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ACHIEVING THE REQUIRED COOLANT FLOW DISTRIBUTION FOR THE ACCELERATOR PRODUCTION OF TRITIUM (APT) TUNGSTEN NEUTRON SOURCE

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ABSTRACT

The Accelerator Production of Tritium neutron source consists of clad tungsten targets, which are concentric cylinders with a center rod. These targets are arranged in a matrix of tubes, producing a large number of parallel coolant paths. The coolant flow required to meet thermal-hydraulic design criteria varies with location. This paper describes the work performed to ensure an adequate coolant flow for each target for normal operation and residual heat-removal conditions.

INTRODUCTION

Figure 1 shows the target arrangement. The beam travels in the z direction and is rastered in the x and y directions at a sufficiently high frequency to produce an effectively constant thermal power distribution. The power density changes significantly from front to back (the z direction). The targets have been designed to have progressively more tungsten per tube from front to rear in the z direction, which helps to produce a more nearly even power deposition profile.

The target tubes in a given plane perpendicular to the z axis are arranged in ladders, with supply and return lines arranged in the y direction. The tubes containing the targets are called rungs.

Thermal-hydraulic design criteria call for the targets to operate with substantial surface subcooling at the exit of each target for normal operation and anticipated operational occurrences. This requirement ensures that two-phase parallel channel instabilities do not occur. The targets also have decay heating when shut down after a period of operation. The residual heat-removal (RHR) system has been designed to remove decay heat for normal shutdown and accident conditions. The flow needed to remove the thermal energy deposited within the constraints of the thermal-hydraulic design criteria for a typical rung in each ladder has been determined from design point studies.

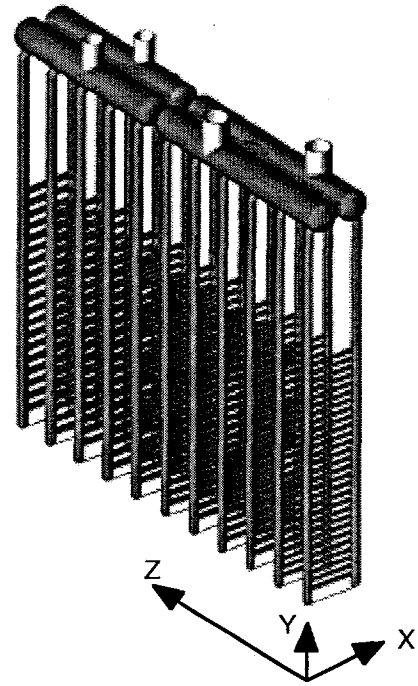

Fig. 1. Schematic of the neutron source.

This paper describes the work performed to ensure adequate flow distributions in the y (rung-to-rung) and z (ladder-to-ladder) directions for normal operation and RHR conditions. This work builds on previous work that

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experimentally examined rung-to-rung flow distributions and validated tools for evaluating these distributions for design and safety-related calculations.[1] The Transient Reactor Analysis Code (TRAC), a Los Alamos National Laboratory computer code developed to model nuclear reactor transients, was shown to model the rung-to-rung flow distributions within a ladder adequately. However, there is a tendency for the rung-to-rung flow distribution to be skewed within a ladder. The relative sizes of the ladder s vertical pipes (called the downcomer) that supply the rungs and return the flow (called the riser) can be adjusted to minimize, though not totally eliminate, the rung-to-rung flow maldistribution.

The design of the front six ladders incorporates this sizing optimization. This was not performed for the back five ladders, which use larger diameter rungs, because of constraints related to fabricating the joints between the rungs and the vertical pipes that supply and return the coolant.

TRAC calculations were used to determine the flow distributions for the ladders and the exit pressures for each rung. These values were input to a detailed target thermal-hydraulics model to determine the exit surface subcooling for the targets in the rungs. Flows then were adjusted from the design point values where necessary. With the flow optimized for the front six ladders, the design point flows were adequate. To meet thermal-hydraulic design criteria, the flow rates needed to be increased beyond design point values for three of the five rear ladders. This increased the total coolant flow required by 2% to 3%. A 3% flow increase has been incorporated into an adjusted nominal flow rate, along with other uncertainty factors.

To get the required ladder-to-ladder flow distribution, a TRAC model of the entire target cooling system was used. Each ladder was modeled as a single flow resistance. Form-loss coefficients were determined for five of the six front ladder downcomers, the supply line feeding the rear five ladders, and four of the five rear-ladder downcomers to produce the desired ladder-to-ladder flow distribution. Orifices were sized to produce these form losses. Flow conditions through these orifices were calculated and shown to meet the criteria for maximum flow velocity and to have adequate margin from conditions where cavitation could occur.

TRAC models of the individual, detailed ladders were used to examine flow phenomena under decay-heating conditions and low flow rates. At sufficiently low flow rates (~1%), buoyancy effects lead to unstable conditions with flow reversals and the potential for target dryout. At flows of 3% to 4% of the nominal point design flow rate, the rung-to-rung flows are relatively uniform. The design requirements call for each RHR loop to produce a flow that is 4% of the nominal flow. To examine the ladder-to-ladder distribution of RHR flows, the TRAC system model was used. The TRAC calculations showed that there is some skewing of flow toward the rear ladders. If each RHR loop is designed to provide at least 4% of the minimum operating envelope flow, which includes factors to account for uncertainties, then all of the ladders receive at least 4% of the point design flow rate.

RUNG-TO-RUNG DISTRIBUTIONS

Each ladder constitutes a manifold system, with the downcomer and riser serving as supply and return manifolds. The rungs constitute the "branches." Achieving uniform flow in the branches of a manifold system of this type has been the subject of much research in a variety of application areas. A brief literature review was included in a previous paper.[1] In a manifold system of this type, optimizing the ratio of supply and return manifold sizes can produce a nearly uniform distribution of flow through the branches. In earlier work[1] we reported results from an experimental program with a range of supply and return manifold sizes. Code validation also was performed against the experiments. Figure 2 shows the results of data/TRAC comparisons for three of the tests (repeated from Ref. 1). The plots are arranged so that the bars on the graph correspond to the position of the rungs in the ladders. The plots show ratios of supply to return manifold areas of 1.0, 0.69, and 0.6. The ratio of 0.69 is very near the optimum. Note that TRAC did very well in predicting the distributions.

In the ladder design for the APT tungsten neutron source, the ratio of supply and return manifold sizes for the front six ladders was optimized to produce nearly uniform flow distributions. Because of mechanical fabrication constraints, the rear five ladders were not optimized for uniform flow distributions. The rear five ladders use rungs with a diameter larger than that used for the front six ladders. This limits the changes to the supply and return (downcomer and riser) diameters that could be made for the purpose of optimizing the flow distribution. The decision was made to compensate for the less-uniform distribution by increasing the flow rate.

A key requirement of the thermal-hydraulic design criteria developed for this project is that the surface subcooling at the exit for each rung be maintained at

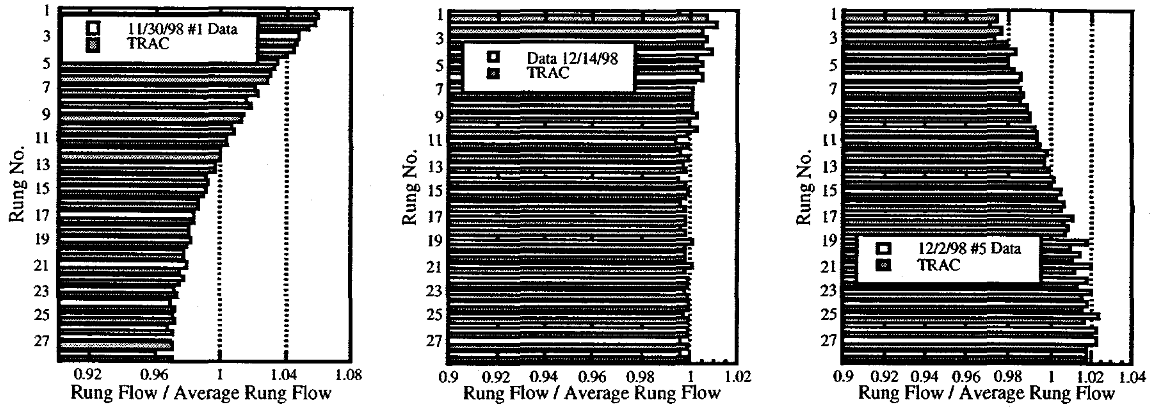

Fig. 2. Data/TRAC comparisons for tests with supply to return manifold ratios of 1.0, 0.69, and 0.60.

40°C or greater. This criterion was developed to ensure that two-phase parallel channel instabilities do not occur. The 40°C value for the exit subcooling was chosen considering uncertainties and biases in the calculation of these values.

To ensure that flows through the ladders are adequate for meeting the subcooling limit, detailed TRAC models were created for each ladder and run with boundary conditions from a TRAC system model of the entire target cooling system. Initially, the point design flow rates were used. The rung flows and exit pressures then were input to a detailed model for the rung thermal hydraulics. Where the flow distribution caused the exit surface subcooling to be less than 40°C, flows were increased to compensate.

With the optimization performed for the front ladders, the point design flow rates are adequate. In ladders 7 through 9, flows must be increased to compensate for the maldistribution of rung flows. Figure 3 shows the surface exit subcooling for ladder 2, which was optimized, and shows ladder 7 with the point design flow rate and the flow rate increased to produce an exit subcooling greater than 40°C. Again, ladder 7 is one of the ladders that is not optimized to produce a nearly uniform flow distribution. Ladders 10 and 11 do not require an increase in flow rate because the flows through these ladders, where the power deposited is much lower, are high relative to the power deposition because of a requirement to maintain turbulent flow through all rungs under normal operating conditions. Table 1 shows the percent increase in flow rates required.

LADDER-TO-LADDER DISTRIBUTIONS

A TRAC-PF1/MOD2 model of the APT target primary heat removal system was used for ladder-to-ladder distributions. Each ladder is modeled as a single lumped-flow resistance. The balance of the loop is modeled in considerable detail, including lengths, diameters, elevations, fittings, pumps, and heat exchangers. The desired flow through each ladder was determined from the detailed thermal-hydraulic considerations and the rung-to-rung distribution results. Table 2 shows the fraction of flow for each ladder. The following calculations were based on a minimum operating envelope flow rate of 547.4 kg/s, which includes factors of 1.05, 1.05, and 1.03 times the point-design flow rate to account for uncertainties in the delay time for beam trip, the uncertainty in the ladder-to-ladder flow distribution, and the rung-to-rung distributions.

To obtain the desired flow distribution in the model, form-loss coefficients were placed in the TRAC pipe components representing the ladder downcomers. An

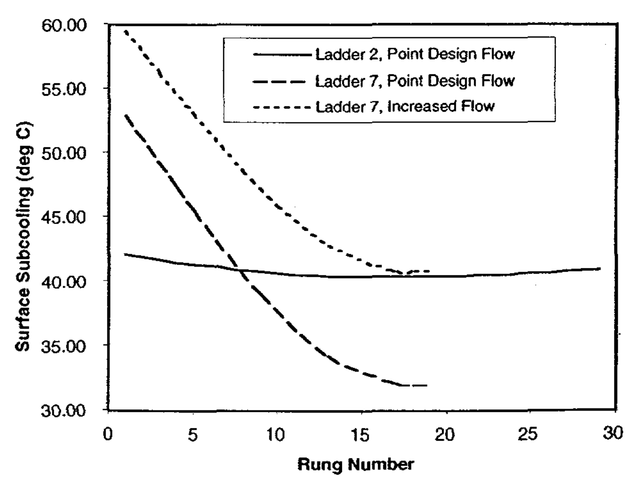

Fig. 3. Rung exit surface subcooling for ladder 2 with optimized flow distribution and ladder 7 without optimized flow distribution.

TABLE 1
POINT DESIGN FLOW RATES AND PERCENTAGE INCREASE NECESSARY TO ACHIEVE 40°C SURFACE SUBCOOLING FOR EACH RUNG

Ladder	Flow Rate % Increase
1	0%
2	0%
3	0%
4	0%
5	0%
6	0%
7	10.7%
8	10.9%
9	4.7%
10	0%
11	0%
Totals	0%

iterative procedure was used where results of a steady-state run were used to calculate new values for the form losses. The new values then were put into the input deck and the calculation repeated. Because these calculations were performed with a system model that includes the upstream piping and parallel flow paths, the form losses are sufficient to force the split between front and back ladder modules, as well.

Next, the minimum pressure drop for a back-module ladder was moved upstream into the pipe feeding the back-ladder supply manifold. The remainder of the back-module-ladder form-loss coefficient factors (K factors) was adjusted to decrease the downcomer pressure drop by this amount. The ΔP moved to the supply line is 22.7 psid (1.57e5 Pa) from a form-loss coefficient (K) = 3.12 based on the velocity in the 6-in. nominal pipe (inner diameter = 6.067 in.). Approximately 15 runs and 3 hours were required to achieve the desired flow distribution to better than three significant figures.

To examine the feasibility of orificing to achieve the downcomer form losses in Table 3, calculations were made to size a set of orifices and determine the orifice conditions. The sizing was based on the use of quadrant-edged orifices that have a quarter-round leading edge. In this study, a 1/8-in. radius was assumed for this rounding. This type of orifice should be less sensitive to erosion than orifice types that depend on relatively sharp corners. In addition, this type of orifice is used in some flow metering applications because the flow resistance varies less with changes in the Reynolds number (Re) at low Re s than most other orifice types. A correlation giving form losses for this type of orifice from Idelchik[2] was used. The sizes of the orifices appear reasonable, although the velocities of some of the front-ladder orifices exceed the erosion limit (20 m/s) slightly. If necessary, orifices in series (orifice stacks) could be used in the front ladders. The downcomer inner diameter is 2.87 in. for the first six ladders and 3.37 in. for the last five ladders.

The cavitation index as defined by Blevins[3] also was calculated. Blevins states that incipient cavitation occurs for cavitation index values of 2 to 4. Large-scale cavitation occurs at a cavitation index less than 1.

A limitation of these studies is that manifolds were modeled as plena having a constant internal pressure. In reality, manifold effects will cause a pressure distribution. Modeling these effects was beyond the scope of this study. We are aware of the problem from previous work on rung-to-rung flow distributions within a single ladder. This limitation is not expected to have a large effect on the final results. To get exact orifice sizes, experimental work will be needed. The calculated orifice sizes should be sufficiently accurate to answer questions adequately about orifice throat velocity, pressure, and flow regime.

FLOW DISTRIBUTIONS UNDER RHR CONDITIONS

With RHR flow it is important that both ladder-to-ladder and rung-to-rung flow distributions are adequate. TRAC has the necessary capabilities to model laminar and transition flows, as well as turbulent flows, with one exception. TRAC does not have a built-in capability to model changes in orifice-flow resistances. Also, these resistances are not well defined. Where orifice flows drop into laminar and transition regions, sensitivity studies have been used to examine the possible effects. This applies mainly to the target bundle support plates, which act as orifice plates. The TRAC system model described previously was used to model ladder-to-ladder distributions. Detailed TRAC models of the individual ladders were used to study rung-to-rung distribution phenomena. However, the ladder-to-ladder flow distributions are adequate for RHR conditions. Within individual ladders, buoyancy effects can cause instabilities if flow rates are insufficient with possible overheating and dryout. The flow rates specified for RHR flow have adequate margin to avoid the unstable regime. The system modeling shows that these flows can be readily attained.

To model the ladder-to-ladder flow distribution, the TRAC system model was used with the primary coolant pumps shut off and one RHR pump at a time turned on. A

TABLE 2. LADDER-TO-LADDER FLOW RATES AS A PERCENTAGE OF THE TOTAL TPHRS FLOW RATE

Lad. 1	Lad. 2	Lad. 3	Lad. 4	Lad. 5	Lad. 6	Lad. 7	Lad. 8	Lad. 9	Lad. 10	Lad. 11
9.3 %	11.50%	11.42%	10.70%	11.08%	10.21%	11.65%	8.34%	5.25%	5.06%	5.45%

TABLE 3. RESULTS OF ORIFICE-SIZING CALCULATIONS

Ladder	K Factors Based on Down-comer Velocity	Diam. of Orifice (in.)	Diam. of Orifice: Diameter of Down-comer	Velocity of Orifice (m/s)	ΔP across Orifice (psid)	Cavitation Index
1	1.678	2.114	0.737	20.55	16.6	4.3
2	0	——	1	13.74	——	——
3	0.3083	2.486	0.866	18.20	4.57	5.9
4	0.7888	2.299	0.801	19.93	10.3	4.7
5	0.5311	2.384	0.831	19.19	7.40	5.2
6	1.175	2.205	0.768	20.67	13.9	4.3
7	0	2.186	1	——	——	——
8	4.34	2.186	0.649	17.17	19.29	6.4
9	16.5	1.720	0.510	17.46	22.60	6.0
10	18.2	1.687	0.500	17.51	22.83	6.0
11	14.7	1.759	0.522	17.35	22.16	6.1

pump controller was used to control the speed of a generic pump model to achieve the desired flow rates because pumps have not yet been specified for the RHR loops. With a flow rate of 4% of the minimum operating envelope flow of 547.4 kg/s, the orifices described in the previous section would still have Re s above 10,000. In this range, the form loss for the orifices change little from nominal values. The distribution is skewed slightly toward the rear-module ladders. Table 4 shows the distribution.

The characteristics of individual ladders at different flow rates were calculated and compared to the flows from the system model calculations. Figure 4 shows the flow distributions for ladder 2 as a function of flow rate. These calculations used a decay power 10 s after beam shutdown following 274 days of irradiation. At 4% of the nominal point design flow rate, the flow distribution is relatively uniform. As the flow rate decreases, the distribution becomes more and more skewed until (at approximately 0.9%) there is two-phase flow and a flow reversal in the top rung of the ladder. Similar phenomena were seen for the other ladders.

TABLE 4. LADDER-TO-LADDER FLOW DISTRIBUTION FOR RHR LOOP 1 OPERATING TO PRODUCE APPROXIMATELY 4% OF THE MINIMUM OPERATING ENVELOPE FLOW RATE (PUMP SPEED 117 RAD/S)

Ladder	Fraction of Min. Operating Envelope Flow	Fraction of Point Design Flow Rate
1	0.0365	0.040
2	0.0354	0.039
3	0.0363	0.040
4	0.0362	0.040
5	0.0358	0.040
6	0.0363	0.040
7	0.0446	0.055
8	0.0469	0.058
9	0.0477	0.055
10	0.0474	0.053
11	0.0466	0.052
Totals	0.0397	

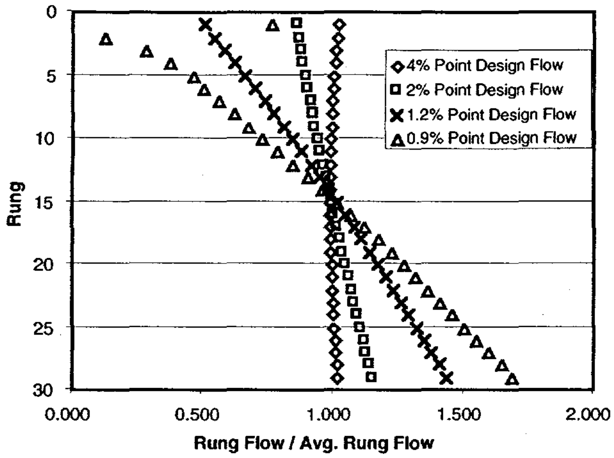

Fig. 4. Rung-to-rung flow distribution for ladder 2 as a function of flow rate.

In the above discussion and plot, we showed that an unstable condition occurs at sufficiently low flow rates. Another way to consider this instability is that the buoyant forces act as a pump, thus increasing the pressures in the riser. Figure 5 shows the pressure difference between the downcomer and riser for three different conditions. These are cells in descending order between the manifold connection and the top rung. The fifth cell connects to the top rungs. The top four cells are of equal length. The 2% flow case shows a steady increase in the pressure difference between the downcomer and riser. At 1.2% flow, the top two cells have a lower pressure than the corresponding downcomer cells. As the flow rate decreases, the fraction of the pipes with a negative ΔP increases. At 0.9% flow, the negative ΔP has dropped to below the level of the topmost rung. With this condition, the flow is reversed through the top rung. If the crossover between positive and negative ΔP had occurred right at a rung, that rung would not have significant flow.

The bundle support plates that hold the tungsten rings composing the targets act as orifice plates in their resistance to flow. Calculations of the Re through the support plates show that the flow through the orifice plates will be laminar. Several references were located with orifice form-loss coefficients in laminar and transition flows.[2,4] Both show similar phenomena. The curves from both references are parameterized as a function of the ratio of the orifice area and the pipe area (β). The bundle support plates have β values ranging from 0.5509 to 0.9109 based on the flow area within the bundles. It is evident that there is not a direct correspondence between the curves and the bundle support plates because the support plates will probably look more like a thick-edged orifice in a region with a flow area change from upstream to downstream. The curves should still provide useful qualitative information.

In the β range of interest, the form-loss coefficient is relatively constant with Re s for turbulent conditions (greater than 1000). As the Re drops below approximately 1000, there is a drop in the form-loss coefficient value of approximately an order of magnitude. As the Re decreases further, the form-loss coefficient becomes relatively constant and then begins curving upward. By an Re of 100, flow through the orifice becomes fully laminar and the form-loss coefficient becomes a line of constant slope on a log-log curve, increasing with decreased Re.

For the 3% flow cases, the Re ranges from approximately 20 in ladder 9 to approximately 300 in ladder 2. If the form-loss coefficient vs Re dependencies between the support plates and the figure are consistent, the flow resistance for the support plates can vary over a considerable range. Of particular concern are cases with a very skewed flow distribution where the top rungs operate at a significantly lower Re than the lower rungs. This causes the support-plate form-loss coefficients to be higher in the upper rungs, which creates a more pronounced skewing.

A simple hand calculation was used to compare the magnitude of the frictional loss through the bundle with the support-plate loss. This calculation used the average bundle flow for 2% flow through bundle 2. This produced a support-plate Re of 287. The support-plate form-loss coefficients used were values calculated for turbulent

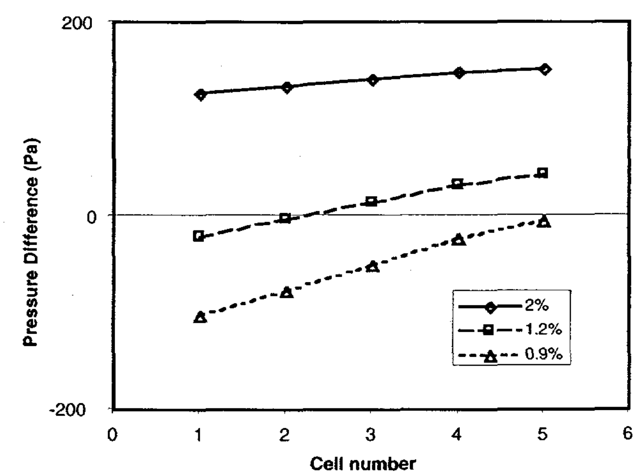

Fig. 5. Pressure difference between downcomer and riser cells as a function of flow rate.

flows for the TRAC model. Judging from the curve in Ref. 4, these should be high in this Re range. The bundle friction factor was taken as 64/Re for laminar flow. The resulting calculation showed that the ratio of the frictional pressure drop across the bundle was approximately 7.5 times the irrecoverable pressure drop through the two support plates. Thus, we should expect that the frictional losses should be approximately an order of magnitude greater than the support-plate form losses. As a check on the effects that the support-plate form-loss coefficient has on the flow distribution, parametric cases were run with the support-plate form-loss coefficient increased and decreased by an order of magnitude. Figure 6 shows this result. It appears that the magnitude of the support-plate form-loss coefficient value is relatively unimportant when compared to changes in the flow rate.

In examining how the support-plate form-loss coefficient values and the bundle friction factor vary with Re, it appears desirable to have the flows through each of the bundles in a ladder vary over a relatively small range. Thus, it is desirable to use flow rates of 3% to 4% of the nominal flow where the rung-to-rung flow distributions have minimal skewing.

CONCLUSION

The paper discusses the research performed as part of designing the APT target assemblies and specifying flow rates to

- optimize the APT target ladder design to minimize rung-to-rung flow maldistributions,
- adjust flow rates to compensate for these flow maldistributions,
- determine orifice form-loss coefficients needed to force the desired ladder-to-ladder flow distribution,
- size orifices to achieve the desired flow splits,
- verify the feasibility of using these orifices,
- determine lower limits on residual-heat-removal flow rates, and
- ensure that the specified residual-heat-removal rates provide adequate margin for all of the rungs for all of the ladders.

This work demonstrates the feasibility of obtaining the desired flow distributions from ladder to ladder and rung to rung within the ladders. Prototypic testing will be necessary to obtain final orifice sizing to carry through this scheme.

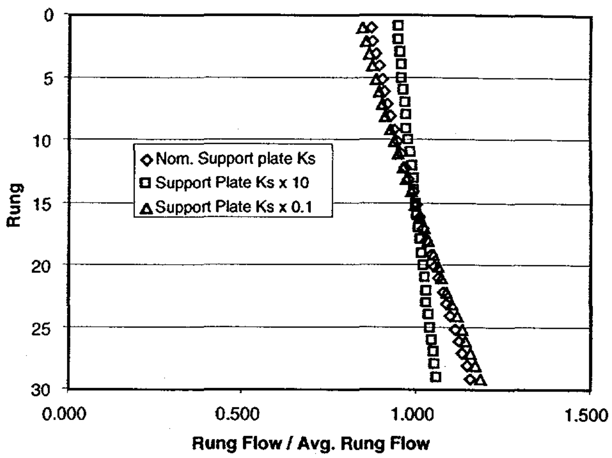

Fig. 6. Effect of bundle-support-plate form-loss coefficient on flow distribution.

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