configuration, from the standpoint of freeboard in the guide tubes, occurs during a SCRAM, as will be discussed in the results section.

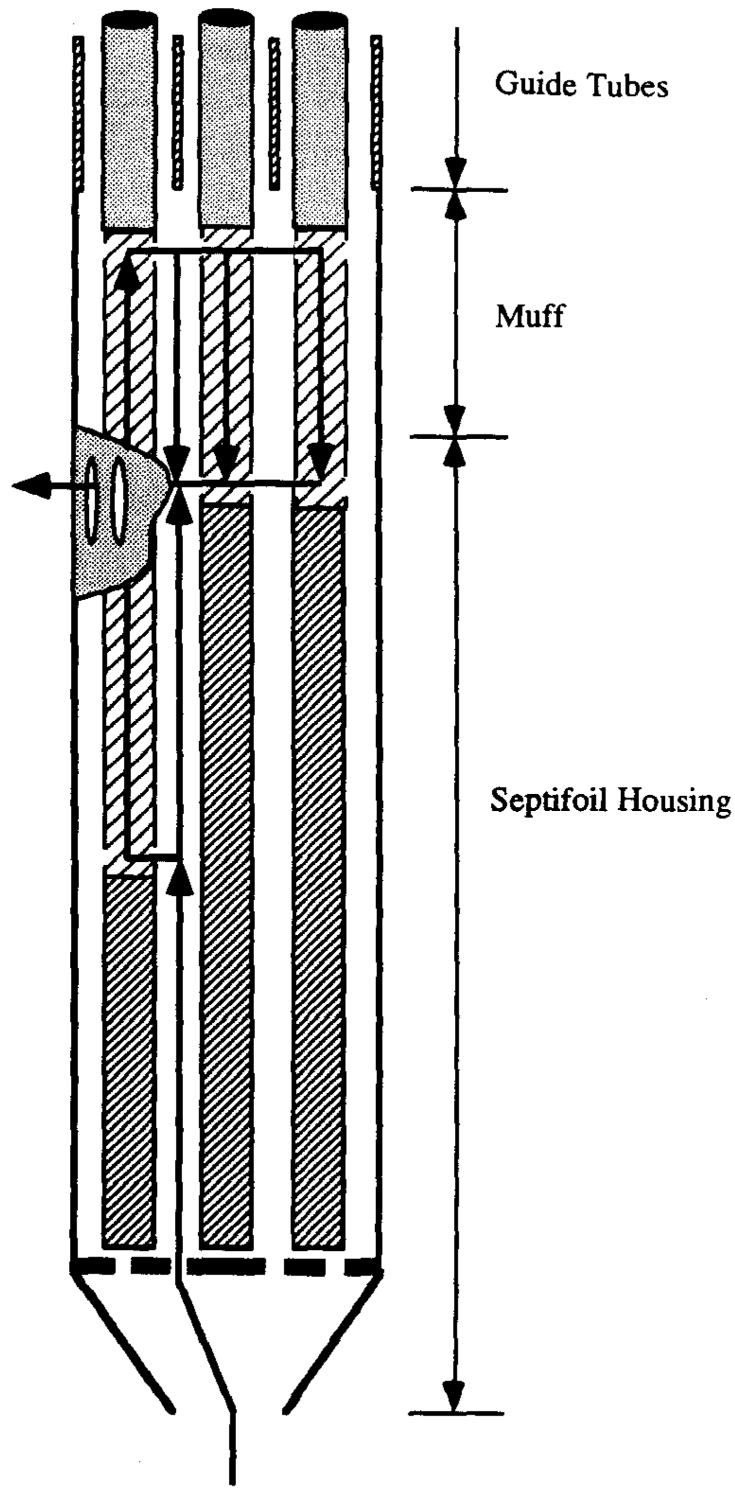

Figure 7. Flow Paths in a Septifoil with all Control Rods Inserted

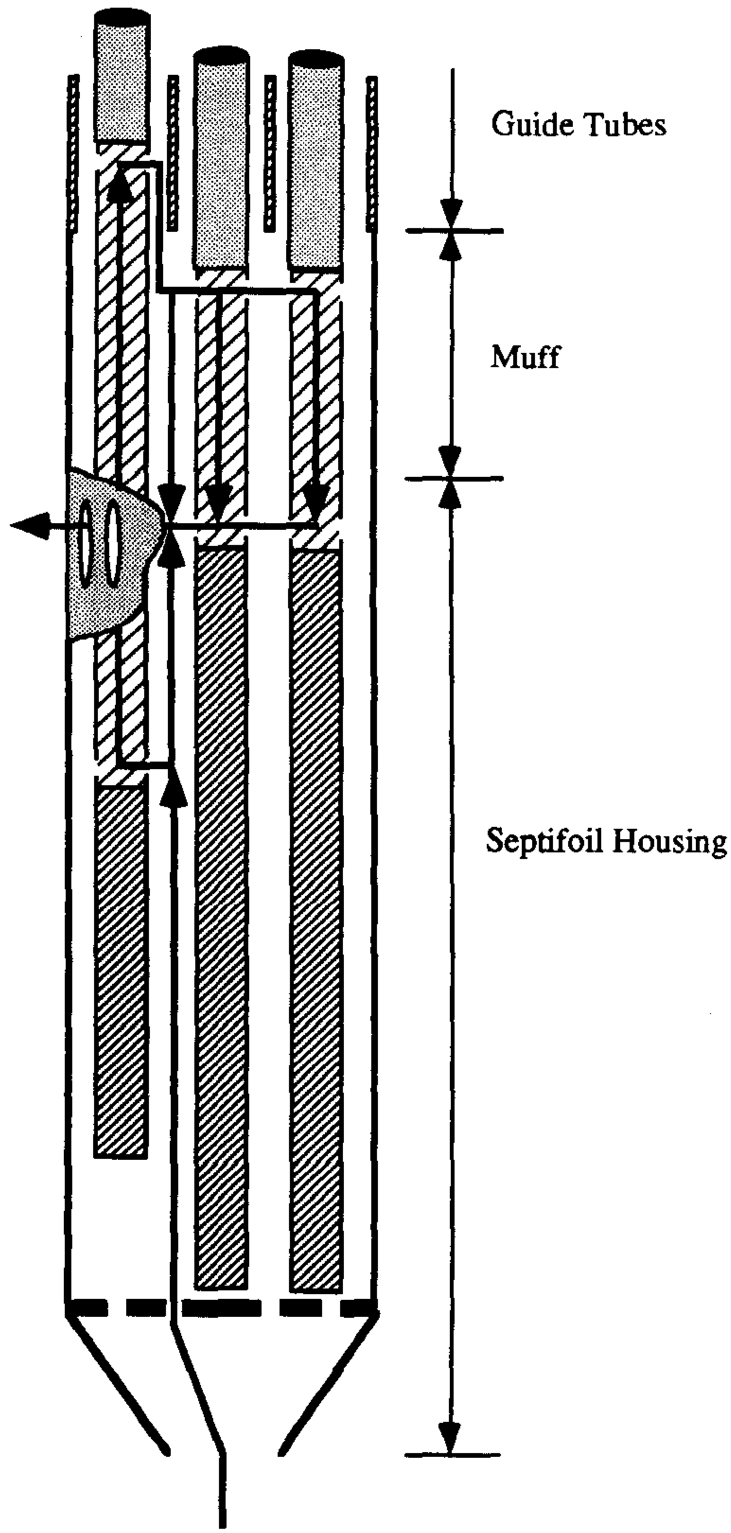

Figure 8. Flow Paths in a Septifoil with the Partial Rods Moved Up

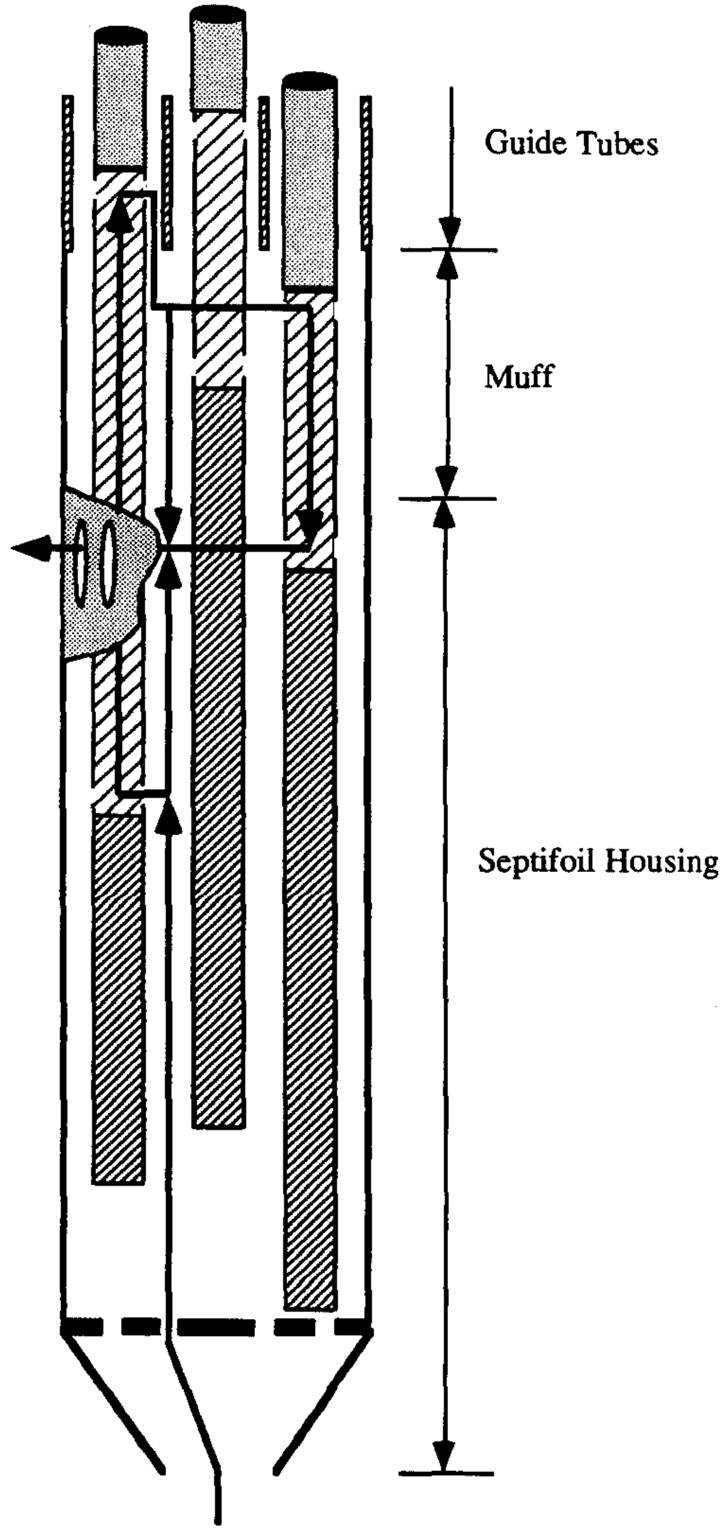

Figure 9. Flow Paths in a Septifoil with the Partial Rods Moved Up and Full Length Rods both partially Withdrawn and Fully Inserted

Septifoil Model

All of the rod configurations discussed in the previous section can be modelled as a single flow network, shown in Figure 10. This network consists of six legs and three interior nodes. Leg #1 is the flow path from the septifoil entrance to the lower drain holes in the partial length control rod extension tubes. Leg #2 is the flow path that continues axially up the septifoil to the level of the slots, and leg #3 is the flow path up the partial rod extension tubes and back down into the muff to the level of the upper extension tube holes of the fully inserted full length rods. Leg #4 is the return flow path through the full length rod extension tubes, and leg #5 is the parallel path down the muff, past the guide plates. Leg #6 is the flow path of the septifoil effluent through the housing holes and slots. The dependent variables in this problem are the flow rates in each of the legs, and the interior nodal pressures. There are nine unknowns that require the simultaneous solution of nine equations. An expression for the pressure drop as a function of the flow rate can be derived from the mechanical energy equation, for each leg of the network. Imposing continuity at each of the interior nodes yields three additional equations, for a total of nine. The boundary conditions for this problem are the inlet and outlet pressures. Alternately, flow rate may be prescribed at the inlet boundary, and inlet pressure replaces inlet flow rate as an unknown.

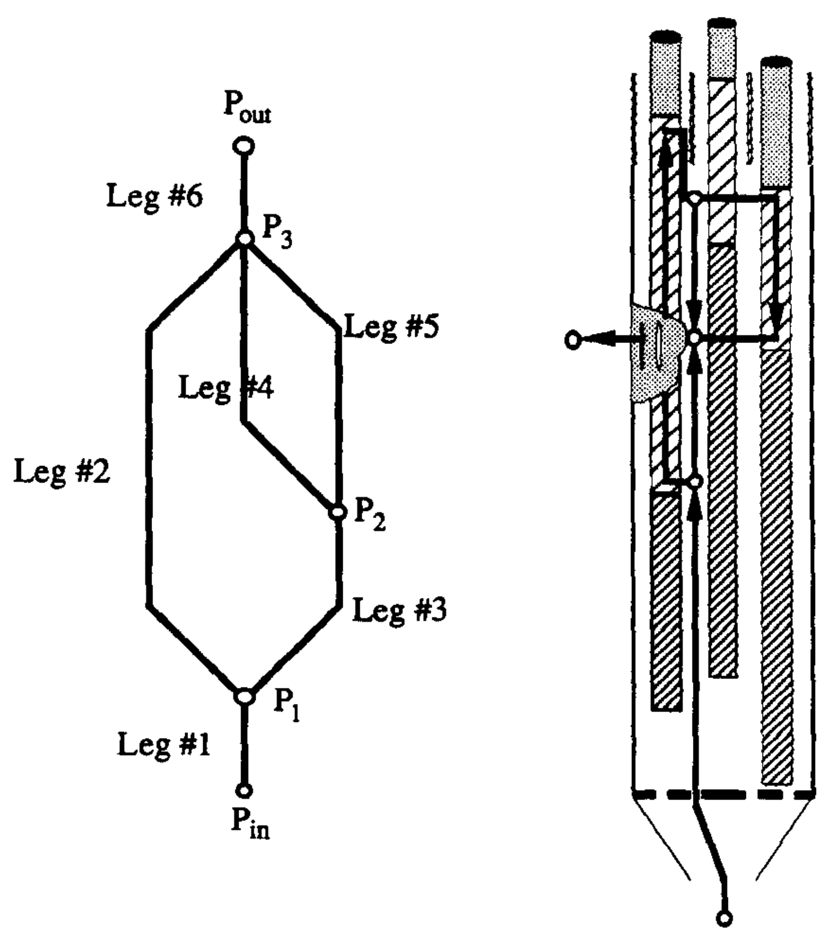

Figure 10. Septifoil Flow Network

The equations for the network leg pressure drops have the form of equation (1). These are non-linear algebraic equations. Sections of a leg with different geometries are handled by changing flow areas and hydraulic diameters. Entrance and exit form losses are inserted where appropriate. The nodal continuity equations have the form of equation (2). The specific leg equations are listed in Appendix A. Appendix B has the necessary septifoil dimensions for the model and contains a detailed description of the septifoil components.

$$\Delta P = P_2 - P_1 = \frac{\rho}{2}(V_1^2 - V_2^2) + \rho g(z_1 - z_2) - \sum K\frac{\rho V^2}{2} - \sum \frac{fL}{D_h}\frac{\rho V^2}{2} \quad (1)$$

$$\sum Q_{in} = \sum Q_{out} \quad (2)$$

Since these simultaneous equations are non-linear, an iterative solution technique must necessarily be used. Newton's method, (Conte & de Boor, 1972), is used, and the partial derivatives in the Jacobian matrix are approximated by finite-differences. LU decomposition, (Press et al., 1989), is used to solve the set of linear equations that consist of the Jacobian matrix and the dependent variable updates. This numerical scheme converges very fast. Appendix C has a code listing and a sample of the input and output.

Results

The septifoil hydraulic model described above has been benchmarked against Heat Transfer Laboratory data, used to simulate the K-reactor overflow incident, used to investigate the effect of rod positions on freeboard, and used to simulate K-reactor start-up, operation and scram for septifoil flow throttled to 70 gpm. These results are presented below following a discussion of code verification.

Verification of code results: Several measures have been taken to give high confidence that the hydraulic model described in the preceding section has been correctly implemented in the FORTRAN source code listed in Appendix C. The source code was carefully checked line-by-line by Greg Flach, Andy Shadday, Larry Koffman and Neal Askew. The code output for a particular case was confirmed through a hand calculation (Flach, 1992, pp. 3-27). The code was benchmarked against Heat Transfer Laboratory data as described below. The agreement between code and data is excellent. Finally, the separate effects and K-reactor simulation results presented below were carefully examined to ensure the correct qualitative physical behavior was exhibited by the code.

Benchmarking comparison: (Steimke et al., 1992) describe the Heat Transfer Laboratory measurements of guide tube freeboard in a prototypic Type Q septifoil mock-up. Table I gives the flow rate and control rod positions for each of the cases considered. All cases except number 4 can be modeled. Case number 4 is excluded because at least one full rod is required to be fully inserted by the hydraulic model. An initial comparison of code predictions to data indicated the form loss coefficient for flow exiting the partial rod guide tubes was inaccurate (initially set to 1.0). Based on case numbers 1-3, 5-15, 18 and 21-31, the form loss coefficient was adjusted to 2.75 to achieve better agreement with the data. Table II summarizes the resulting code predictions of freeboard and inlet pressure compared to HTL data for cases 1-3 and 5-31. The agreement is excellent and gives high confidence that the hydraulic model has been accurately formulated and correctly implemented.

Table I Flowrate and rod positions for HTL experiment

Cas	Flow Rate (gpm)	Partial Rod Elev. (in)	Full Rod G Elev. (in)	Full Rod E Elev. (in)	Full Rod B Elev. (in)	Full Rod C Elev. (in)	Full Rod F Elev. (in)
1	68	18	72	72	72	72	0
2	68	18	159	159	159	159	0
3	68	24	123	123	123	123	0
4	68	18	12	12	12	12	12
5	68	18	0	0	0	0	0
6	58	18	0	0	0	0	0
7	78	18	0	0	0	0	0
8	68	15	0	0	0	0	0
9	68	12	0	0	0	0	0
10	68	21	0	0	0	0	0
11	68	24	0	0	0	0	0
11A	68	19	114	114	114	114	0
12	68	18	123	123	123	123	0
13	68	24	130	130	130	130	0
14	68	24	140	140	140	140	0
15	68	24	150	150	150	150	0
16	68	18	177	159	159	159	0
17	68	18	159	159	159	177	0
18	68	18	117	117	117	117	0
19	68	18	177	159	177	177	0
20	73	18	177	159	177	177	0
21	68	0	0	0	0	0	0
22	73	0	0	0	0	0	0
23	70	18	159	159	159	159	0
24	70	18	164	164	164	164	0
25	70	18	154	154	154	154	0
26	70	12	113	113	113	113	0
27	68	8	109	109	109	109	0
28	106	0	0	0	0	0	0
29	70	0	0	0	0	0	0
30	70	18	0	0	0	0	0
31	70	8	109	109	109	109	0

Table II Benchmarking comparison

HTL No.	Partial Rod Freeboard (in)			Full Rod Freeboard (in)			Inlet Pressure (psig)		
	Data	Code	Diff.	Data	Code	Diff.	Data	Code	Diff.
1	23	24.5	+1.5	55	56.3	+1.3	27.1	26.9	-0.2
2	39	37.7	-1.3	57	57.3	+0.3	24.4	24.3	-0.1
3	17	16.1	-0.9	56	56.4	+0.4	25.4	25.2	-0.2
5	26.5	26.7	+0.2	60.25	60.0	-0.2	29.1	28.3	-0.8
6	37.5	38.3	+0.8	63	63.0	0	25.1	24.4	-0.7
7	11	11.2	+0.2	56	55.8	-0.2	34.0	33.7	-0.3
8	26	26.4	+0.4	60	59.6	-0.4	29.4	28.6	-0.8
9	27	28.1	+1.1	60	59.4	-0.6	29.4	28.7	-0.7
10	25	25.7	+0.7	60	59.8	-0.2	29.4	28.7	-0.7
11	27	27.0	0	61	60.1	-0.9	29.2	28.4	-0.8
11A	24	25.3	+1.3	56	57.2	+1.2	25.6	25.6	0
12	22	20.1	-1.9	56	56.8	+0.8	25.1	25.1	0
13	23	21.2	-1.8	57	57.6	+0.6	25.1	24.9	-0.2
14	29	26.2	-2.8	57	57.7	+0.7	24.9	24.8	-0.1
15	35	32.9	-2.1	58	58.4	+0.4	24.4	24.3	-0.1
16	45	47.9	+2.9	58	59.1	+1.1	24.2	23.8	-0.4
17	47	47.8	+0.8	58	59.1	+1.1	24.1	23.9	-0.2
18	19	16.9	-2.1	56	56.4	+0.4	25.4	25.3	-0.1
19	55	57.3	+2.3	61	62.1	+1.1	23.7	23.3	-0.4
20	52	55.0	+3.0	59	60.5	+1.5	25.3	24.9	-0.4
21	58	57.9	-0.1	58	57.9	-0.1	29.2	28.2	-1.0
22	56	56.2	+0.2	56	56.2	+0.2	31.3	30.3	-1.0
23	39	36.9	-2.1	56	57.5	+1.5	24.8	24.8	0
24	42	40.0	-2.0	57	58.1	+1.1	24.7	24.7	0
25	35	33.5	-1.5	56	56.9	+0.9	25.1	25.0	-0.1
26	17	17.9	+0.9	52	54.2	+2.2	26.0	26.1	+0.1
27	23	25.4	+2.4	52	54.2	+2.2	25.4	25.5	+0.1
28	38	39.1	+1.1	38	39.1	+1.1	48.8	49.0	+0.2
29	57	57.6	+0.6	57	57.6	+0.6	30.1	29.2	-0.9
30	24	24.1	+0.1	59	60.2	+1.2	30.2	29.5	-0.7
31	20	23.3	+3.3	51	53.6	+2.6	26.1	26.2	+0.1
All	r.m.s. difference = 1.7"			r.m.s. difference = 1.1"			r.m.s. difference = 0.49 psig		

K-reactor septifoil overflow simulation: An overflow of D2O occurred in K-reactor as the partial control rods were raised above the orifice plate. Figure 11 illustrates the guide tube freeboards predicted by the present hydraulic model. Overflow is computed for partial rod positions beyond 6 in. above the orifice plate which is consistent with the K-reactor event. Details of the simulation are given by (Flach 1992, pp. 64-65). One method of avoiding overflow is to reduce septifoil flow. All of the subsequent results are for septifoil flow throttled to about 70 gpm which yields a positive freeboard assuming one full rod is always fully inserted.

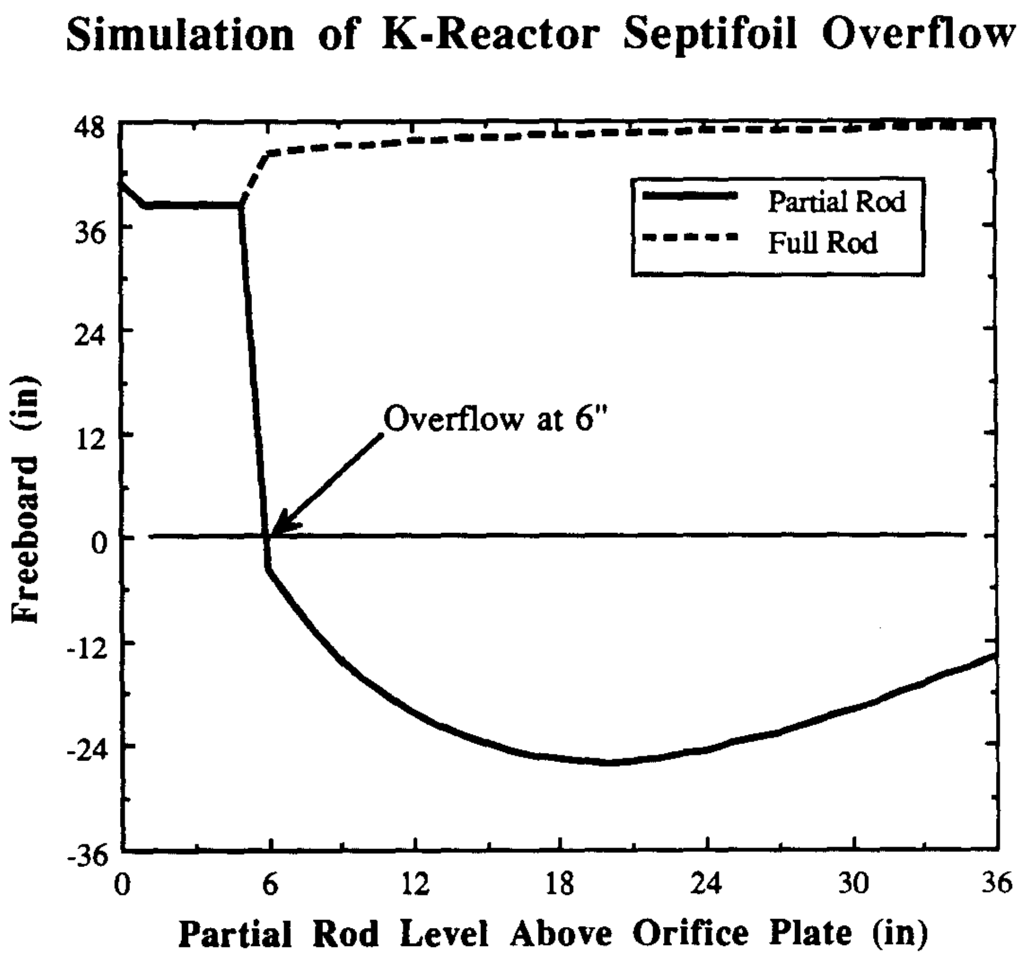

Figure 11 Simulation of K-reactor overflow incident.

Separate effects: Several separate effects studies were conducted to aid understanding of Type Q septifoil hydraulic behavior. For all simulations the flow is a constant 70 gpm of H2O and the outlet blanket gas pressure is set to 4.5112 psig. The equivalent blanket gas pressure for D2O is 5 psig. One full rod is assumed be at 0" above the orifice plate. The two partial rods and four remaining full rods are moved together. The temperature is set to 30°C.

Figure 12 illustrates the effect of partial rod position on freeboard with all full rods fully inserted. Three distinct regimes are observed as shown in Figure 12. A small drop in freeboard occurs when the upper holes in the partial rod extension tubes move above the top guide plate in the septifoil muff. The clearance between the plate and extension tubes is small enough to slightly pressurize the space above the plate. Freeboard increases slightly as the partial rod is further withdrawn because the lower holes in the partial rod extension tubes see a lower pressure with increasing elevation. As the upper holes of the partial rods enter their guide tubes, the partial rod guide tubes are significantly pressurized due to the large frictional and form losses for downward flow out the guide tubes. In this region two competing effects are observed. As the partial rod moves up, the resistance to flow out of the partial rod guide tubes increases. This tends to decrease freeboard. On the other hand, the pressure transmitted through the extension tube to the guide tube by the lower set of holes decreases. This tends to increase freeboard. As a result of these two factors the freeboard exhibits a minimum which occurs at 18 in.

Figure 13 illustrates the effect of full rod position on freeboard. The partial rods are assumed to be at 21 in and one full rod is assumed to always be down. Three distinct regions are again observed. An initial drop in freeboard occurs when four out of the five full rod upper extension tube holes are moved into their respective guide tubes. This event effectively reduces the area for downward flow through full rod extension tubes by 80%. However, apparently even a single full rod extension tube provides sufficient area such that the losses are minor as evidenced by only a small reduction in freeboard. Until the full rod tips reach the lower partial rod extension tube holes, no further change in freeboard is observed. This is because the flow geometry between the outlet and lower holes in the partial rod extension tubes is unchanged. For a fixed outlet pressure and flow rate, the pressure profiles and therefore freeboard are unchanged. As the full rod tips are raised above the lower partial rod holes a discontinuous drop is freeboard is observed. This effect is caused by the higher pressure upstream of the rod tips required to accelerate the flow through an area contraction and overcome form losses. The partial rod guide tubes experience this pressure differential as the rod tips pass the lower partial rod holes. As the full rods are raised further, the frictional losses between the lower holes and outlet decrease. For a fixed flow and outlet pressure, this means the pressure at the lower partial rods holes decreases and freeboard increases.

The lowest freeboard in Figure 13 occurs when the full rods are positioned at 119 in. above the orifice plate. Figure 14 demonstrates that this condition is also the worst-case of all partial rod positions. Figure 15 shows the pressure profile in detail for nearly the worst case. Figure 15 is for full rods at 125 in. rather 119 in. The purpose is to separate the pressures surrounding the lower partial rods holes for clarity in Figure 15.

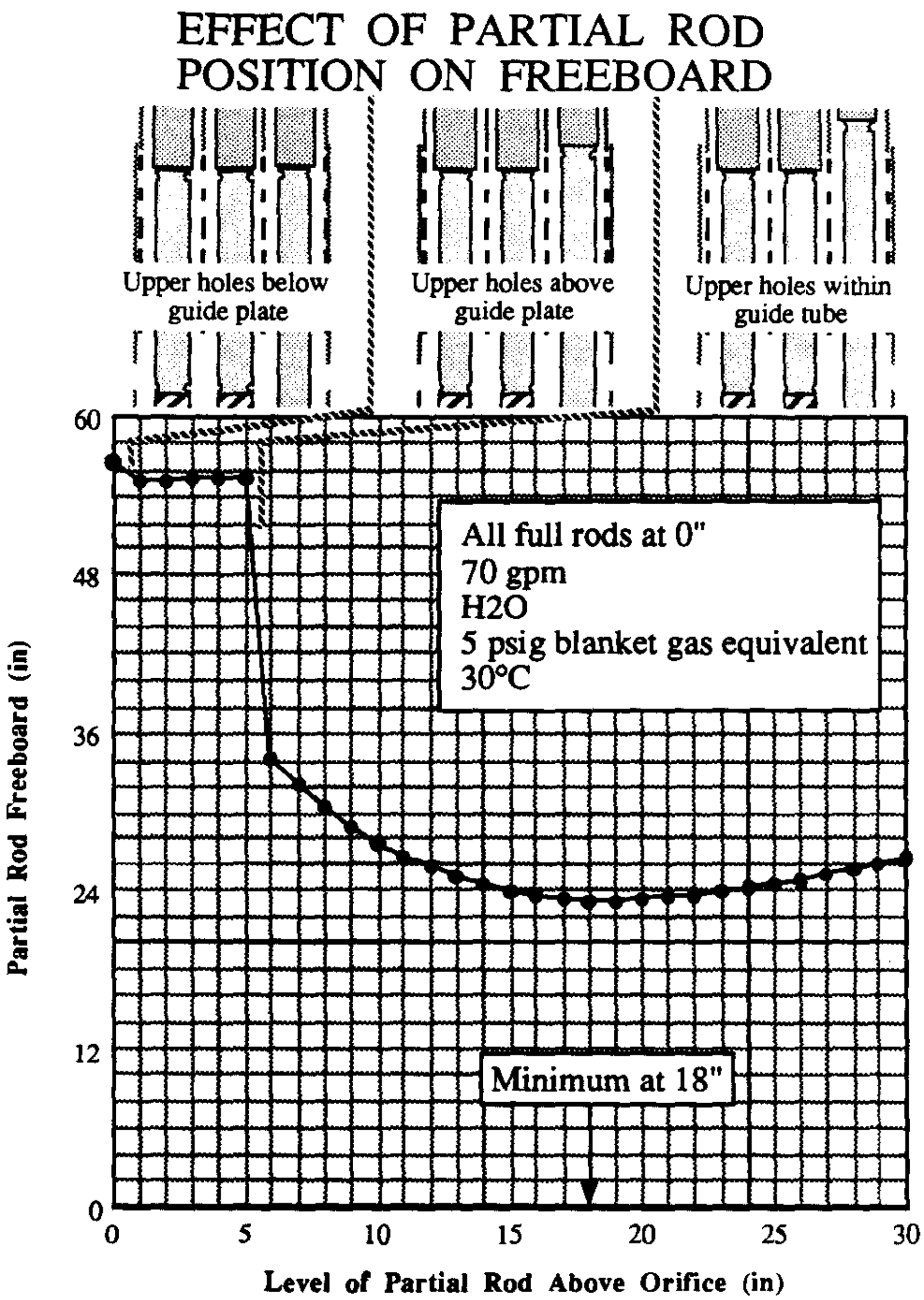

Figure 12 Effect of partial rod position on freeboard.

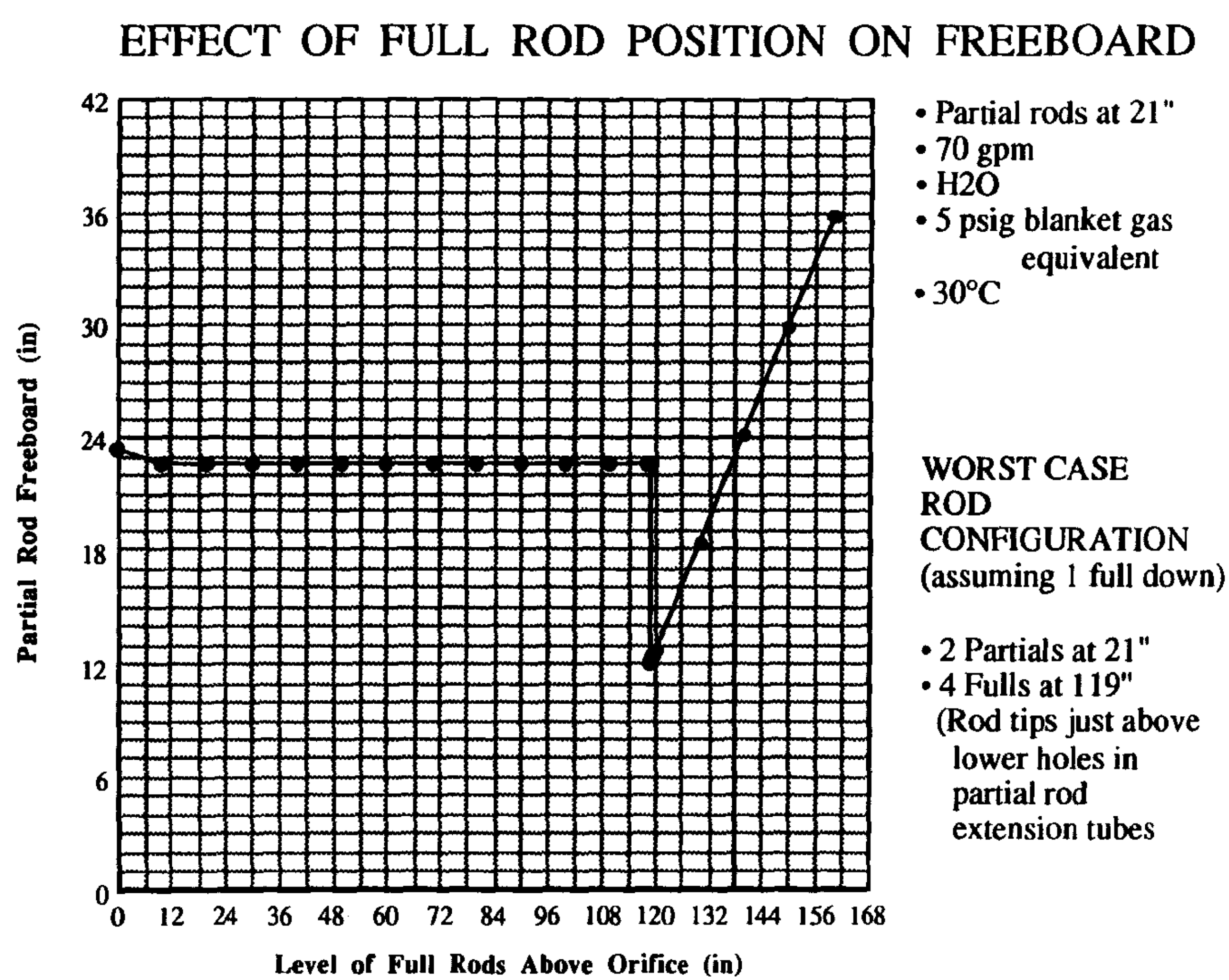

Figure 13a. Effect of rod position on freeboard

EFFECT OF FULL ROD POSITION ON FREEBOARD (cont'd)

FULL RODS **DOWN**	FULL ROD TIPS **BELOW** LOWER HOLES OF PARTIAL RODS	FULL ROD TIPS **ABOVE** LOWER HOLES OF PARTIAL RODS

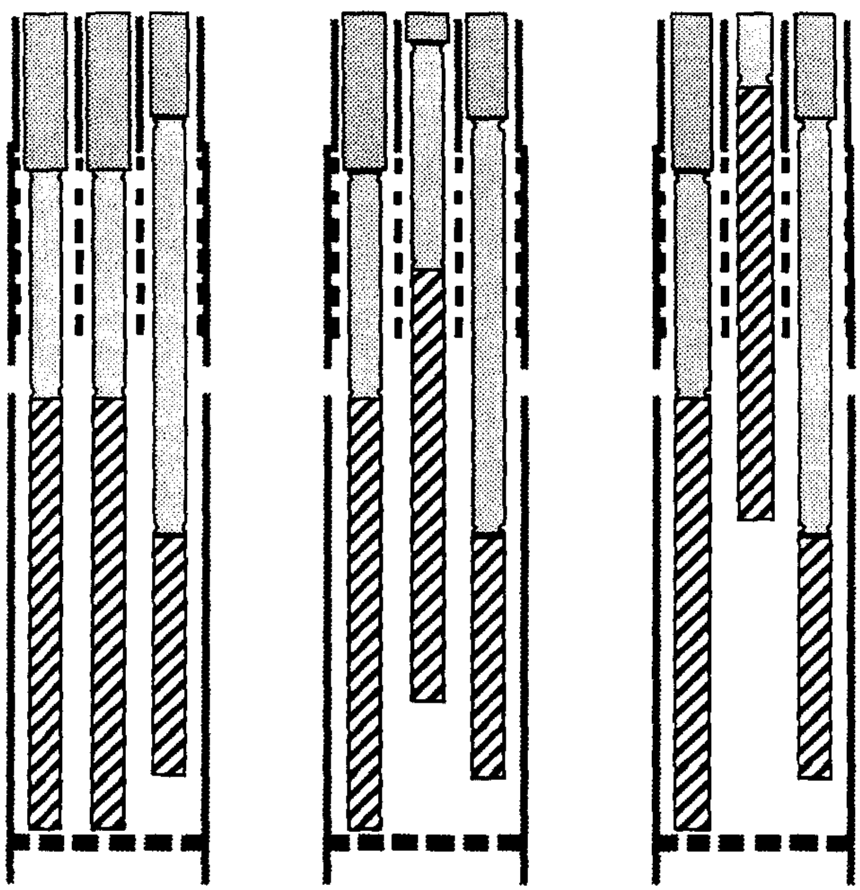

Figure 13b Effect of full rod position on freeboard (continued).

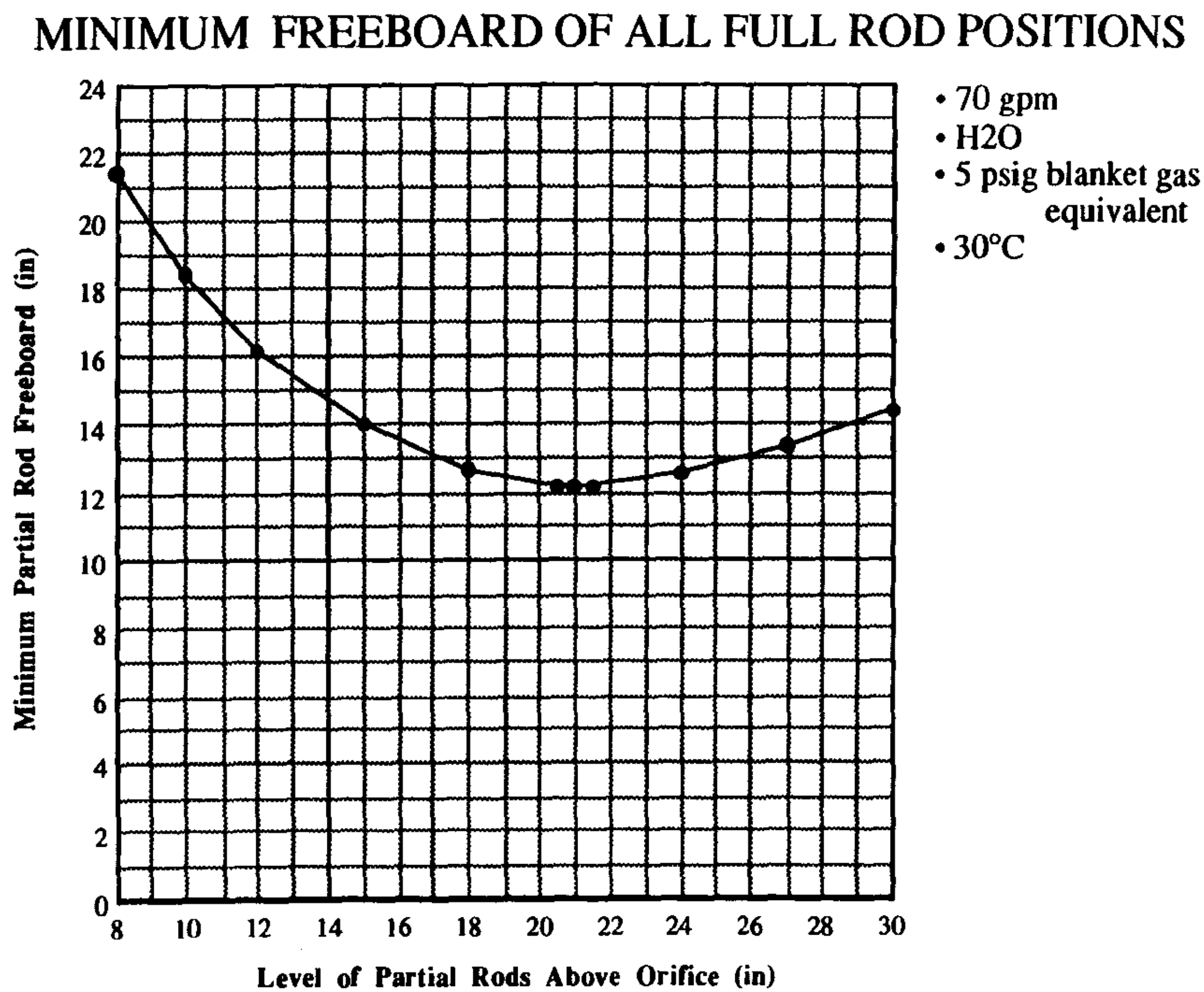

Figure 14. Minimum partial rod guide tube freeboard of all full rod positions (one full rod always inserted)

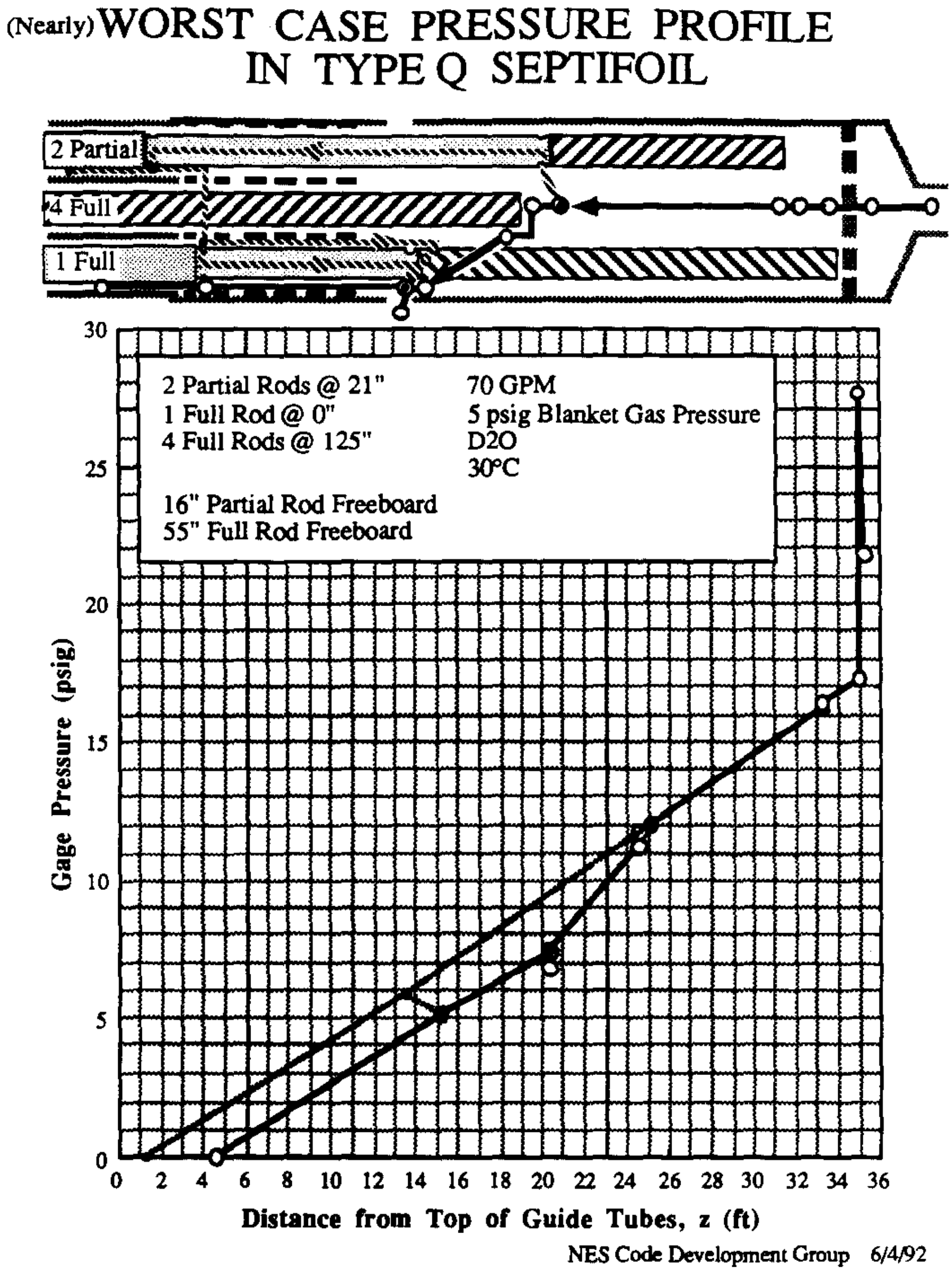

Figure 15 Pressure profile for nearly worst case rod configuration.

The Heat Transfer Laboratory experiment was conducted using H2O. In order to make the experimental results as directly applicable to K-reactor (D2O) as possible, volumetric flow rate and outlet liquid height were preserved. That is the outlet pressure for the experiment was set such that the freeboard under no flow conditions was identical to that in the reactor under no flow. This approach was expected to give nearly equivalent freeboard results between the HTL experiment and K-reactor. To quantify the difference, code simulations were performed for the worst case configuration of two partials at 21 in., four fulls at 119 in., 70 gpm and 30°C. One run was made for D2O and 5 psig blanket gas pressure and a second for H2O and 4.5112 psig. The computed partial rod guide tube freeboards are 11.99 in. and 12.14 in. for H2O and D2O, respectively. The difference is negligible and confirms the approach taken experimentally. More detailed information is given by (Flach, 1992, pp. 71-76).

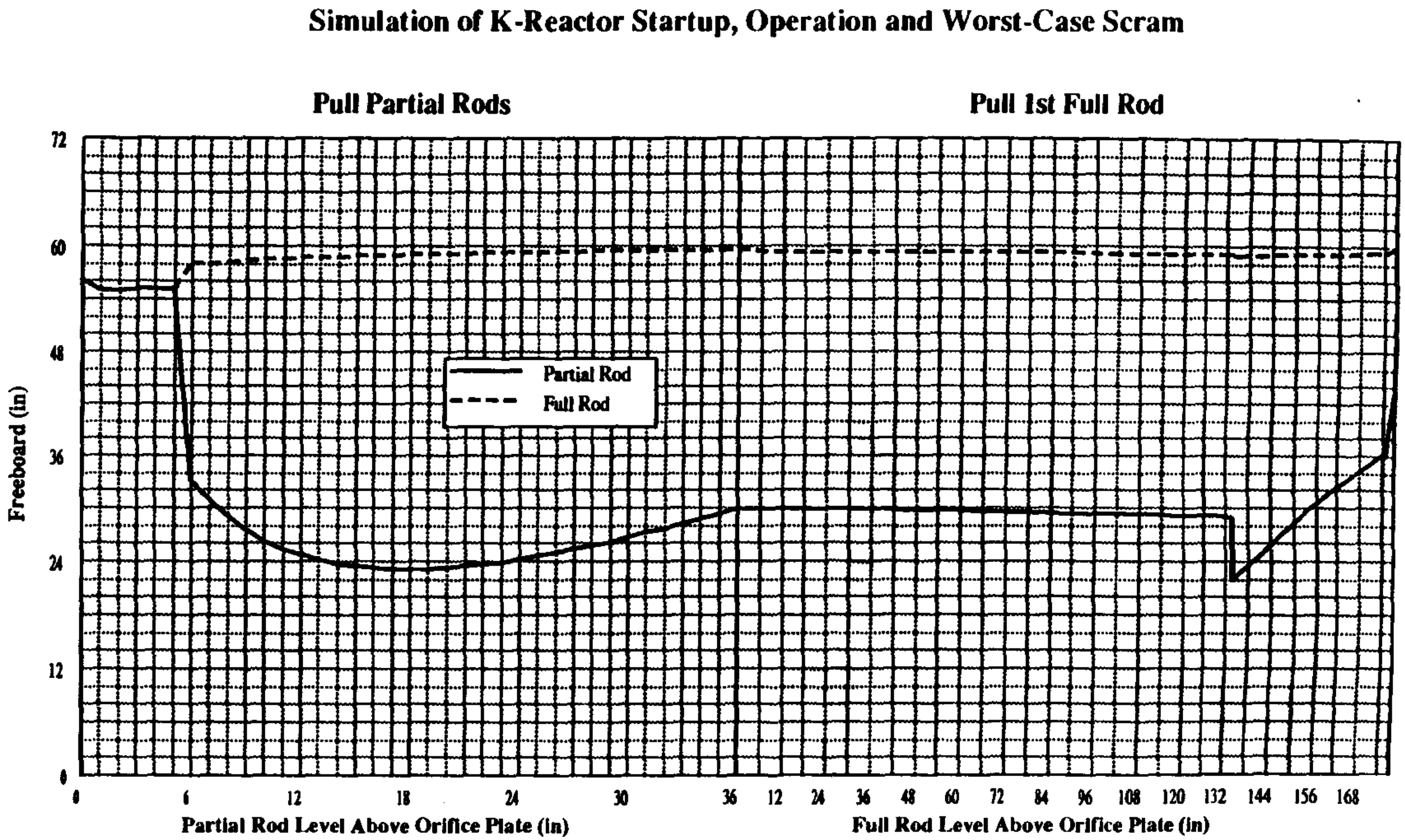

Figure 16a. Simulation of freeboard during reactor startup, operation and SCRAM

Simulation of K-Reactor Startup, Operation and Worst-Case Scram

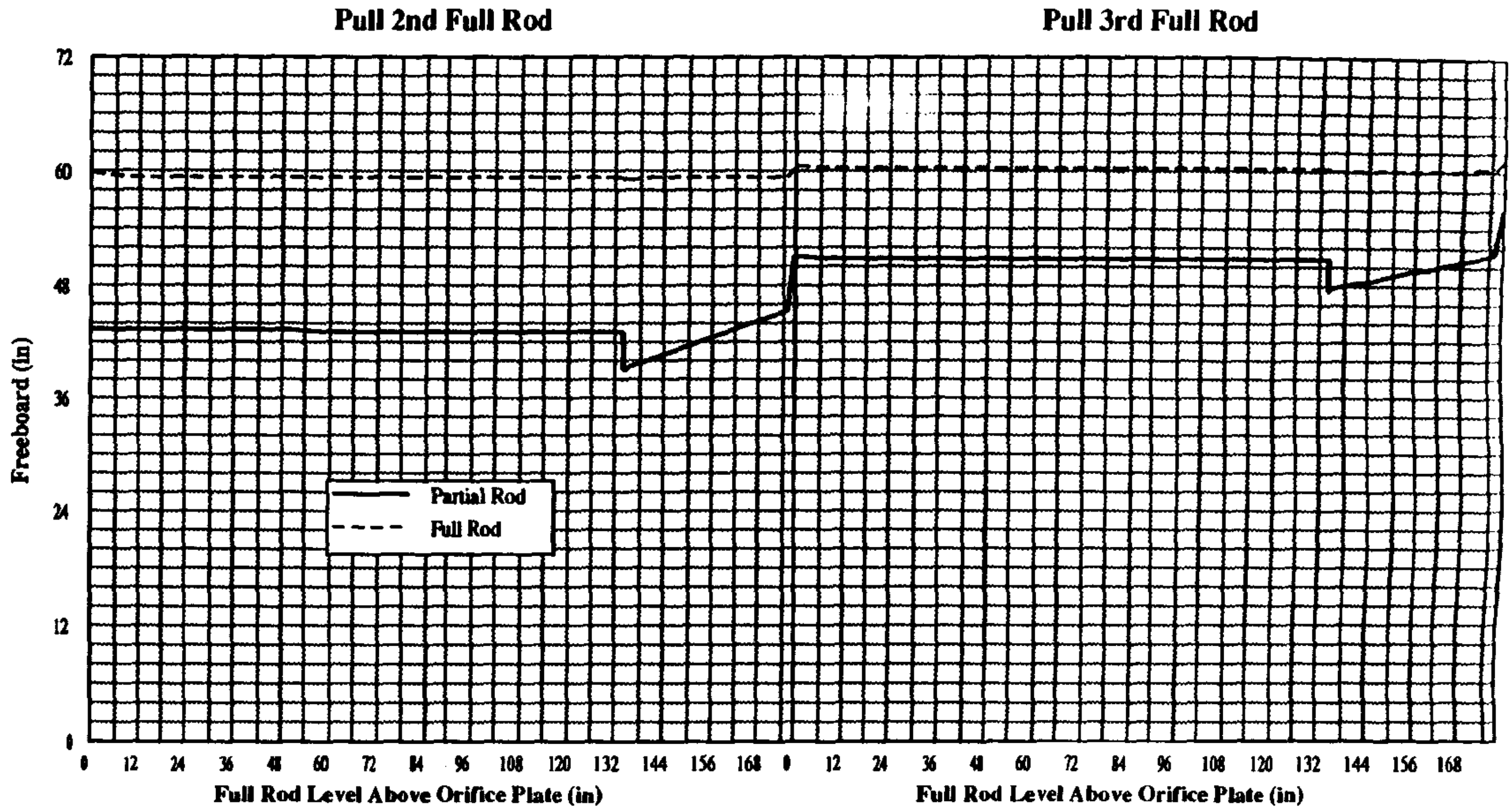

Figure 16b. Simulation of freeboard during reactor startup, operation and SCRAM

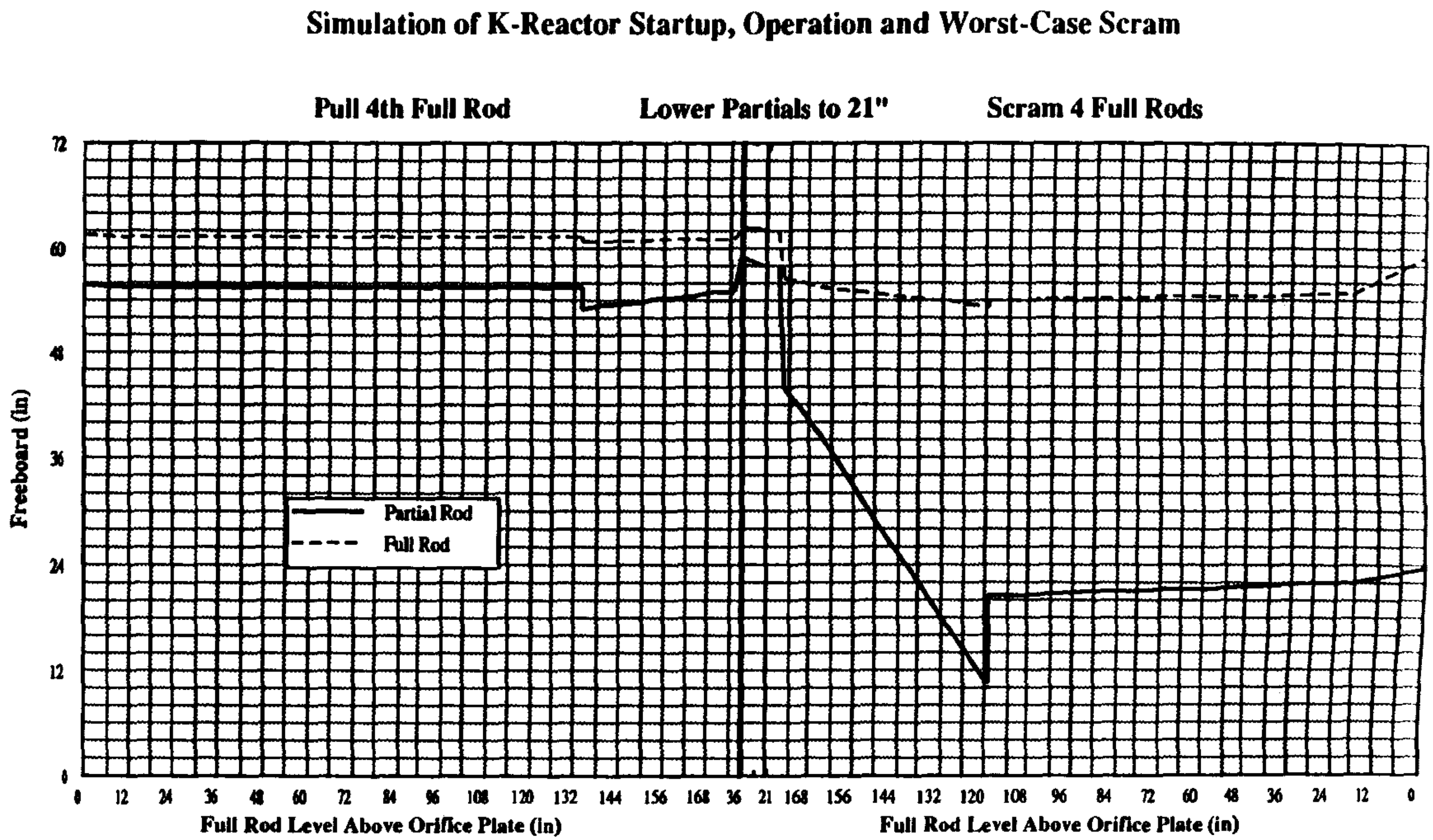

Figure 16c. Simulation of freeboard during reactor startup, operation and SCRAM

Effect of pulling control rods on septifoil system flows: The hydraulic resistance of a septifoil decreases as control rods are pulled, and this increases the total flow to the system. This effect can be important because the septifoil freeboards are sensitive to flow rate. The boundary conditions for the septifoil system flow are the heat exchanger discharge header pressures and the moderator tank pressure at the level of the septifoil slots. The tank pressure is determined by the level of moderator and the blanket gas pressure. It is independent of the septifoil system flow rate. The heat exchanger pressures are functions of the flow rates in the process water loops, and are only slightly influenced by changes in the septifoil system flow. The system response to changing control rod configurations can be reasonably approximated by a model with fixed pressure boundary conditions.

Figure 17 is a schematic of half of the septifoil supply system and a single lumped septifoil. The septifoil supply system is modelled with a single heat exchanger and a length of pipe equivalent to the network from three sets of heat exchangers to a ring header, as shown in Figure 5. Leg #1 of the septifoil model network, Figure 10, is extended upstream from the upflow pin to the heat exchanger, and the momentum equation for this leg is appropriately modified to account for the system pressure drop (Shadday, 1992). With this modification, the septifoil model will correctly predict the change in flow rate as control rods are moved, and the change in guide tube freeboards. Since a single lumped septifoil is modelled, the system response is for the case where all septifoils have the same control rod configuration. It is reasonable to model only half of the septifoil system because the two ring header pressures are essentially the same during normal operation (Shadday, 1991).

The system flow response was calculated for both full flow conditions and throttled flow at approximately 70 gpm. Equation (3) is the form of the expression for the system pressure drop, with an additional valve form loss coefficient to account for flow throttling. The required heat exchanger pressure for full flow of 100 gpm per septifoil, with all control rods fully inserted, is 118.84 psig (Shadday, 1992). This is within 2% of the average RELAP best estimate pressure. This pressure was used in the calculation of the throttling valve loss coefficient. Table III presents the system response for two rod configurations: all rods fully inserted; and the worst configuration considered, the two partial rods at 21 inches, four full rods at 119 inches, and one full rod fully inserted. Both full flow and throttled flow results are shown. Also shown in italics are the results if the flow rates are assumed to remain constant as the control rods are moved. At full flow conditions, the flow rate increases by 3.38 gpm when the control rods are moved to the specified configuration. The flow rate increases 1.21 gpm for the throttled case. At full flow, there is a 7.86 inch error in the partial rod guide tube freeboard associated with neglecting the increase in flow rate, and a 2.1 inch error with throttled flow. The effect of moving control rods on system flow is proportionally less for throttled flow than full flow because the throttled valves significantly increase the system flow resistance and make the changes associated with control rod movement proportionally less important.

$$\Delta P_{sys} = \rho(K_{sys} + K_{valve})Q^2 + \rho g \Delta z \qquad (3)$$

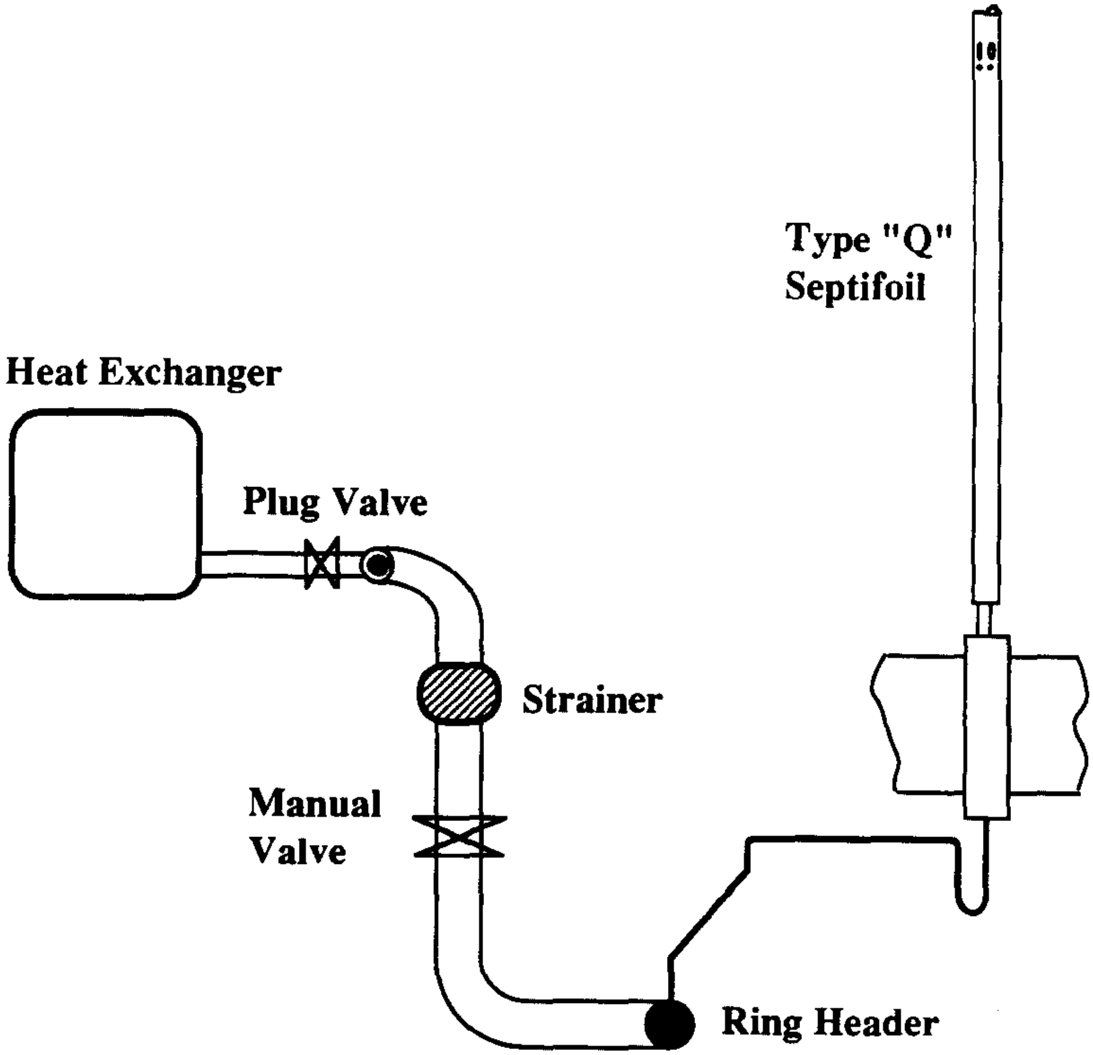

Figure 17. Schematic for a model of a septifoil and the supply system

Table III Septifoil flow response to control rod movement

All Control Rods In	2 Partials @ 21" 4 Fulls @ 119" 1 Full Inserted
Full Septifoil Flow	
Flow Rate = 99.98 gpm Freeboard Full Rods = 41.21" Freeboard Partial Rods = 41.21"	Flow Rate = 103.36 gpm Freeboard Full Rods = 38.31" Freeboard Partial Rods = -55.38"
	Flow Rate = 99.98 gpm *Freeboard Full Rods = 40.29"* *Freeboard Partial Rods = -47.52"*
Throttled Septifoil Flow	
Flow Rate = 69.93 gpm Freeboard Full Rods = 56.29" Freeboard Partial Rods = 56.29"	Flow Rate = 71.14 gpm Freeboard Full Rods = 54.76" Freeboard Partial Rods = 10.16"
	Flow Rate = 69.93 gpm *Freeboard Full Rods = 55.26"* *Freeboard Partial Rods = 12.26"*

K-reactor freeboard simulation for throttled septifoil flow: Following the overflow incident, K-reactor was restarted with septifoil flow throttled to 70 gpm nominally. Figure 16 illustrates the predicted freeboard levels for start-up, operation, and a scram with the partial rods at 21 in. (worst-case). The hydraulic model is a steady-state one. Transient effects during the scram portion of the simulation have not been considered. The simulation indicates the freeboard may be as low as about 11 in. during a worst rod configuration scram. The hydraulic behavior shown in Figure 16 is similar to the separate effects simulations considered above.

Conclusions

From the septifoil hydraulic model results presented above, the following conclusions are drawn:

- An accurate hydraulic model of the Type Q septifoil has been developed which is applicable to operating conditions of K-reactor.
- The hydraulic behavior of the Type Q septifoil, which leads to an overflow of D2O in K-reactor, is well understood.
- Assuming one full rod is always inserted, the minimum freeboard occurs for two partial control rods at 21 in. and four full rods at 119 in. above the orifice plate. (This condition could occur during a scram.)
- The Heat Transfer Laboratory experiment conducted using H2O yields results which are directly applicable to K-reactor (D2O).
- For septifoil flow throttled to 70 gpm and one full control rod always fully inserted, the minimum control rod guide tube freeboard is predicted to be 11 in. on a best-estimate basis. The best-estimate prediction precludes overflow; however, a conservative estimate of minimum freeboard accounting for uncertainties and deviations from nominal conditions has not been generated.

References

Conte S. D., and de Boor C., 1972, Elementary Numerical Analysis: an Algorithmic Approach, McGraw-Hill Book Company.

Flach, G. P., 1992, "Detailed notes on septifoil hydraulic model testing and results", QA task 92-057-1 calculation sheets.

Olson H. P., 1974, "Control and Safety Rod Cooling for the Savannah River Plant Reactors", DPSTSY-100-3, October 1974.

Press W. H., Flannery B. P., Teukolsky S. A., Vetterling W. T., 1989, Numerical Recipes the Art of Scientific Computing (FORTRAN version), Cambridge University Press.

Shadday, M. A., 1991, "Hydraulic Characteristics of the Type Q Septifoil", WSRC-TR-91-612, November 1991.

Shadday, M. A., 1992, "Notes for Septifoil Hydraulic Model", QA task 92-057-1 calculation sheets.

Steimke, J. L., G. L. Hovis, C. M. Hart, M. D. Fowley and J. C. Whitehouse, 1992, "Measurements of Septifoil Freeboard (U)", NES-ETH-920194, July 3.

This page intentionally left blank

Appendix A Septifoil Model Equations

The governing equations for the flows in the network legs are derived from the mechanical energy equation. An appropriate schematic of each leg of the septifoil model is shown along with the governing equation. The nomenclature convention for the equations and schematics is as follows: circled numbers in the schematic and subscripts are specific to that leg, the flow rate subscripts are an exception, and they refer to the leg number. More detail can be found in Appendix C, the code listing.

There are two network junctions where the flow splits and one where flows join. The junction pressures for the flow splits are defined to be in the inflow legs. For the joining flow junction, the pressure is defined to be in the outflow leg. The end velocities for several of the legs cannot therefore be expressed in terms of the leg flow rates. Figure A1 is a schematic of the two types of junctions that occur in the network

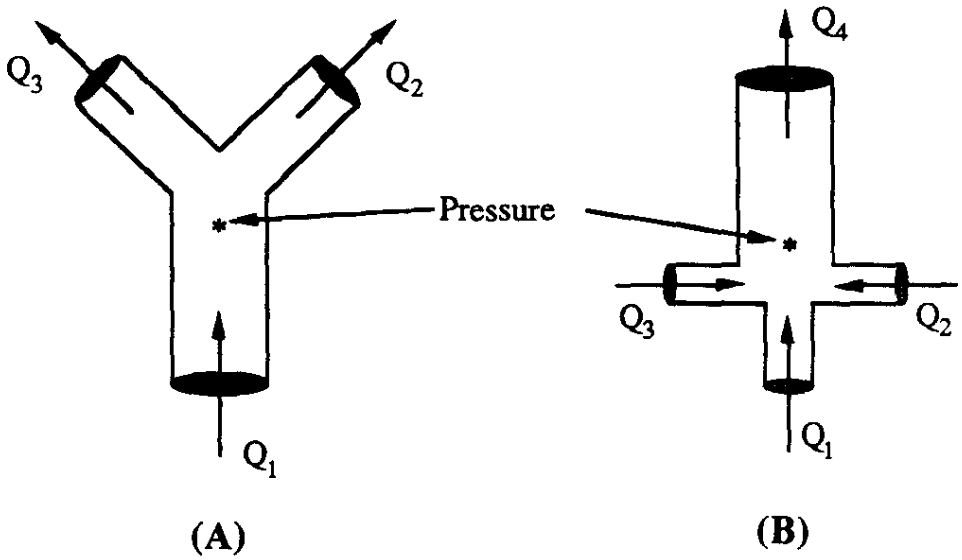

Figure A1. Flow Splits and Junctions.

The reversible junction losses in the two outflow legs of the dividing junction, (A), are approximated by defining the entrance velocities of the two outflow legs as follows:

$$V_{12} = \frac{Q_2}{\sqrt{Q_2^2 + Q_3^2}} \times V_1 \qquad V_{13} = \frac{Q_3}{\sqrt{Q_2^2 + Q_3^2}} \times V_1 \tag{A1}$$

The same procedure is used to define the exit velocities of the three inflow legs of the joining junction, (B).

$$V_{i4} = \frac{Q_i}{\sqrt{Q_1^2 + Q_2^2 + Q_3^2}} \times V_4 \tag{A2}$$

Leg #1 is the flow path from the septifoil upflow pin to the lower holes in the partial length control rod extension tubes. Figure A2 is a schematic of this flow path. The irreversible losses associated with the bottom end fitting, the diffuser and orifice plate, are accounted for by a single form loss coefficient. The part of the flow path from the orifice plate to the extension tube holes is divided into three sections with different numbers of control rods, and consequently flow areas and hydraulic diameters. Irreversible losses associated with flow over the rod tips are handled with loss coefficients, see Appendix B. The schematic shows the partially withdrawn full length control rods above the partial rods. Their axial position is arbitrary, and they could be above the extension tube holes, leaving only two sections in the septifoil housing portion of leg #1. Equation (A3) is the momentum equation for this leg.

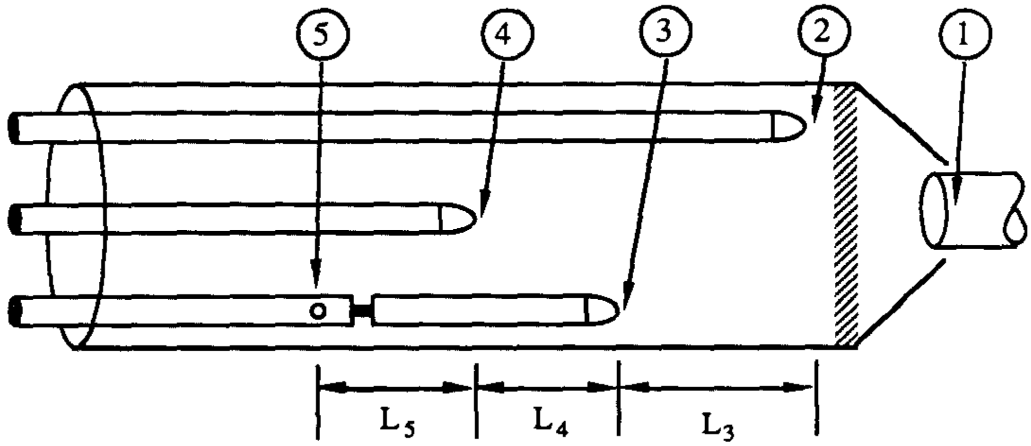

Figure A2. Leg #1 of the Septifoil Model.

$$P_5 - P_1 = -\frac{\rho}{2}\left(\frac{1}{A_5^2} - \frac{1}{A_1^2} + \frac{K_B}{A_1^2} + \frac{K_{RT}}{A_2^2} + \frac{K_{RT}}{A_3^2} + \frac{K_{RT}}{A_4^2} + \frac{f_3 L_3}{D_{H_3} A_3^2} + \frac{f_4 L_4}{D_{H_4} A_4^2} + \frac{f_5 L_5}{D_{h_5} A_5^2}\right) Q_1^2 - \rho g (z_5 - z_1) \tag{A3}$$

Leg #2 is the flow path, inside of the septifoil housing, from the lower holes of the partial rod extension tubes to the septifoil slots. This flow path is shown in Figure A3. The schematic shows the partially withdrawn full length rods above the extension tube holes, and therefore the leg divided into two sections. If the rod tips are below the extension tube holes, as shown in Figure A2, leg #2 will consist of one section. Equation (A4) is the momentum equation for leg #2.

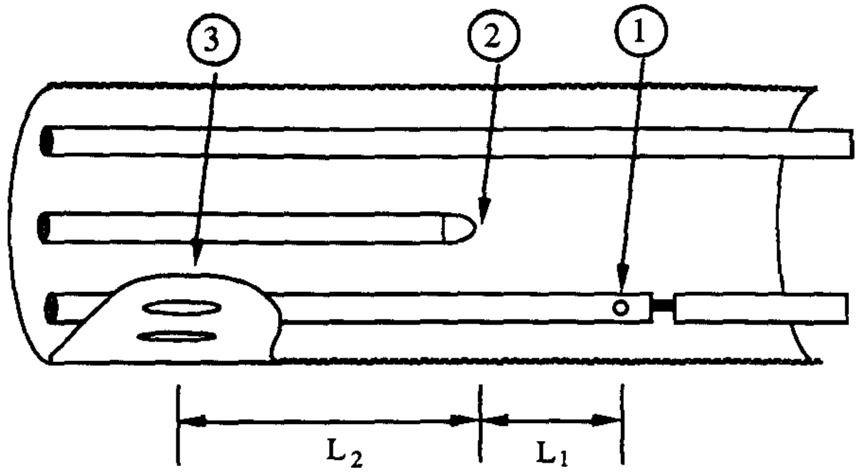

Figure A3. Leg #2 of the Septifoil Model

$$P_3 - P_1 = \frac{\rho}{2}V_{12}^2 - \frac{\rho}{2}V_{26}^2 - \frac{\rho}{2}\left(\frac{K_{RT}}{A_1^2} + \frac{f_1 L_1}{D_{H_1} A_1^2} + \frac{f_2 L_2}{D_{H_2} A_2^2}\right)Q_2^2 - \rho g(z_3 - z_1) \qquad \text{(A4)}$$

Leg #3 is the flow path through the partial length control rod extension tubes, up into the guide tubes, down into the septifoil muff, and past the top guide plate. At the end of this leg, the flow splits into two parallel paths down the septifoil muff. Equation (A5) is the momentum equation for leg #3.

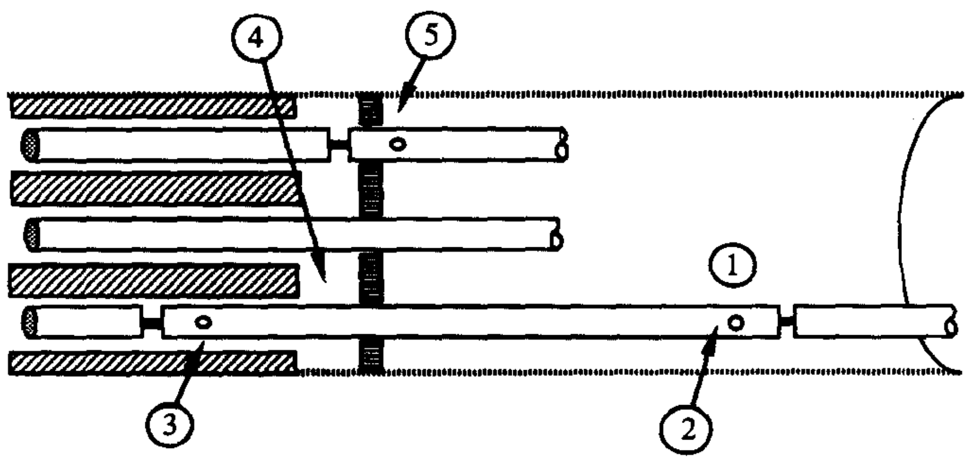

Figure A4. Leg #3 of the Septifoil Model

$$P_5 - P_1 = \frac{\rho}{2}V_{13}^2 - \frac{\rho}{2}\left[\frac{1}{A_5^2} + \left(K_{ent} + K_{ext} + \frac{f_{et}L_2}{D_{H_2}}\right)\frac{1}{A_2^2} + \frac{f_{gt}L_3}{D_{H_3}A_3^2} + \frac{K_{exgt}}{A_3^2} + \frac{f_{cas}L_{cas}}{D_{H_{cas}}A_4^2} + \frac{f_{gp}L_{gp}}{D_{H_{gp}}A_{gp}^2}\right]Q_3^2 - \rho g(z_5 - z_1) \quad \text{(A5)}$$

Legs 4 and 5 of the network are the parallel flow paths down the septifoil muff. Leg #4 is the flow path down the extension rods of the fully inserted full length control rods. Leg #5 is the flow path down the muff and past the guide plates. Figure A5 is the appropriate schematic for the momentum equations for both legs. Equation (A6) is the momentum equation for leg #4, and equation (A7) is the momentum equation for leg #5.

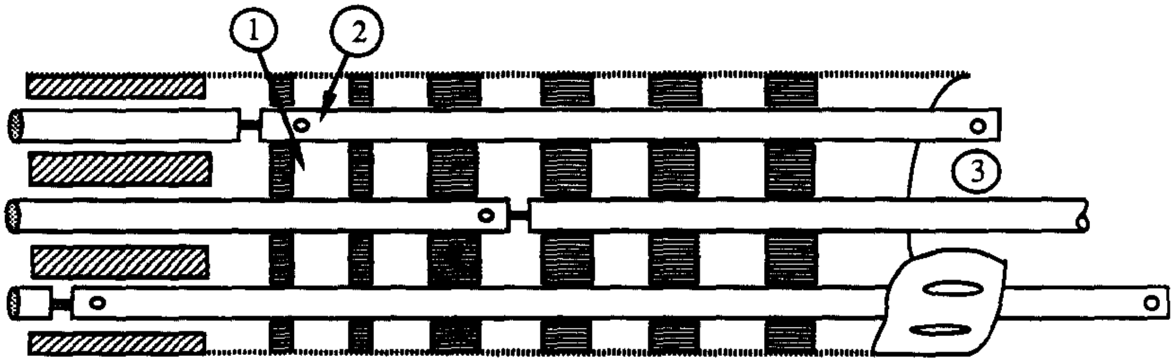

Figure A5. Legs 4 & 5 of the Septifoil Model

$$P_3 - P_1 = \frac{\rho}{2}V_{34}^2 - \frac{\rho}{2}V_{46}^2 - \frac{\rho}{2}\left(\frac{K_{ent} + K_{ext}}{A_2^2} + \frac{f_2L_2}{D_{H_2}A_2^2}\right)Q_4^2 - \rho g(z_3 - z_1) \quad \text{(A6)}$$

$$P_3 - P_1 = \frac{\rho}{2}V_{35}^2 - \frac{\rho}{2}V_{56}^2 - \frac{\rho}{2}\left(\frac{f_{cas}L_{cas}}{D_{H_{cas}}A_{cas}^2} + \frac{f_{gp}L_{gp}}{D_{H_{gp}}A_{gp}^2}\right)Q_5^2 - \rho g(z_3 - z_1) \quad \text{(A7)}$$

Leg #6 is the flow path out of the septifoil through the slots and holes. Legs 2, 4, and 5 feed flow into a junction, inside of the septifoil at the level of the slots. The septifoil effluent leaves this junction through leg #6. The flow through the slots is controlled by a discharge coefficient, (Shadday, 1991). Equation (A8) is the expression for the slot velocity, and equation (A9) is the equation transformed into the functional form as the other momentum equations.

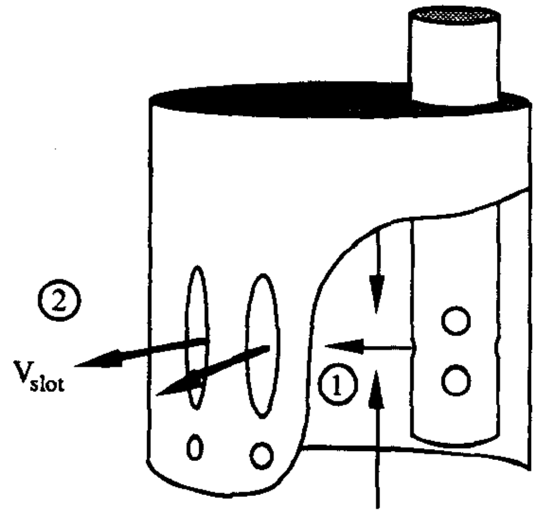

Figure A6. Leg #6 of the Septifoil Model

$$V_{slot} = C_D\sqrt{\frac{2}{\rho}(P_1 - P_2) + V_1^2} \tag{A6}$$

$$P_2 - P_1 = -\frac{\rho}{2}\left(\frac{1}{A_S^2C_D^2} - \frac{1}{A_1^2}\right)Q_6^2 \tag{A7}$$

This page intentionally left blank

Appendix B Septifoil Dimensions & Form Losses

The dimensions that are used in the septifoil model are listed, and shown, where appropriate, on schematics.

The entrance boundary condition is the pressure in the upflow pin that sticks up from the tank bottom, as shown in Figure B1. This pin has an inside diameter of one inch. The flow enters the septifoil through a bottom end fitting that consists of a diffuser followed by an orifice plate. The irreversible losses in the bottom end fitting can be calculated with a form loss coefficient of 1.7 and the flow velocity in the upflow pin (Shadday, 1991). The flow area and hydraulic diameter downstream of the orifice plate are those for a septifoil housing without control rods.

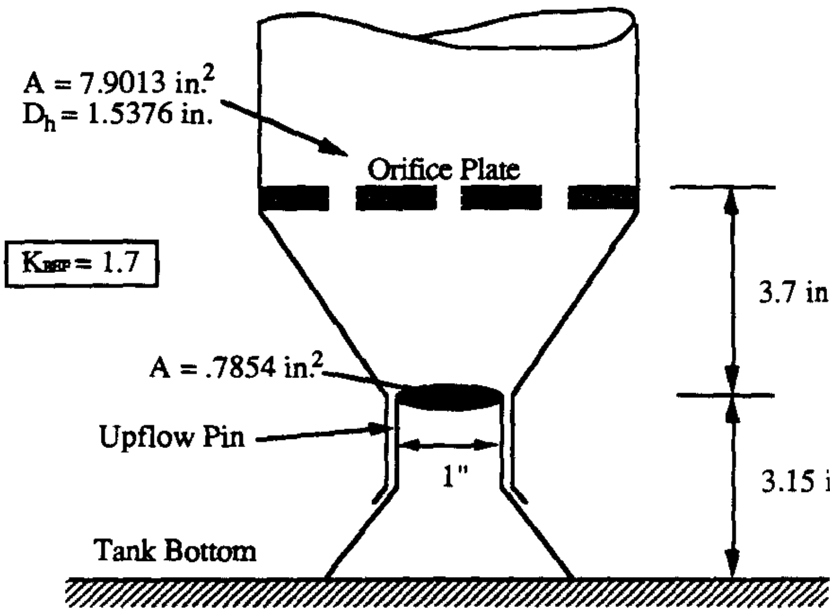

Figure B1. Septifoil Bottom End Fitting

The flow areas and hydraulic diameters inside of the septifoil housing change with the number of control rods present. Table B1 lists these dimensions as functions of the number of control rods.

Table B1. Flow Areas and Hydraulic Diameters of the Septifoil Housing

# Control Rods	Area (in.^{2})	D_h (in.)
0	7.901	1.538
1	7.207	1.226
2	6.513	.985
3	5.819	.791
4	5.125	.633
5	4.431	.502
6	3.737	.391
7	3.043	.295

There are irreversible losses associated with flow over a rod tip. Equation (B1) is a relation for the form loss coefficient for a single rod tip (Shadday, 1991). The Reynolds number is based on the upstream velocity and the rod diameter. If there are several rod tips at the same axial position, the loss coefficient is multiplied by the number of rod tips.

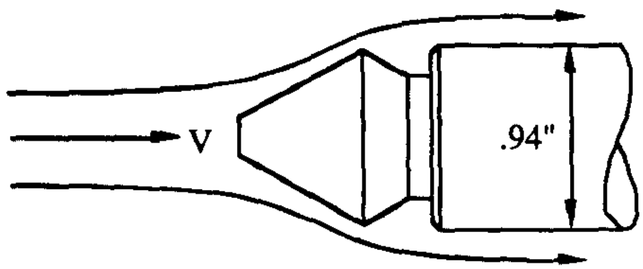

Figure B2. Flow Over a Control Rod Tip

$$K_{RT} = \frac{1.8718 \times 10^8}{Re_D^2} - \frac{2.64515 \times 10^4}{Re_D} + 1.48569 \qquad \text{(B1)}$$

At the top of the septifoil housing, the flow discharges into the reactor tank through twelve slots and holes, shown in Figure B3. Two distinct values for the discharge coefficients were determined from flow tests, (Shadday,1991): 0.34 for the cases where the control rods were inserted into the septifoil below the slots and holes, and 0.55 for the case where the control rods were above the slots. The value of the discharge coefficient changes depending on whether the slot is masked by a control rod. For cases where some of the control rods are fully withdrawn, an average value for the discharge coefficient is determined by interpolation between the two bounding values.

Figure B4 shows the important vertical dimensions inside of the septifoil housing. Also shown are the distances from the rod tips to the lower extension tube drain holes for both full and partial length control rods. When the full length rods are resting on the orifice plate, the lower extension tube drain holes are within a half inch of the slot centerline level. This small difference is neglected in this analysis.

Figure B5 is a schematic of an extension tube. There are eight 3/8 inch drain holes at either end of a tube. The two end drain holes are half masked by the end fittings, so the equivalent flow area is that of seven holes, .773 in^2. The inside diameter of an extension tube is .69 in. For the code, the axial position of the equivalent drain hole is assumed to be at the center pair of the six unmasked holes, as shown in Figure B5.

Figure B6 is a schematic of the septifoil muff and guide tube assembly. The positions of the extension tubes are shown for fully inserted control rods that are resting on the orifice plate. This was the reference position for the tests in the Heat Transfer Laboratory. In the reactor, the 1000 VU position has the rod tips .5 inches above the orifice plate. This discrepancy between the reactor and experiment is neglected in the code, and the reference position is assumed to be the rod tips resting on the orifice plate.

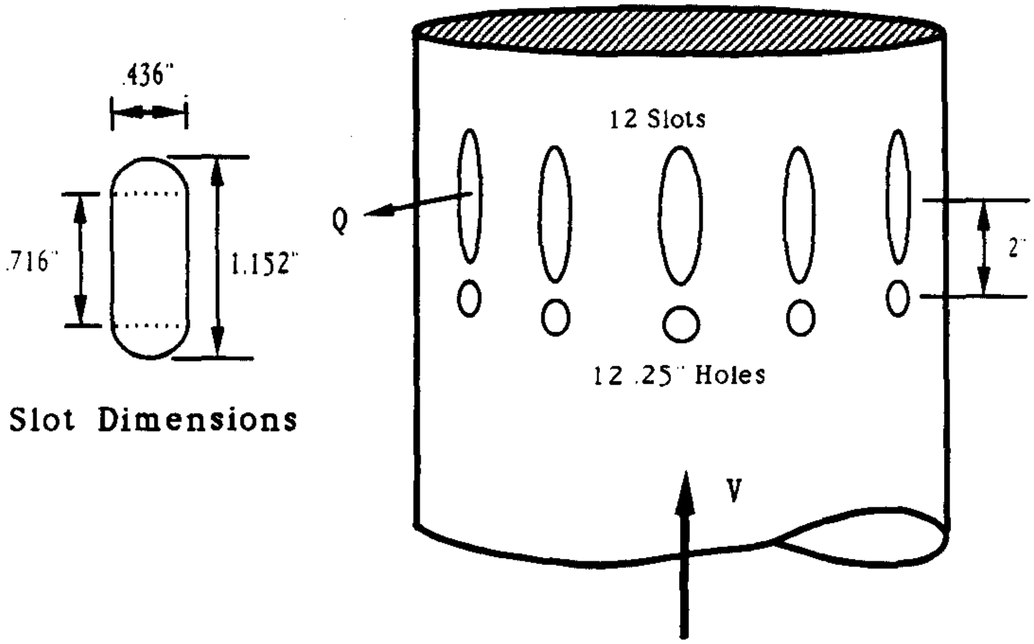

Figure B3. Septifoil Effluent Slots and Holes

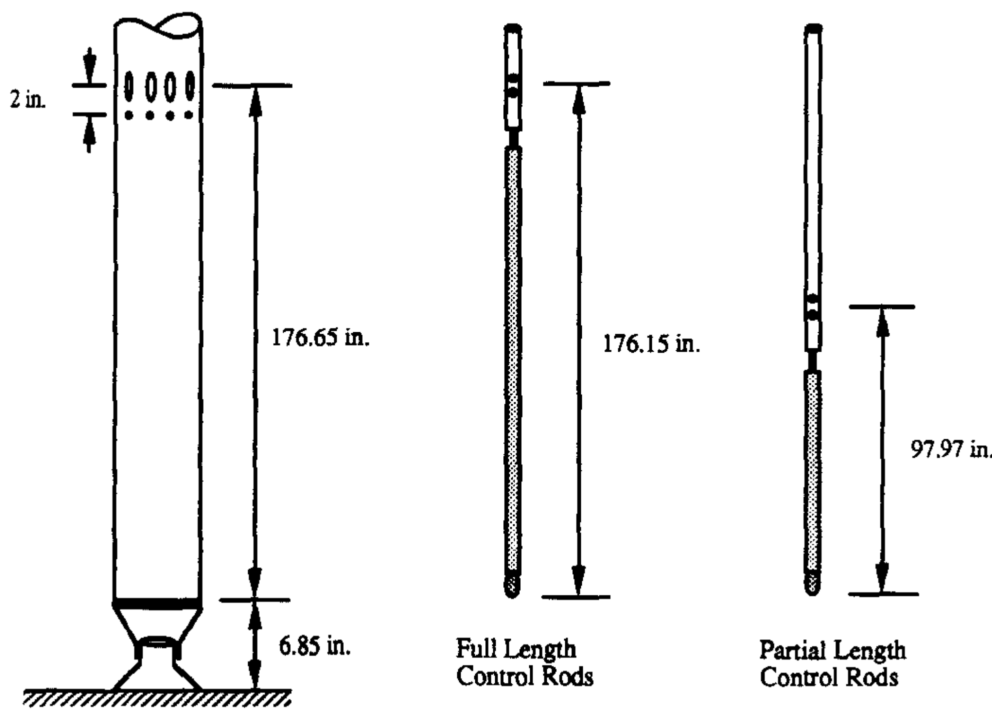

Figure B4. Vertical Distances Inside of the Septifoil Housing

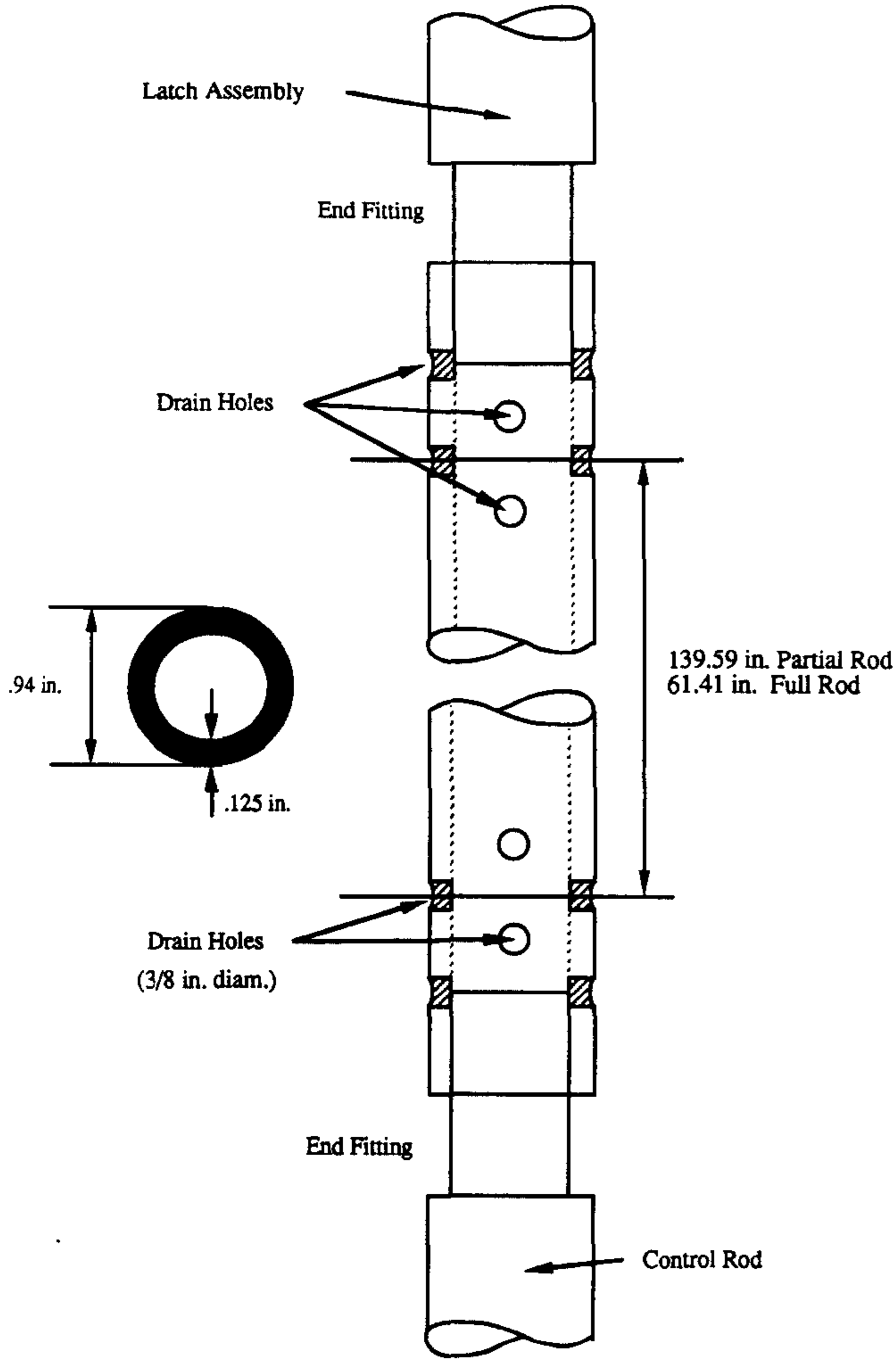

Figure B5. Control Rod Extension Tube

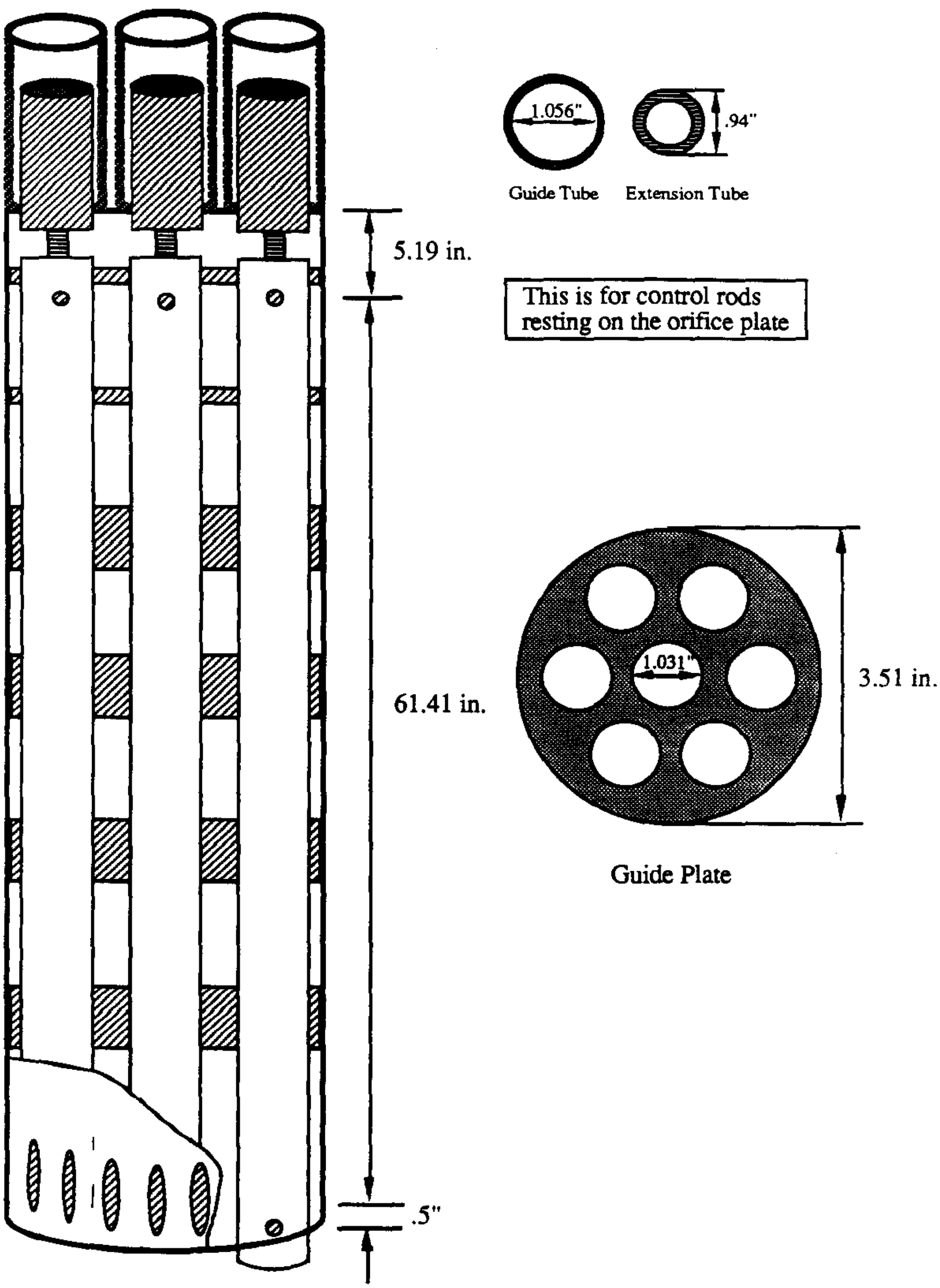

Figure B6. Septifoil Muff and Guide Tube Dimensions

There are six guide plates in the septifoil muff. The bottom four are 4.5 inches thick, and the top two are one inch thick. The guide holes through which the control rods pass have diameters of 1.031 in. When control rods are fully withdrawn, the rod tips are even with the tops of the septifoil slots. The rods are therefore never withdrawn from the muff. The total flow area for the seven annular regions in a guide plate is .986 in^2, and the hydraulic diameter of an annular region is .091 in. The guide holes are well rounded, so entrance and exit form losses are neglected for the flow past the plates. Between the guide plates, the muff is fairly open. The flow area is 4.818 in^2, and the hydraulic diameter is .608 in.

When the upper drain holes of the partial length rod extension tubes are withdrawn into the guide tubes, part of flow path leg #3 is the lengths of the annular regions formed by the guide tubes and the partial length rod extension tubes, between the drain holes and the top of the muff. The flow area for a single annular cross-section is .182 in^2 and the hydraulic diameter is .116 in.

Table B2 is a list of septifoil component drawings from which the dimensions in this appendix were determined.

Table B2. Septifoil Drawings

Septifoil Component	Drawing Number
Septifoil Housing, Muff, & Guide Tubes	ST-MDX5-10074
Septifoil Muff	W151074
Muff Housing	133589
Long Guide Plates	131206
Short Guide Plates	131235
Control Rods & Extension Tubes	ST-MDX4-10005

APPENDIX C: FORTRAN Source Code Listing

PROGRAM SEPT11

```
      program sept11
c
c     *****************************************************************
c     * PROGRAM SEPT11                                                *
c     *                                                               *
c     *                                                               *
c     *****************************************************************
c
      real kent3, kext3, kexgt3,
     &     kent4, kext4
      character*40 label
      character*6 labelp
c
      external func11
c
      include 'arrays.inc'
      include 'props.inc'
      include 'bcs.inc'
      include 'knobs.inc'
      include 'leg1.inc'
      common /leg3/ kent3, kext3, kexgt3
      common /leg4/ kent4, kext4
c
      parameter (zero=0.0, ten=10.0)
      parameter (patm=101325.0, tconv=273.15, pconv=6895.0,
     &           qconv=6.309e-5, zconv=0.0254, zconv2=0.3048)
      parameter (dzbg=45.875*0.0254, dztbst=183.5*0.0254)
c
      data zin /423.93/,
c
cc   &     zom /420.  /,
cc   &     zop /420.  /,
c
cc   &     zpm /420.  /,
cc   &     zpp /420.  /,
c
cc   &     zfim/420.  /,
cc   &     zfip/420.  /,
c
     &     z1  /322.16/,
c
     &     zpgt/182.87/,
     &     zfgt/177.68/,
c
     &     z2  /182.87/,
c
     &     z3  /243.68/,
cc   &     z3m /243.68/,
c
     &     zout/243.68/
c
      data g/9.80665/
c
c     READ INPUT
c
      read(5,700) label
      read(5,*) ibc, pin, q1, pbg, ilq, iexp, isys, temp
      read(5,*) dzp, dzfi, np, nfi, nfd, nfu
```

```
      if (ibc .eq. 1) then
         read(5,*) p1, p2, p3, q1, q2, q4
      else
         read(5,*) pin, p1, p2, p3, q2, q4
      end if
      read(5,*) epsp, epsq, itermx
      read(5,*) kent3, kext3, kexgt3, kent4, kext4, er12, er345
c
      write(6,800) label
      write(6,900) ibc, pin, q1, pbg, ilq, iexp, isys, temp,
     &             dzp, dzfi, np, nfi, nfd, nfu,
     &             epsp, epsq, itermx,
     &             kent3, kext3, kexgt3, kent4, kext4, er12, er345
c
      epsp = epsp*patm
      epsq = epsq*qconv
c
      delp = ten*epsp
      delq = ten*epsq
c
c     SET PROPERTIES
c
      temp = temp + tconv
      call liquid(patm,temp,ilq,rho,hf,vis,cpf,condf,sigma)
      rhog = rho*g
c
c     CONVERT FROM OLD ENGLISH TO S.I.
c
      dzp  = dzp *zconv
      dzfi = dzfi*zconv
c
      zin  = zin *zconv
cc    zom  = zom *zconv
cc    zop  = zop *zconv
cc    zfim = zfim*zconv
cc    zfip = zfip*zconv
cc    zpm  = zpm *zconv
cc    zpp  = zpp *zconv
      z1   = z1  *zconv
      z2   = z2  *zconv
cc    z3m  = z3m *zconv
      z3   = z3  *zconv
      zout = zout*zconv
c
      zpgt = zpgt*zconv
      zfgt = zfgt*zconv
c
      pin = pin*pconv + patm
      p1  = p1 *pconv + patm
      p2  = p2 *pconv + patm
      p3  = p3 *pconv + patm
      if (iexp .eq. 1) then
         pout = (pbg*pconv + patm) - rhog*dztbst
      else
         pout = (pbg*pconv + patm) + rhog*dzbg
      end if
c
      q1 = q1*qconv
      q2 = q2*qconv
      q3 = q1 - q2
      q4 = q4*qconv
      q5 = q3 - q4
      q6 = q1
```

```
c
c     CORRECT PRESSURE LOCATIONS FOR ROD POSITION
c
      z1   = z1   - dzp
      zpgt = zpgt - dzp
cc    zpm  = zpm  - dzp
cc    zpp  = zpp  - dzp
c
cc    zfim = zfim - dzfi
cc    zfip = zfip - dzfi
c
c     SET-UP GEOMETRY FOR LEGS 1 & 2
c
      call inpl1
      call inpl2
c
c     STUFF X VECTOR
c
      if (ibc .eq. 1) then
         nq = 6
         x(1) = q1
         x(2) = q2
         x(3) = q3
         x(4) = q4
         x(5) = q5
         x(6) = q6
         x(7) = p1
         x(8) = p2
         x(9) = p3
      else
         nq = 5
         x(1) = q2
         x(2) = q3
         x(3) = q4
         x(4) = q5
         x(5) = q6
         x(6) = pin
         x(7) = p1
         x(8) = p2
         x(9) = p3
      end if
c
c     PERFORM NEWTON ITERATION
c
      call newton(nq,epsp,epsq,itermx,delq,delp,funcl1)
c
c     UNSTUFF X VECTOR
c
      if (ibc .eq. 1) then
         q1 = x(1)
         q2 = x(2)
         q3 = x(3)
         q4 = x(4)
         q5 = x(5)
         q6 = x(6)
         p1 = x(7)
         p2 = x(8)
         p3 = x(9)
      else
         q2  = x(1)
         q3  = x(2)
         q4  = x(3)
         q5  = x(4)
```

```
            q6   = x(5)
            pin  = x(6)
            p1   = x(7)
            p2   = x(8)
            p3   = x(9)
         end if
c
c        COMPUTE FREEBOARD IN SEPTIFOIL GUIDE TUBES
c
         call leg13(q1,q2,q3,dp3,dppgt,dpfgt)
         ppgt = p1 + dppgt
         pfgt = p1 + dpfgt
c
         ppfb = patm
         pffb = patm
c
         zpfb = zpgt - (ppgt - ppfb)/rhog
         zffb = zfgt - (pfgt - pffb)/rhog
c
c        COMPUTE INTERMEDIATE PRESSURES
c
cc       call leg11(q1,dp1,dpom,dpop,dppm,dppp)
cc       pom = pin + dpom
cc       pop = pin + dpop
cc       ppm = pin + dppm
cc       ppp = pin + dppp
c
cc       call leg12(q1,q2,q3,q4,q5,q6,dp2,dpfim,dpfip,dp3m)
cc       pfim = p1 + dpfim
cc       pfip = p1 + dpfip
cc       p3m  = p1 + dp3m
c
c        COMPUTE HTL RIG PRESSURES
c
         if (iexp .eq. 1) then
            phtli = pin + 3511.5 + 2.0244e+9*q1**2
            phtlo = p3 - (rhog*1.426*zconv)
         end if
c
c        CONVERT FROM S.I. TO OLD ENGLISH
c
         zin  = zin /zconv2
cc       zom  = zom /zconv2
cc       zop  = zop /zconv2
cc       zpm  = zpm /zconv2
cc       zpp  = zpp /zconv2
cc       zfim = zfim/zconv2
cc       zfip = zfip/zconv2
         z1   = z1  /zconv2
         z2   = z2  /zconv2
cc       z3m  = z3m /zconv2
         z3   = z3  /zconv2
         zout = zout/zconv2
c
         zpgt = zpgt/zconv2
         zfgt = zfgt/zconv2
         zpfb = zpfb/zconv2
         zffb = zffb/zconv2
c
         q1 = q1/qconv
         q2 = q2/qconv
         q3 = q3/qconv
         q4 = q4/qconv
```

```
      q5 = q5/qconv
      q6 = q6/qconv
c
      pin  = (pin  - patm)/pconv
      p1   = (p1   - patm)/pconv
      p2   = (p2   - patm)/pconv
      p3   = (p3   - patm)/pconv
      pout = (pout - patm)/pconv
c
      ppgt = (ppgt - patm)/pconv
      pfgt = (pfgt - patm)/pconv
      ppfb = (ppfb - patm)/pconv
      pffb = (pffb - patm)/pconv
c
      phtli = (phtli - patm)/pconv
      phtlo = (phtlo - patm)/pconv
c
cc    pom  = (pom  - patm)/pconv
cc    pop  = (pop  - patm)/pconv
cc    ppm  = (ppm  - patm)/pconv
cc    ppp  = (ppp  - patm)/pconv
cc    pfim = (pfim - patm)/pconv
cc    pfip = (pfip - patm)/pconv
cc    p3m  = (p3m  - patm)/pconv
c
c     WRITE RESULTS
c
      if (iexp .eq. 1) then
         write(6,910) q1, q2, q3, q4, q5, q6, phtli,
     &                pin, p1, p2, p3, pout, phtlo,
     &                ppgt, pfgt,
     &                zffb*12.0, zpfb*12.0
      else
         write(6,911) q1, q2, q3, q4, q5, q6,
     &                pin, p1, p2, p3, pout,
     &                ppgt, pfgt,
     &                zffb*12.0, zpfb*12.0
      end if
c
      write(6,920)
      labelp = 'pin   '
      write(6,930) zin , pin , labelp
cc    labelp = 'pom   '
cc    write(6,930) zom , pom , labelp
cc    labelp = 'pop   '
cc    write(6,930) zop , pop , labelp
cc    labelp = 'ppm   '
cc    write(6,930) zpm , ppm , labelp
cc    labelp = 'ppp   '
cc    write(6,930) zpp , ppp , labelp
      labelp = 'p1    '
      write(6,930) z1  , p1  , labelp
cc    labelp = 'pfim  '
cc    write(6,930) zfim, pfim, labelp
cc    labelp = 'pfip  '
cc    write(6,930) zfip, pfip, labelp
cc    labelp = 'p3m   '
cc    write(6,930) z3m , p3m , labelp
      labelp = 'p3    '
      write(6,930) z3  , p3  , labelp
      labelp = 'pout  '
      write(6,930) zout, pout, labelp
      write(6,940)
```

```
c
      labelp = 'p3    '
      write(6,930) z3  , p3  , labelp
      labelp = 'pfgt  '
      write(6,930) zfgt, pfgt, labelp
      labelp = 'pffb  '
      write(6,930) zffb, pffb, labelp
      write(6,940)
c
      labelp = 'p1    '
      write(6,930) z1  , p1  , labelp
      labelp = 'ppgt  '
      write(6,930) zpgt, ppgt, labelp
      write(6,940)
c
      labelp = 'ppgt  '
      write(6,930) zpgt, ppgt, labelp
      labelp = 'p2    '
      write(6,930) z2  , p2  , labelp
      labelp = 'p3    '
      write(6,930) z3  , p3  , labelp
      write(6,940)
c
      labelp = 'ppgt  '
      write(6,930) zpgt, ppgt, labelp
      labelp = 'ppfb  '
      write(6,930) zpfb, ppfb, labelp
      write(6,940)
c
      if (iexp .eq. 1) then
         write(20,950) zpfb*12.0, zffb*12.0, phtli, phtlo, label
      else
         write(20,951) zpfb*12.0, zffb*12.0, label
      end if
c
c     FORMATS
c
700   format(a40)
800   format(/,1x,a40)
c
900   format(/,2x,'----- INPUT -----',/,
     &       2x,'Inlet BC? (1=prs, 2=flow)     ibc: ',   i1,/,
     &       2x,'Pin pressure (only one  pin(psig): ', f6.2,/,
     &       2x,'Pin flowrate  is used)     q1(gpm): ', f7.3,/,
     &       2x,'Blanket gas pressure    pbg(psig): ', f6.2,/,
     &       2x,'Liquid (1=H2O, 2=D2O)          ilq: ',   i1,/,
     &       2x,'HTL Rig? (1=yes, 0=no)        iexp: ',   i1,/,
     &       2x,'Inlet? (1=pin, 2,3=Hx)        isys: ',   i1,/,
     &       2x,'Temperature                temp(C): ', f6.2,/,
     &       2x,'Partial rod position       dzp(in): ', f6.2,/,
     &       2x,'Full intermediate pos.   dzfi(in): ', f6.2,/,
     &       2x,'No. of partials                 np: ',   i2,/,
     &       2x,'No. of full intermediates      nfi: ',   i2,/,
     &       2x,'No. of full completely down    nfd: ',   i2,/,
     &       2x,'No. of full completely up      nfu: ',   i2,/,
     &       2x,'Convergence tolerances        epsp: ', e9.2,/,
     &       2x,'                              epsq: ', e9.2,/,
     &       2x,'Max. no. of iterations      itermx: ',   i3,/,
     &       2x,'Leg 3 entrance K             kent3: ', e9.2,/,
     &       2x,'Leg 3 exit K                 kext3: ', e9.2,/,
     &       2x,'Leg 3 guide tube exit K    kexgt3: ', e9.2,/,
     &       2x,'Leg 4 entrance K             kent4: ', e9.2,/,
     &       2x,'Leg 4 exit K                 kext4: ', e9.2,/,
```

```
     &       2x,'Legs 1-2 roughness          er12(m): ', e9.2,/,
     &       2x,'Legs 3-5 roughness         er345(m): ', e9.2,//)
c
910   format(2x,'----- OUTPUT -----',/,
     &       2x,'Leg 1 flowrate              q1(gpm): ', f6.2,/,
     &       2x,'Leg 2 flowrate              q2(gpm): ', f6.2,/,
     &       2x,'Leg 3 flowrate              q3(gpm): ', f6.2,/,
     &       2x,'Leg 4 flowrate              q4(gpm): ', f6.2,/,
     &       2x,'Leg 5 flowrate              q5(gpm): ', f6.2,/,
     &       2x,'Leg 6 flowrate              q6(gpm): ', f6.2,//,
     &       2x,'Pressure htl inlet      phtli(psig): ', f6.2,/,
     &       2x,'Pressure inlet            pin(psig): ', f6.2,/,
     &       2x,'Pressure 1                 p1(psig): ', f6.2,/,
     &       2x,'Pressure 2                 p2(psig): ', f6.2,/,
     &       2x,'Pressure 3                 p3(psig): ', f6.2,/,
     &       2x,'Pressure outlet          pout(psig): ', f6.2,/,
     &       2x,'Pressure htl outlet     phtlo(psig): ', f6.2,/,
     &       2x,'Pressure pgt              pgt(psig): ', f6.2,/,
     &       2x,'Pressure fgt              fgt(psig): ', f6.2,//,
     &       2x,'Freeboard-full             zffb(in): ', f6.2,/,
     &       2x,'Freeboard-partial          zpfb(in): ', f6.2,//)
c
911   format(2x,'----- OUTPUT -----',/,
     &       2x,'Leg 1 flowrate              q1(gpm): ', f6.2,/,
     &       2x,'Leg 2 flowrate              q2(gpm): ', f6.2,/,
     &       2x,'Leg 3 flowrate              q3(gpm): ', f6.2,/,
     &       2x,'Leg 4 flowrate              q4(gpm): ', f6.2,/,
     &       2x,'Leg 5 flowrate              q5(gpm): ', f6.2,/,
     &       2x,'Leg 6 flowrate              q6(gpm): ', f6.2,//,
     &       2x,'Pressure inlet            pin(psig): ', f6.2,/,
     &       2x,'Pressure 1                 p1(psig): ', f6.2,/,
     &       2x,'Pressure 2                 p2(psig): ', f6.2,/,
     &       2x,'Pressure 3                 p3(psig): ', f6.2,/,
     &       2x,'Pressure outlet          pout(psig): ', f6.2,/,
     &       2x,'Pressure pgt              pgt(psig): ', f6.2,/,
     &       2x,'Pressure fgt              fgt(psig): ', f6.2,//,
     &       2x,'Freeboard-full             zffb(in): ', f6.2,/,
     &       2x,'Freeboard-partial          zpfb(in): ', f6.2,//)
c
920   format(2x,'z(ft)      p#(psig)')
930   format(2x,f7.2,2x,f7.2,2x,a6)
940   format(1x)
c
950   format(1x,4(f6.2,2x),a40)
951   format(1x,2(f6.2,2x),16x,a40)
c
      stop
      end
```

SUBROUTINE NEWTON

```
      subroutine newton(nq,epsp,epsq,itermx,delq,delp,func)
c
c     *******************************************************************
c     * SUBROUTINE NEWTON                                               *
c     *                                                                 *
c     *                                                                 *
c     *******************************************************************
c
      include 'arrays.inc'
      parameter (zero=0.0, one=1.0)
      data iter/0/
c
c     START ITERATION LOOP
c
1     continue
c
      iter = iter + 1
      write(*,*) iter
c
c     CHECK FOR MAXIMUM NUMBER OF ITERATIONS
c
      if (iter .gt. itermx) then
         write(*,*) 'maximum number of NEWTON iterations exceeded'
         go to 2
      end if
c
c     COMPUTE F VECTOR
c
      call func(n,x,f)
c
c     GENERATE JACOBIAN MATRIX dF/dx
c
      do 30 i=1,n
c
         do 10 j=1,n
            x2(j) = x(j)
10       continue
c
         if (i .le. nq) then
            delx = delq
         else
            delx = delp
         end if
         x2(i) = x2(i) + delx
c
         call func(n,x2,f2)
c
         do 20 j=1,n
            dfdx(j,i) = (f2(j) - f(j))/delx
20       continue
c
30    continue
c
c     INVERT JACOBIAN MATRIX
c
      do 50 i=1,n
         do 40 j=1,n
            dfxinv(i,j) = zero
            dfdx2(i,j) = dfdx(i,j)
40       continue
         dfxinv(i,i) = one
```

```
50    continue
c
      call ludcmp(dfdx2,n,n,indx,d)
c
      do 60 j=1,n
         call lubksb(dfdx2,n,n,indx,dfxinv(1,j))
60    continue
c
c     COMPUTE RESIDUALS & UPDATE X VECTOR
c
      do 80 i=1,n
c
         dx(i) = zero
         do 70 j=1,n
            dx(i) = dx(i) - dfxinv(i,j)*f(j)
70       continue
c
         x(i) = x(i) + dx(i)
c
80    continue
c
c     CHECK FOR CONVERGENCE
c
      dqmax = zero
      do 90 i=1,nq
         dqmax = max(dqmax, dx(i))
90    continue
c
      dpmax = zero
      do 100 i=nq+1,n
         dpmax = max(dpmax, dx(i))
100   continue
c
      if (dqmax .ge. epsq .or. dpmax .ge. epsp) go to 1
c
2     continue
c
      return
      end
```

SUBROUTINE FUNC11

```
      subroutine func11(n,x,f)
c
c     ******************************************************************
c     * SUBROUTINE FUNC11                                              *
c     *                                                                *
c     *                                                                *
c     ******************************************************************
c
      dimension x(n), f(n)
      include 'bcs.inc'
c
c     UNSTUFF X VECTOR
c
      if (ibc .eq. 1) then
         q1 = x(1)
         q2 = x(2)
         q3 = x(3)
         q4 = x(4)
         q5 = x(5)
         q6 = x(6)
         p1 = x(7)
         p2 = x(8)
         p3 = x(9)
      else
         q2  = x(1)
         q3  = x(2)
         q4  = x(3)
         q5  = x(4)
         q6  = x(5)
         pin = x(6)
         p1  = x(7)
         p2  = x(8)
         p3  = x(9)
      end if
c
c     COMPUTE POTENTIAL, KINETIC & IRREVERSIBLE dP's
c
      call leg11(q1,dp1,dpom,dpop,dppm,dppp)
      call leg12(q1,q2,q3,q4,q5,q6,dp2,dpfim,dpfip,dp3m)
      call leg13(q1,q2,q3,dp3,dppgt,dpfgt)
      call leg14(q2,q3,q4,q5,q6,dp4)
      call leg15(q2,q3,q4,q5,q6,dp5)
      call leg16(q6,dp6)
c
c     CREATE F VECTOR
c
      f(1) = q1 - q6
      f(2) = q1 - q2 - q3
      f(3) = q3 - q4 - q5
c
      f(4) = p1   - pin - dp1
      f(5) = p3   - p1  - dp2
      f(6) = p2   - p1  - dp3
      f(7) = p3   - p2  - dp4
      f(8) = p3   - p2  - dp5
      f(9) = pout - p3  - dp6
c
      return
      end
```

SUBROUTINE INP11

```
      subroutine inp11
c
c     *****************************************************************
c     * INPUT LOGIC TO DETERMINE AREAS, LENGTHS, AND NUMBER OF ROD TIPS*
c     * FOR REGIONS IN LEG #1 BASED ON INPUT ROD POSITIONS.           *
c     *                                                               *
c     * CURRENT LOGIC ASSUMES THAT ONE FULL ROD IS ALWAYS DOWN, THE TWO*
c     * PARTIAL RODS MOVE TOGETHER, AND THE REMAINING FOUR FULL RODS   *
c     * MOVE TOGETHER.                                                 *
c     *                                                               *
c     * a1 & a2 are constants in formulation                          *
c     * dlp is height from bottom of partial to holes                 *
c     * dzpmax is maximum height of partials                          *
c     *                                                               *
c     *****************************************************************
c
      include 'leg1.inc'
      include 'areas.inc'
      include 'knobs.inc'
c
      parameter (dlp=97.97*0.0254, dzpmax=53.68*0.0254)
c
c     CONVERT TO SI
c
      a1 = 0.7854*0.0254**2
      a2 = 7.9013*0.0254**2
c
      do 10 i=0,7
        a(i) = a(i)*0.0254**2
        dh(i) = dh(i)*0.0254
10    continue
c
c     DEDUCE ROD CONFIGURATION
c
      if(dzfi .lt. 0.0 .or. dzp .lt. 0.0) then
        write(*,1000) dzp/0.0254,dzfi/0.0254
        stop ' Negative heights are unphysical'
c
      else if(dzp .gt. dzpmax) then
        write(*,1000) dzp/0.0254,dzfi/0.0254
        stop ' Partial rod height can not exceed 53.68 inches'
c
      else if(dzfi .eq. 0.0 .and. dzp .eq. 0.0) then
        num3 = np + nfd + nfi
        num4 = np + nfd + nfi
        num5 = np + nfd + nfi
        dl3 = dlp
        dl4 = 0.0
        dl5 = 0.0
        nrt2 = np + nfd + nfi
        nrt3 = 0
        nrt4 = 0
c
      else if(dzfi .eq. 0.0) then
        num3 =      nfd + nfi
        num4 = np + nfd + nfi
        num5 = np + nfd + nfi
        dl3 = dzp
        dl4 = dlp
        dl5 = 0.0
        nrt2 =      nfd + nfi
```

```
        nrt3 = np
        nrt4 = 0
c
      else if(dzp .eq. 0.0) then
        if(dzfi .gt. dlp) then
          num3 = np + nfd
          num4 = np + nfd
          num5 = np + nfd
          dl3 = dlp
          dl4 = 0.0
          dl5 = 0.0
          nrt2 = np + nfd
          nrt3 = 0
          nrt4 = 0
        else
          num3 = np + nfd
          num4 = np + nfd + nfi
          num5 = np + nfd + nfi
          dl3 = dzfi
          dl4 = dlp - dzfi
          dl5 = 0.0
          nrt2 = np + nfd
          nrt3 =            nfi
          nrt4 = 0
        endif
c
      else if(dzfi .gt. dlp+dzp) then
        num3 =      nfd
        num4 = np + nfd
        num5 = np + nfd
        dl3 = dzp
        dl4 = dlp
        dl5 = 0.0
        nrt2 =      nfd
        nrt3 = np
        nrt4 = 0
c
      else if(dzfi .gt. dzp) then
        num3 =      nfd
        num4 = np + nfd
        num5 = np + nfd + nfi
        dl3 = dzp
        dl4 = dzfi - dzp
        dl5 = dlp + dzp - dzfi
        nrt2 =      nfd
        nrt3 = np
        nrt4 =            nfi
c
      else if(dzfi .lt. dzp) then
        num3 =      nfd
        num4 =      nfd + nfi
        num5 = np + nfd + nfi
        dl3 = dzfi
        dl4 = dzp - dzfi
        dl5 = dlp
        nrt2 =      nfd
        nrt3 =            nfi
        nrt4 = np
c
      else if(dzfi .eq. dzp) then
        num3 =      nfd
        num4 = np + nfd + nfi
        num5 = np + nfd + nfi
```

```
        dl3 = dzfi
        dl4 = dlp
        dl5 = 0.0
        nrt2 =       nfd
        nrt3 = np        + nfi
        nrt4 = 0
c
      else
        write(*,1000) dzp/0.0254,dzfi/0.0254
 1000   format(//,' Height of partials:  dzp =',f5.1,/,
     &            ' Height of fulls:     dzfi =',f5.1,/)
        stop ' Case not accounted for in Leg#1'
c
      endif
c
c     SET AREAS AND HYDRAULIC DIAMETERS
c
      a3 = a(num3)
      a4 = a(num4)
      a5 = a(num5)
      dh3 = dh(num3)
      dh4 = dh(num4)
      dh5 = dh(num5)
c
      return
      end
```

SUBROUTINE INP12

```
      subroutine inp12
c
c     ******************************************************************
c     * INPUT LOGIC TO DETERMINE AREAS, LENGTHS, AND NUMBER OF ROD TIPS*
c     * FOR REGIONS IN LEG #2 BASED ON INPUT ROD POSITIONS.            *
c     *                                                                *
c     * CURRENT LOGIC ASSUMES THAT ONE FULL ROD IS ALWAYS DOWN, THE TWO*
c     * PARTIAL RODS MOVE TOGETHER, AND THE REMAINING FOUR FULL RODS   *
c     * MOVE TOGETHER.                                                 *
c     *                                                                *
c     * dlp   - HEIGHT FROM BOTTOM OF PARTIAL TO HOLES                 *
c     * dslot - HEIGHT FROM ORIFICE TO SLOTS                           *
c     ******************************************************************
c
      include 'leg2.inc'
      include 'areas.inc'
      include 'knobs.inc'
c
      parameter (dlp=97.97*0.0254, dslot=176.65*0.0254)
c
c     CONVERT TO SI
c
      do 10 i=0,7
        a(i) = a(i)*0.0254**2
        dh(i) = dh(i)*0.0254
10    continue
c
c     DEDUCE ROD CONFIGURATION
c
      if (dzfi .ge. dslot) then
        num1 = np + nfd
        num2 = np + nfd
        dl1 = dslot - dlp - dzp
        dl2 = 0.0
        nrt1 = 0
c
      else if (dzfi .gt. dzp + dlp) then
        num1 = np + nfd
        num2 = np + nfd + nfi
        dl1 = dzfi - dlp - dzp
        dl2 = dslot - dzfi
        nrt1 = nfi
c
      else if (dzfi .le. dzp + dlp) then
        num1 = np + nfd + nfi
        num2 = np + nfd + nfi
        dl1 = dslot - dlp - dzp
        dl2 = 0.0
        nrt1 = 0
c
      else
        write(*,900) dzp/0.0254,dzfi/0.0254
900     format(//,' Height of partials:  dzp =',f5.1,/,
     &            ' Height of fulls:     dzfi =',f5.1,/)
        stop ' Case not accounted for in Leg#2'
c
      endif
c
c     SET AREAS AND HYDRAULIC DIAMETERS
c
      a1 = a(num1)
```

```
      a2 = a(num2)
      dh1 = dh(num1)
      dh2 = dh(num2)
c
      return
      end
```

SUBROUTINE LEG11

```
      subroutine leg11(q1,dp1,dpom,dpop,dppm,dppp)
c
c     ******************************************************************
c     * SUBROUTINE LEG11:  THIS CALCULATES THE PRESSURE DROP IN        *
c     * LEG #1 OF THE INTERNAL SEPTIFOIL FLOW NETWORK.  THIS IS THE    *
c     * LEG FROM THE UPFLOW PIN TO THE BOTTOM HOLES IN THE PARTIAL     *
c     * CONTROL ROD EXTENSION TUBES.                                   *
c     ******************************************************************
c
      include 'props.inc'
      include 'leg1.inc'
c
      parameter (half=0.5, one=1.0)
      parameter
     & (zkbef=1.7, cc1 = 1.8718e8, cc2 = 2.64515e4, cc3 = 1.48569)
c
c     COMPUTE VELOCITIES
c
      v1 = q1/a1
      v2 = q1/a2
      v3 = q1/a3
      v4 = q1/a4
      v5 = q1/a5
c
c     COMPUTE ROD TIP FORM LOSS COEFFICIENTS
c
      red = max(one, rho*abs(v2)*0.02388/vis)
      zkrt2 = float(nrt2)*(cc1/red**2 - cc2/red + cc3)
c
      red = max(one, rho*abs(v3)*0.02388/vis)
      zkrt3 = float(nrt3)*(cc1/red**2 - cc2/red + cc3)
c
      red = max(one, rho*abs(v4)*0.02388/vis)
      zkrt4 = float(nrt4)*(cc1/red**2 - cc2/red + cc3)
c
c     COMPUTE FRICTION FACTORS
c
      call frict(v3,dh3,one,er12,ffac3)
      call frict(v4,dh4,one,er12,ffac4)
      call frict(v5,dh5,one,er12,ffac5)
c
c     COMPUTE ELEVATION CHANGE
c
      dz = d13 + d14 + d15 + 3.2*0.0254
c
c     COMPUTE dP
c
      dkbef = zkbef/a1**2
c
      dkrt2 = zkrt2/a2**2
      dkrt3 = zkrt3/a3**2
      dkrt4 = zkrt4/a4**2
c
      dkf3 = ffac3*d13/(dh3*a3**2)
      dkf4 = ffac4*d14/(dh4*a4**2)
      dkf5 = ffac5*d15/(dh5*a5**2)
c
      c = -half*rho*(dkbef + dkrt2 + dkrt3 + dkrt4
     &                   + dkf3  + dkf4  + dkf5 )
c
      dp1 = half*rho*(v1**2 - v5**2) + c*abs(q1)*q1 - rhog*dz
```

```
c
c     VALVE THROTTLED TO 70 GPM
      if (isys .eq. 2) then
         dpl = dpl + 1.2776*rhog - rho*3.063807e+7*ql**2
c
c     VALVE OPEN
      else if (isys .eq. 3) then
         dpl = dpl + 1.2776*rhog - rho*1.32222e+7*ql**2
c
      end if
c
      com = -half*rho*(0.0)
c
      cop = -half*rho*(dkbef + dkrt2)
c
      cpm = -half*rho*(dkbef + dkrt2 + dkf3)
c
      cpp = -half*rho*(dkbef + dkrt2 + dkf3 + dkrt3)
c
      dpom = half*rho*(vl**2 - v2**2) + com*abs(ql)*ql
     &       - rhog*(3.2*0.0254)
c
      dpop = half*rho*(vl**2 - v3**2) + cop*abs(ql)*ql
     &       - rhog*(3.2*0.0254)
c
      dppm = half*rho*(vl**2 - v3**2) + cpm*abs(ql)*ql
     &       - rhog*(dl3 + 3.2*0.0254)
c
      dppp = half*rho*(vl**2 - v4**2) + cpp*abs(ql)*ql
     &       - rhog*(dl3 + 3.2*0.0254)
c
      return
      end
```

SUBROUTINE LEG12

```
      subroutine leg12(q1,q2,q3,q4,q5,q6,dp2,dpfim,dpfip,dp3m)
c
c     ****************************************************************
c     * SUBROUTINE LEG12:  THIS CALCULATES THE PRESSURE DROP IN      *
c     * LEG #2 OF THE INTERNAL SEPTIFOIL FLOW NETWORK.  THIS IS THE  *
c     * LEG FROM THE BOTTOM HOLES IN THE PARTIAL CONTROL ROD EXTENSION *
c     * TUBES TO THE SEPTIFOIL SLOTS.                                *
c     ****************************************************************
c
      include 'props.inc'
      include 'leg2.inc'
c
      parameter (zero=0.0, half=0.5, one=1.0)
      parameter (cc1=1.8718e8, cc2=2.64515e4, cc3=1.48569)
c
c     COMPUTE VELOCITIES
c
      v1 = q2/a1
      v2 = q2/a2
      v6 = q6/a2
c
      denom = q2**2 + q3**2
      if (denom .gt. zero) then
         v12 = q2/sqrt(denom)*v1
      else
         v12 = zero
      end if
c
      denom = q2**2 + q4**2 + q5**2
      if (denom .gt. zero) then
         v62 = q2/sqrt(denom)*v6
      else
         v62 = zero
      end if
c
c     COMPUTE ROD TIP FORM LOSS COEFFICIENT
c
      red = max(one, rho*abs(v1)*0.02388/vis)
      zkrt1 = float(nrt1)*(cc1/red**2 - cc2/red + cc3)
c
c     COMPUTE FRICTION FACTORS
c
      call frict(v1,dh1,one,er12,ffac1)
      call frict(v2,dh2,one,er12,ffac2)
c
c     COMPUTE ELEVATION CHANGE
c
      dz = dl1 + dl2
c
c     COMPUTE dP
c
      dkrt1 = zkrt1/a1**2
      dkf1 = ffac1*dl1/(dh1*a1**2)
      dkf2 = ffac2*dl2/(dh2*a2**2)
c
      c = -half*rho*(dkrt1 + dkf1 + dkf2)
c
      dp2 = half*rho*(v12**2 - v62**2) + c*abs(q2)*q2 - rhog*dz
c
      cfim = -half*rho*(dkf1)
      cfip = -half*rho*(dkrt1 + dkf1)
```

```
c
      dpfim = half*rho*(v12**2 - v1**2) + cfim*abs(q2)*q2 - rhog*dl1
      dpfip = half*rho*(v12**2 - v2**2) + cfip*abs(q2)*q2 - rhog*dl1
      dp3m  = half*rho*(v12**2 - v2**2) + c    *abs(q2)*q2 - rhog*dz
c
      return
      end
```

SUBROUTINE LEG13

```
      subroutine leg13(q1,q2,q3,dp3,dppgt,dpfgt)
c
c     ******************************************************************
c     * SUBROUTINE LEG13:  THIS CALCULATES THE PRESSURE DROP IN        *
c     * LEG #3 OF THE INTERNAL SEPTIFOIL FLOW NETWORK.  THIS IS THE    *
c     * LEG FROM THE BOTTOM HOLES IN THE PARTIAL CONTROL ROD           *
c     * EXTENSION TUBES, UP TO THE GUIDE TUBES, AND BACK TO THE TOP    *
c     * HOLES OF THE FULLY INSERTED FULL ROD EXTENSION TUBES.          *
c     ******************************************************************
c
      real kent, kext, kexgt
c
      include 'areas.inc'
      include 'props.inc'
      include 'knobs.inc'
      common /leg3/ kent, kext, kexgt
c
      parameter (zero=0.0, half=0.5, one=1.0,
     &           zconv=0.0254, cdh = 64.0/96.0)
c
      parameter
     & (a2=0.7479*0.0254**2, dh2=0.690*0.0254,
     &  a3=0.3640*0.0254**2, dh3=0.116*0.0254,
     &  a4=4.8183*0.0254**2, dh4=0.608*0.0254,
     &  a5=0.9870*0.0254**2, dh5=0.091*0.0254,
     &  a6=4.8183*0.0254**2)
c
      parameter (zlet = 139.59*0.0254,
     &           zlgt0=  -5.19*0.0254,
     &           zlcs =   4.19*0.0254,
     &           zlgp =   1.00*0.0254,
     &           dz0  = 139.59*0.0254,
     &           zlp  =  97.97*0.0254)
c
c     COMPUTE AREAS & LENGTHS
c
      if (dzfi .gt. (dzp + zlp)) then
         a1 = a(nfd+np)    *zconv**2
      else
         a1 = a(nfd+np+nfi)*zconv**2
      end if
c
      zlgt = zlgt0 + dzp
      dz   = zlet - (zlgt + zlcs + zlgp)
      dzpgt = zlet
      dzfgt = dz - zlgt0
c
c     COMPUTE VELOCITIES
c
      v1 = q1/a1
      v2 = q3/a2
      v3 = q3/a3
      v4 = q3/a4
      v5 = q3/a5
      v6 = q3/a6
c
      denom = q2**2 + q3**2
      if (denom .gt. zero) then
         v13 = q3/sqrt(denom)*v1
      else
         v13 = zero
```

```
      end if
c
c     COMPUTE FRICTION FACTORS
c
      call frict(v2,dh2,one,er345,fet)
      call frict(v3,dh3,cdh,er345,fgt)
      call frict(v4,dh4,one,er345,fcs)
      call frict(v5,dh5,cdh,er345,fgp)
c
c     TEST FOR SPECIAL CASES
c
      if (zlgt .le. zero) then
         fgt   = zero
         kexgt = zero
      end if
c
      cutoff = zlgp + half*(-zlgt0 - zlgp)
      if (dzp .lt. cutoff) then
         fcs = zero
      end if
c
      if (dzp .lt. zlgp) then
         fgp = zero
      end if
c
      if      (zlgt .ge. zero) then
         vpgt = v3
      else if (zlgt .ge. (zlgt0 + zlgp)) then
         vpgt = v4
      else if (zlgt .gt. (zlgt0 + 0.01)) then
         vpgt = v5
      else
         vpgt = v6
      end if
c
c     COMPUTE dP's
c
      dp3    = v13**2 - v6**2
     &      - ( (kent + fet*zlet/dh2 + kext )*abs(v2)*v2
     &         +(        fgt*zlgt/dh3 + kexgt)*abs(v3)*v3
     &         +(        fcs*zlcs/dh4        )*abs(v4)*v4
     &         +(        fgp*zlgp/dh5        )*abs(v5)*v5 )
c
      dppgt = v13**2 - vpgt**2
     &      - ( (kent + fet*zlet/dh2 + kext )*abs(v2)*v2 )
c
      dpfgt = v13**2 - v4**2
     &      - ( (kent + fet*zlet/dh2 + kext )*abs(v2)*v2
     &         +(        fgt*zlgt/dh3 + kexgt)*abs(v3)*v3 )
c
      dp3   = half*rho*dp3   - rhog*dz
      dppgt = half*rho*dppgt - rhog*dzpgt
      dpfgt = half*rho*dpfgt - rhog*dzfgt
c
      return
      end
```

SUBROUTINE LEG14

```
      subroutine leg14(q2,q3,q4,q5,q6,dp4)
c
c     ****************************************************************
c     * SUBROUTINE LEG14:  THIS CALCULATES THE PRESSURE DROP IN       *
c     * LEG #4 OF THE INTERNAL SEPTIFOIL FLOW NETWORK.  THIS IS THE   *
c     * RETURN PATH THROUGH THE EXTENSION TUBE OF THE FULLY INSERTED  *
c     * FULL LENGTH CONTROL RODS.                                     *
c     ****************************************************************
c
      real kent, kext
c
      include 'props.inc'
      include 'knobs.inc'
      include 'areas.inc'
      common /leg4/ kent, kext
c
      parameter (zero=0.0, half=0.5, one=1.0, zconv=0.0254)
c
      parameter ( a1=4.8183*0.0254**2,
     &            a20=0.3739*0.0254**2, dh2=0.690*0.0254)
c
      parameter (zlet= 61.41*0.0254,
     &           zlst=176.65*0.0254,
     &           dz  =-60.91*0.0254)
c
c     COMPUTE AREAS & LENGTHS
c
      a2 = float(nfd)*a20
c
      if (dzfi .ge. zlst) then
         a3 = a(nfd+np)     *zconv**2
      else
         a3 = a(nfd+np+nfi)*zconv**2
      end if
c
c     COMPUTE VELOCITIES
c
      v1 = q3/a1
      v2 = q4/a2
      v3 = q6/a3
c
      denom = q4**2 + q5**2
      if (denom .gt. zero) then
         v14 = q4/sqrt(denom)*v1
      else
         v14 = zero
      end if
c
      denom = q4**2 + q5**2 + q2**2
      if (denom .gt. zero) then
         v64 = q4/sqrt(denom)*v3
      else
         v64 = zero
      end if
c
c     COMPUTE FRICTION FACTORS
c
      call frict(v2,dh2,one,er345,fet)
c
c     COMPUTE dP's
c
```

```
      dp4  = v14**2 - v64**2
     &      - (kent + fet*zlet/dh2 + kext)*abs(v2)*v2
c
      dp4  = half*rho*dp4  - rhog*dz
c
      return
      end
```

SUBROUTINE LEG15

```
      subroutine leg15(q2,q3,q4,q5,q6,dp5)
c
c     ****************************************************************
c     * SUBROUTINE LEG15:  THIS CALCULATES THE PRESSURE DROP IN        *
c     * LEG #5 OF THE INTERNAL SEPTIFOIL FLOW NETWORK.  THIS IS THE    *
c     * RETURN PATH PAST THE GUIDE PLATES.                             *
c     *                                                                *
c     * dslot - HEIGHT FROM ORIFICE TO SLOTS                           *
c     * a4    - FLOW AREA INSIDE OF THE SEPTIFOIL AT THE SLOT LEVEL    *
c     *                                                                *
c     ****************************************************************
c
      include 'props.inc'
      include 'knobs.inc'
      include 'areas.inc'
c
      parameter (zero=0.0, half=0.5, one=1.0)
      parameter
     & (a1=4.8183*0.0254**2,
     &  a2=4.8183*0.0254**2, dh2=0.6080*0.0254, dl2=41.91*0.0254,
     &  a3=0.9861*0.0254**2, dh3=0.091 *0.0254, dl3=19.0 *0.0254,
     &  dslot=176.65*0.0254, cdh=64.0/96.0)
c
c     SET AREA BASED ON POSITION OF FULL-INTERMEDIATE RODS
c
      if(dzfi .ge. dslot) then
        a4 = a(nfd+np)     *0.0254**2
      else
        a4 = a(nfd+np+nfi)*0.0254**2
      endif
c
c     CALCULATE VELOCITIES
c
      v1 = q3/a1
      v2 = q5/a2
      v3 = q5/a3
      v4 = q6/a4
c
      denom = q4**2 + q5**2
      if (denom .gt. zero) then
         v15 = q5/sqrt(denom)*v1
      else
         v15 = zero
      end if
c
      denom = q4**2 + q5**2 + q2**2
      if (denom .gt. zero) then
         v65 = q5/sqrt(denom)*v4
      else
         v65 = zero
      end if
c
c     CALCULATE FRICTION FACTORS FOR "C" CASING ASSY & GUIDE PLATES
c
      call frict(v2,dh2,one,er345,fcas)
      call frict(v3,dh3,cdh,er345,fgp)
c
c     SET ELEVATION CHANGE
c
      dz = -(dl2 + dl3)
c
```

```
c     CALCULATE dP
c
      c = -half*rho*(fcas*dl2/(dh2*a2**2) + fgp*dl3/(dh3*a3**2))
c
      dp5 = half*rho*(v15**2 - v65**2) + c*abs(q5)*q5 - rhog*dz
c
      return
      end
```

SUBROUTINE LEG16

```
      subroutine leg16(q6,dp6)
c
c     ******************************************************************
c     * SUBROUTINE LEG16:  THIS CALCULATES THE PRESSURE DROP IN        *
c     * LEG #6 OF THE INTERNAL SEPTIFOIL FLOW NETWORK.  THIS IS THE    *
c     * FLOW THROUGH THE SEPTIFOIL SLOTS.                              *
c     *                                                                *
c     * a1    - FLOW AREA INSIDE OF THE SEPTIFOIL AT THE SLOT LEVEL    *
c     * a2    - TOTAL FLOW AREA FOR THE SLOTS AND HOLES                 *
c     * dslot - HEIGHT FROM ORIFICE TO SLOTS                           *
c     * dz    - DISTANCE FROM EXTENSION TUBE LOWER HOLES               *
c     *         TO HOUSING SLOTS                                       *
c     * cd    - SLOT DISCHARGE COEFFICIENT                             *
c     *                                                                *
c     ******************************************************************
c
      include 'props.inc'
      include 'knobs.inc'
      include 'areas.inc'
c
      parameter (half=0.5, one=1.0)
      parameter
     & (a2=6.1268*0.0254**2, dslot=176.65*0.0254, dz=0.5*0.0254)
c
c     SET AREA AND Cd BASED ON POSITION OF FULL-INTERMEDIATE RODS
c
      if(dzfi .ge. dslot) then
        a1 = a(nfd+np)*0.0254**2
        cd = 0.56 - float(nfd+np)/7.0*(0.56 - 0.34)
      else
        a1 = a(nfd+np+nfi)*0.0254**2
        cd = 0.56 - float(nfd+np+nfi)/7.0*(0.56 - 0.34)
      endif
c
c     COMPUTE dP
c
      c = -half*rho*(one/(a2*cd)**2 - one/a1**2)
c
      dp6 = c*q6**2 - rhog*dz
c
      return
      end
```

SUBROUTINE FRICT

```
      subroutine frict(u,dh,cdh,eps,fric)
c
c     *****************************************************************
c     *  SUBROUTINE FRICT                                             *
c     *                                                               *
c     *                                                               *
c     *****************************************************************
      include 'props.inc'
      parameter (one=1.0, two=2.0,
     &           sixty4=64.0, rel=2300.0, ret=4000.0, fl=64.0/2300.0,
     &           a=2.35294, b=5411.76)
      parameter (c1=1.14, c2=21.25, c3=0.9)
c
      ft(relr, re) = one/(c1 - two*log10(relr + c2/re**c3))**2
c
      de = cdh*dh
      relr= eps/de
      re = max(one, rho*abs(u)*de/vis)
c
      if (re .le. rel) then
         fric = sixty4/re
      else if (re .ge. ret) then
         fric = ft(relr, re)
      else
         fric = (a - b/re)*(ft(relr, ret) - fl) + fl
      end if
c
      return
      end
```

SUBROUTINE LIQUID

```
      subroutine liquid(p,tf,m,rof,hf,visf,cpf,condf,sigma)
c
c     ****************************************************************
c     *                                                              *
c     * INPUT:                                                       *
c     *      p = PRESSURE IN Pa                                      *
c     *     tf = LIQUID TEMPERATURE IN K                             *
c     *      m = IDENTIFIER (m=1 FOR H2O, m=2 FOR D2O)               *
c     *                                                              *
c     * OUTPUT:                                                      *
c     *    rof = DENSITY OF LIQUID IN kg/m^3                         *
c     *     hf = ENTHALPY OF LIQUID IN J/kg                          *
c     *   visf = DYNAMIC VISCOSITY OF SATURATED LIQUID H2O IN Pa-s   *
c     *    cpf = SPECIFIC HEAT OF SATURATED LIQUID H2O IN J/kg-K     *
c     *  condf = THERMAL CONDUCTIVITY OF SATURATED LIQUID H2O IN W/m-K *
c     *  sigma = SURFACE TENSION OF LIQUID H2O IN N/m                *
c     *                                                              *
c     * RANGES:                                                      *
c     *   Up to 1 MPa                                                *
c     *   275K to 450K                                               *
c     *                                                              *
c     ****************************************************************
c
      parameter (two=2.0, tconv=273.15)
c
      dimension      drhodp(2), c01(2), c02(2), c03(2), c04(2), c05(2),
     &         c06(2), c07(2), c08(2), c09(2), c10(2), c11(2), c12(2),
     &         c13(2), c14(2), c15(2), c16(2), c17(2), c18(2), c19(2)
c
c---- H2O PROPERTIES
c
      data drhodp(1)/4.58e-7/
      data c01(1)/-38.874/,     c02(1)/0.29129/,
     &     c03(1)/-5.7014e-4/, c04(1)/4.0606e-7/
      data c05(1)/850.87/, c06(1)/1.2788/, c07(1)/-2.6526e-3/
      data c08(1)/-1.1094e+6/, c09(1)/3960.2/, c10(1)/0.36868/
c
c     LIQUID VISCOSITY, HEAT CAPACITY & CONDUCTIVITY DATA (RESPECTIVELY)
      data c11(1)/+2.41277e-5/, c12(1)/+5.74268e+2/, c13(1)/+1.3916e+2/
      data c14(1)/3960.2/, c15(1)/0.36868/
      data  c16(1)/ 0.57032432e+0/, c17(1)/0.17996615e-2/,
     &     c18(1)/-0.72881959e-5/, c19(1)/0.32412245e-8/
c
c---- D2O PROPERTIES
c
      data drhodp(2)/5.29e-7/
      data c01(2)/-39.686/,     c02(2)/0.29393/,
     &     c03(2)/-5.7036e-4/, c04(2)/4.0230e-7/
      data c05(2)/919.86/, c06(2)/1.5412/, c07(2)/-3.0963e-3/
      data c08(2)/-1.1856e+6/, c09(2)/4340.2/, c10(2)/-0.20733/
c
c     LIQUID VISCOSITY, HEAT CAPACITY & CONDUCTIVITY DATA (RESPECTIVELY)
      data c11(2)/3.34625e-5/, c12(2)/490.126/, c13(2)/157.884/
      data c14(2)/4340.2/, c15(2)/-0.20733/
      data  c16(2)/ 0.56340135e+0/, c17(2)/0.14504443e-2/,
     &     c18(2)/-0.79650470e-5/, c19(2)/0.71584948e-8/
c
c---- COMMON PROPERTIES TO H2O & D2O
c
c     SURFACE TENSION (SAME FOR H2O & D2O)
      data c20/+0.75743910e-1/, c21/-0.14302481e-3/,
```

```
     &      c22/-0.29108772e-6/, c23/+0.28387790e-9/
c
c---- COMPUTE LIQUID PROPERTIES
c
      sp = exp(c01(m) + (c02(m) + (c03(m) + c04(m)*tf)*tf)*tf)
      rofs = c05(m) + (c06(m) + c07(m)*tf)*tf
      rof = rofs + drhodp(m)*(p - sp)
      hf = c08(m) + (c09(m) + c10(m)*tf)*tf
c
      tinc = tf - tconv
      visf = c11(m)*exp(c12(m)/(tf - c13(m)))
      cpf = c14(m) + two*c15(m)*tf
      condf = c16(m) + (c17(m) + (c18(m) + c19(m)*tinc)*tinc)*tinc
      sigma = c20 + (c21 + (c22 + c23*tinc)*tinc)*tinc
c
      return
      end
```

SUBROUTINE LUDCMP

```
      subroutine ludcmp(a,n,np,indx,d)
      parameter (nmax=100,tiny=1.0e-20)
      dimension a(np,np),indx(n),vv(nmax)
      d=1.
      do 12 i=1,n
        aamax=0.
        do 11 j=1,n
          if (abs(a(i,j)).gt.aamax) aamax=abs(a(i,j))
11      continue
        if (aamax.eq.0.) pause 'singular matrix.'
        vv(i)=1./aamax
12    continue
      do 19 j=1,n
        do 14 i=1,j-1
          sum=a(i,j)
          do 13 k=1,i-1
            sum=sum-a(i,k)*a(k,j)
13        continue
          a(i,j)=sum
14      continue
        aamax=0.
        do 16 i=j,n
          sum=a(i,j)
          do 15 k=1,j-1
            sum=sum-a(i,k)*a(k,j)
15        continue
          a(i,j)=sum
          dum=vv(i)*abs(sum)
          if (dum.ge.aamax) then
            imax=i
            aamax=dum
          endif
16      continue
        if (j.ne.imax)then
          do 17 k=1,n
            dum=a(imax,k)
            a(imax,k)=a(j,k)
            a(j,k)=dum
17        continue
          d=-d
          vv(imax)=vv(j)
        endif
        indx(j)=imax
        if(a(j,j).eq.0.)a(j,j)=tiny
        if(j.ne.n)then
          dum=1./a(j,j)
          do 18 i=j+1,n
            a(i,j)=a(i,j)*dum
18        continue
        endif
19    continue
      return
      end
```

SUBROUTINE LUBKSB

```
      subroutine lubksb(a,n,np,indx,b)
      dimension a(np,np),indx(n),b(n)
      ii=0
      do 12 i=1,n
        ll=indx(i)
        sum=b(ll)
        b(ll)=b(i)
        if (ii.ne.0)then
          do 11 j=ii,i-1
            sum=sum-a(i,j)*b(j)
11        continue
        else if (sum.ne.0.) then
          ii=i
        endif
        b(i)=sum
12    continue
      do 14 i=n,1,-1
        sum=b(i)
        do 13 j=i+1,n
          sum=sum-a(i,j)*b(j)
13      continue
        b(i)=sum/a(i,i)
14    continue
      return
      end
```

LEG1.INC

```
      common /leg1/ a1, a2, a3,   a4,   a5,
     &                    dh3,  dh4,  dh5,
     &                    dl3,  dl4,  dl5,
     &                    nrt2, nrt3, nrt4, isys
```

LEG2.INC

```
      common /leg2/ a1,   a2,
     &              dh1,  dh2,
     &              dl1,  dl2,
     &              nrt1
```

AREAS.INC

```
c
c     areas & hydraulic diameters for the septifoil as a function
c     of the number of control rods present:
c
c     # Rods          Flow Area (in^2)        Hydraulic Diameter (in)
c
c        0              7.9013                     1.5376
c        1              7.2073                     1.2263
c        2              6.5133                     0.9846
c        3              5.8193                     0.7914
c        4              5.1253                     0.6334
c        5              4.4314                     0.5018
c        6              3.7374                     0.3906
c        7              3.0434                     0.2953
c
      dimension a(0:7), dh(0:7)
c
      data a(0)/7.9013/, dh(0)/1.5376/,
     &     a(1)/7.2073/, dh(1)/1.2263/,
     &     a(2)/6.5133/, dh(2)/0.9846/,
     &     a(3)/5.8193/, dh(3)/0.7914/,
     &     a(4)/5.1253/, dh(4)/0.6334/,
     &     a(5)/4.4314/, dh(5)/0.5018/,
     &     a(6)/3.7374/, dh(6)/0.3906/,
     &     a(7)/3.0434/, dh(7)/0.2953/
```

KNOBS.INC

```
c
      common /knob/ dzp, dzfi, np, nfi, nfd, nfu
c
```

BCS.INC

```
      common /bc/ pin, pout, ql, ibc, nq
```

PROPS.INC

```
      common /prop/ rho,vis,g,rhog,er12,er345
      parameter (n=9)
      dimension x(n), x2(n), f(n), f2(n), dfdx(n,n), dfdx2(n,n),
     &          dfxinv(n,n), dx(n), indx(n)
      common /array/ x,x2,f,f2,dfdx,dfdx2,dfxinv,dx,indx
```

7F.IN

```
Q=70 PL=21 FI=125 (2p,4i,1d,0u) D2O 30C# end of label
2  0.0  70.0  5.0   2  0  1  30.0      ibc,pin,q1,pbg,ilq,iexp,isys,temp
21.0 125.0  2  4  1  0                 dzp,dzfi,np,nfi,nfd,nfu
19.71 11.02  4.59  6.60   63.59  2.84  pin,p1,p2,p3,q2,q4
1.0e-4  1.0e-4   25                    epsp,epsq,itermx
1.0 1.0  2.75   1.0  1.0  1.e-5  1.e-5 kent3,kext3,kexgt3,kent4,kext4,
                                       er12,er345
```

7F.OUT

```
Q=70 PL=21 FI=125 (2p,4i,1d,0u) D2O 30C

----- INPUT -----
Inlet BC? (1=prs, 2=flow)      ibc: 2
Pin pressure (only one  pin(psig):  19.71
Pin flowrate  is used)     q1(gpm):  70.000
Blanket gas pressure    pbg(psig):   5.00
Liquid (1=H2O, 2=D2O)          ilq: 2
HTL Rig? (1=yes, 0=no)        iexp: 0
Inlet? (1=pin, 2,3=Hx)        isys: 1
Temperature                temp(C):  30.00
Partial rod position       dzp(in):  21.00
Full intermediate pos.    dzfi(in): 125.00
No. of partials                 np:  2
No. of full intermediates      nfi:  4
No. of full completely down    nfd:  1
No. of full completely up      nfu:  0
Convergence tolerances        epsp:  0.10E-03
                              epsq:  0.10E-03
Max. no. of iterations      itermx:  25
Leg 3 entrance K             kent3:  0.10E+01
Leg 3 exit K                 kext3:  0.10E+01
Leg 3 guide tube exit K     kexgt3:  0.28E+01
Leg 4 entrance K             kent4:  0.10E+01
Leg 4 exit K                 kext4:  0.10E+01
Legs 1-2 roughness         er12(m):  0.10E-04
Legs 3-5 roughness        er345(m):  0.10E-04


----- OUTPUT -----
Leg 1 flowrate             q1(gpm):  70.00
Leg 2 flowrate             q2(gpm):  64.02
Leg 3 flowrate             q3(gpm):   5.98
Leg 4 flowrate             q4(gpm):   2.79
Leg 5 flowrate             q5(gpm):   3.19
Leg 6 flowrate             q6(gpm):  70.00

Pressure inlet           pin(psig):  21.73
Pressure 1                p1(psig):  11.97
Pressure 2                p2(psig):   5.08
Pressure 3                p3(psig):   7.31
Pressure outlet         pout(psig):   6.83
Pressure pgt             pgt(psig):   5.83
Pressure fgt             fgt(psig):   4.89

Freeboard-full            zffb(in):  54.95
Freeboard-partial         zpfb(in):  15.56


z(ft)     p#(psig)
  35.33     21.73  pin
```

```
  25.10    11.97  p1
  20.31     7.31  p3
  20.31     6.83  pout

  20.31     7.31  p3
  14.81     4.89  pfgt
   4.58     0.00  pffb

  25.10    11.97  p1
  13.49     5.83  ppgt

  13.49     5.83  ppgt
  15.24     5.08  p2
  20.31     7.31  p3

  13.49     5.83  ppgt
   1.30     0.00  ppfb
```

7F.OUT2

```
15.56   54.95                 Q=70 PL=21 FI=125 (2p,4i,1d,0u) D2O 30C
```

This page intentionally left blank

Addendum

The week of July 20-24 John Steimke informed the NES Code Development Group (CDG) that the Cd and Li-Al control rods differ hydraulically. The Cd control rods do not have the hollow extension tubes like the Li-Al rods. The hydraulic model developed by CDG and the NES Experimental Thermal-Hydraulics (ETH) experiment are based on all full rods having the Li-Al design. Therefore, the code and data are consistent with each other, but, both deviate from the actual reactor components. Fortunately, the error weakly affects the results.

The Cd full length rods are withdrawn first so the logic in the LEG14 module can be corrected by changing

```
a2 = float(nfd)*a20
```

to

```
a2 = float(min(3,nfd))*a20
```

Here a20 is the internal area of a single extension tube and nfd is the number of fully inserted full rods.

To assess the effect of the above change on K reactor simulations, the rod configurations in the table below were modelled. Note that the maximum deviation is less than an inch, and the effect is only present when at least four full rods are fully inserted. For three or less full rods down, the previous logic is valid. Based on the results below, the previously generated freeboard results for K-reactor are judged to be valid for practical purposes.

Case (Partials @ 18 in)	Full Rod Freeboard Old (in)	Full Rod Freeboard New (in)	Full Rod Freeboard |Difference| (in)	Partial Rod Freeboard Old (in)	Partial Rod Freeboard New (in)	Partial Rod Freeboard |Difference| (in)
5 full rods down	58.92	58.01	0.91	22.85	22.57	0.28
4 down 1 up	59.30	58.93	0.37	42.54	42.43	0.11
3 down 2 up	60.24	60.24	-	51.51	51.51	-

These results were computed using 70 gpm, 5 psig blanket gas pressure, D2O and 30°C.

The initial technical review by Alan Wu identified a second minor coding error in subroutine LEG12. The velocity v12 was incorrectly based on the flow rate q2 in hydraulic leg 2 instead of q1 in leg 1. The coding was subsequently corrected by replacing the line

$$v12 = q2/sqrt(denom)*v1$$

with

$$v12 = q2/sqrt(denom)*(q1/a1)$$

in subroutine LEG12. Fortunately, the error has a very small effect on the results presented. The reason is that the leading coefficient q2/sqrt(denom) is small because q2 is typically about 10% of q1. For q2/q1 = 0.10, q2/sqrt(denom) = 0.11 for example. The ratio of the above quantities v1 and (q1/a1) is 0.90 for the example. The absolute change in v12 is therefore small. The discrepancy is large when q2 is a large fraction of q1. Three cases thought to be about worst-case were run for this situation to estimate the maximum error in the results presented. The table below indicates the results previously presented are still valid for practical purposes.

Case 1 full rod down 4 full rods @ an intermediate position	Full Rod Freeboard Old (in)	Full Rod Freeboard New (in)	Full Rod Freeboard |Diff.| (in)	Partial Rod Freeboard Old (in)	Partial Rod Freeboard New (in)	Partial Rod Freeboard |Diff.| (in)
dzp = 21" dzfi = 120"	54.77	54.79	0.02	12.71	13.05	0.34
dzp = 0" dzfi = 99"	45.51	45.63	0.12	45.51	45.63	0.12
dzp = 11" dzfi = 100"	53.56	53.71	0.15	23.54	24.63	1.09

These results were computed using 70 gpm, 5 psig blanket gas pressure, D_2O and 30°C.

WESTINGHOUSE INTERNAL DISTRIBUTION

Savannah River Site

G. H. Clare, 703-31A
A. F. McFarlane, 773-A
H. P. Olson, 992W-4
F. D. Benton, 707-C
D. B. Rankin, 706-C
N. Khalil 703-41A
T. Tran 703-41A
P. S. Shieh, 703-41A
P. W. Dickson, 703-F
S. D. Curry, 707-C
T. M. Monahon, 704-K
A. M. Vincent, III, 707-C
A. F. Lentz, 773-56A
J. M. Morrison, 773-56A
T. M. Punch, 707-C
W. F. Swift, 707-C
J. L. Hendrix, 705-1C
J. P. Cohen, 773-41A

Savannah River Technology Center

R. T. Begley, 773-A
F. Beranek, 773-A
A. J. Garrett, 773-A
M. J. Hitchler, CCC
M. R. Buckner, 773-A
N. H. Kuehn III, 773-42A
N. P. Baumann, 773-42A
D. R. Muhlbaier, 786-5A
J. L. Steimke, 786-5A
D. A. Crowley, 773-11A
J. D. Menna, 773-64A
G. W. Richardson, 786-5A
M. A. Shadday, 773.11A
N. M. Askew, 773-64A
G. P. Flach, 773-11A
L. D. Koffman, 773-11A
L. A. Wooten, 992W-1
T. T. Wu, 773-11A
G. T. Geiger, 992W-1
K. R. O'Kula, 992W-1
D. J. Baker, 992W-1
NES File(4), 773-11A
[redacted]