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## TECHNICAL AND QA PLAN: BOILING BEHAVIOR DURING FLOW INSTABILITY (U)

by

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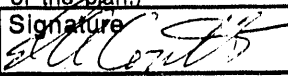
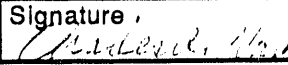
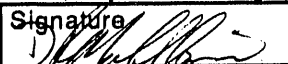
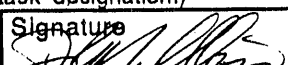
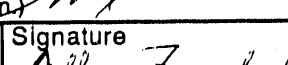
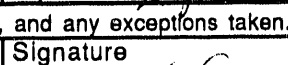
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# Technical and QA Plan

## Title and Approval Page

Task Title Boiling Behavior During Flow Instability			
Revision No. 0		Task No. 91-063-1	
Customer NRTSC/ETH		Customer Specification	Dated
Preparer (Task Leader or Designee) Print Name D. A. Coutts		Signature 	Division NRTSC
			Date 10/3/91
<b>Approvals</b>			
Task Leader (If different than preparer; concurrence with contents of the plan.)			
Print Name D. A. Coutts		Signature 	Division NRTSC
			Date 10/3/91
Technical Reviewer (If required by responsible manager; concurrence with technical content.)			
Print Name C. A. Nash		Signature 	Division NRTSC
			Date 10/3/91
Responsible Manager (Level 4 or higher; concurrence with deliverables, critical task designation.)			
Print Name/3 D. R. Muhlbaier		Signature 	Division NRTSC
			Date 10/4/91
Customer (Concurrence with requirements, deliverables, critical task designation.)			
Print Name/4 D. R. Muhlbaier		Signature 	Division NRTSC
			Date 10/4/91
QA Coordinator (If requested to review; concurrence with the plan.)			
Print Name/5 A. A. Zagrodnik		Signature 	Division NRTSC
			Date 10/9/91
CQF (Concurrence with critical task designation, QA requirements, and any exceptions taken.)			
Print Name/6 K. A. Crawford		Signature 	Division SRL-25
			Date 10/9/91
Distribution (Controlled Identification; include signers of Title and Approval Page.)			
<p>D. A. Coutts, 786-6A  D. R. Muhlbaier, 786-5A  R. Keklak, 786-A  T. J. Steeper, 786-5A  A. A. Zagrodnik, 773-58A  K. A. Crawford, 773-65A  B. S. Johnston, 786-5A</p>			
<p>Keywords  ECS limits, Loss of Coolant Accident, Flow Instability, Nucleate Boiling, Onset of Significant Void, Flow Transient</p>			
Continued on Attachment? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No			

# Technical and QA Plan

Revision No.		Task No.	
0		91-063-1	
Description of Major Revisions			
Revision No.	Page No.	Date	Revision
0	NA	9/3/91	Initial Issue

Refer to NRTSC procedure QAP I-2, "Conduct of Technical Activity," for additional information

# Technical and QA Plan

Revision No. 0				Task No. 91-063-1	
<b>QA Plan Portion</b>					
<i>The following QA procedures apply for this task (indicate Yes, No, or AR-As Required).</i>					
Yes	No	AR	Revision No.	Description	
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		QAP I-2, Conduct of Technical Activity	
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		QAP II-1, Overview of General QA Program Procedures	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>		QAP II-2, Procurement	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>		QAP II-3, Audits, Surveillances, and Appraisals	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>		QAP II-4, Corrective Action	
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		QAP II-5, Preparation, Revision, and Control of NRTSC QA Procedures	
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		QAP II-6, Preparation and Control of Technical Implementing (Field) Procedures	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>		QAP II-7, Documentation of Critical Calculations	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>		QAP II-8, Design Review	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>		QAP II-9, Training and Qualification	
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<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		QAP III-5, Control of Measuring and Test Equipment	
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>		QAP III-6, Test Control	
<i>Identify Responsible Organization, Function, or Person for the following procedures</i>				<i>Identify Below</i>	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>		QAP IV-1, Software Overview	D. A. Coutts
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		QAP IV-2, Software Change Control	D. A. Coutts
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		QAP IV-3, Software Requirements Specification	D. A. Coutts
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		QAP IV-4, Software Design and Implementation	D. A. Coutts
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		QAP IV-5, Software Testing	D. A. Coutts
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		QAP IV-6, Computer Code Control	D. A. Coutts
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		QAP IV-7, Software Maintenance	D. A. Coutts
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		QAP IV-8, Software Retirement	D. A. Coutts
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>		QAP IV-9, Software Certification	D. A. Coutts

Refer to NRTSC procedure QAP I-2, "Conduct of Technical Activity," for additional information

# Technical and QA Plan

Revision No.			Task No.	
0			91-063-1	
The following records are anticipated from this task (indicate Yes, No, or AR-as required).				
Yes	No	AR	Description	List Other Records Below
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Appraisal Reports	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Audit Reports	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Calculation Sheets	
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<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Documentation of Drawings and Revisions for Task	
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Documentation of Instruments Used for Task	
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<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Interim Reports	
<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Laboratory Notebooks	
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<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Software Requirements Specification (SRS)	
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<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Software Test Plan	
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Software Test Report(s); V&V, Benchmarking	
<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	Software User's Manual	
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<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Test Data	

Refer to NRTSC procedure QAP I-2, "Conduct of Technical Activity," for additional information

# Technical and QA Plan

Revision No. 0	Task No. 91-063-1					
<i>Identify documents requiring management, customer, or CQF approval.</i>						
Document	Approving Organization					
	Management Yes    No		Customer Yes    No		CQF Yes    No	
Technical and QA Plan	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Design Input Document	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Technical Procedure	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Final Report	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
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Continued on Attachment? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No						
Identify any exceptions taken to QA procedures.						
Continued on Attachment? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No						
<i>Complete this part only if Section IV procedures (software) are invoked. Identify who will act in each of the following capacities.</i>						
Owner (Typically, the Customer) D. A. Coutts						
Designer (Typically, the Task Leader ) (For designs from outside WSRC, identify who has final technical responsibility; this is typically the task leader.) D. A. Coutts						
Maintainer (Typically, the Task Leader) D. A. Coutts						
Tester(s) (Person(s) other than the developer of the software.) Final Report Technical Reviewer:						

Refer to NRTSC procedure QAP I-2, "Conduct of Technical Activity," for additional information

**1.0 APPROVAL PAGE/QA PORTION**

**2.0 INTRODUCTION**

**2.1 Background Information**

The coolant flow in a nuclear reactor core under normal operating conditions is kept as a subcooled liquid. This coolant is evenly distributed throughout the multiple flow channels with a uniform pressure profile across each coolant flow channel. If the coolant flow is reduced, the flow through individual channels will also decrease. A decrease in coolant flow will result in higher coolant temperatures if the heat flux is not reduced. When flow is significantly decreased, localized boiling may occur. This localized boiling can restrict coolant flow and the ability to transfer heat out of the reactor system. The maximum operating power for the reactor may be limited by how the coolant system reacts to a flow instability<sup>1</sup>. One of the methods to assure safe operation during a reducing flow transient, is to operate at a power level below that necessary to initiate a flow excursion. Several correlations have been used to predict the conditions which will precede a flow excursion<sup>2</sup>. These correlations rely on the steady state behavior of the coolant and are based on steady-state testing.

The individual coolant flow channel behavior during flow excursion is significantly impacted by the multiple path network<sup>3</sup>. When coolant flow is reduced to the flow network the flow through all of flow channels is expected to decrease. If there are no geometric, heat transfer or power dissimilarities the flow to each channel will be equally reduced as a function of the pressure drop across the flow network. In practice the reactor geometry, heat transfer behavior and power flux are not uniform. Some flow channels will be exposed to higher power levels and greater flow restrictions. Because the pressure drop across each channel is the same, as the pressure drop decreases across the entire network some channels will be more susceptible to unstable flow excursions.

When flow through the network is reduced, localized boiling may occur in some of the susceptible channels. This localized boiling may further restrict flow and inhibit heat transfer in the susceptible channels. If the flow reduction is substantial enough, a flow excursion will occur. This process can be seen in Figure 1. Whittle and Forgan generated these demand curves by incrementally reducing the flow through a single channel and measuring the steady state pressure drop at each flow. As the flow was reduced a minimal pressure drop was reached. Further flow decrease resulted in a transition condition and thermal excursion. Four different rectangular geometries and one round tube were evaluated in developing equation 1. Based on these

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1 Whittle & Forgan.  
2 Whittle & Forgan, and Saha & Zuber.  
3 Whittle & Forgan.

evaluations Whittle and Forgan suggested that the onset of the flow excursion can be predicted using equation 1 and that this might coincide with the detachment of water vapor from the channel walls.

$$R = \frac{1}{1 + \frac{\eta}{\left(\frac{L_H}{D_H}\right)}} = \frac{T_{critical} - T_{inlet}}{T_{sat} - T_{inlet}} \quad \text{where } \eta = 25 \quad (1)$$

A second empirical correlation for predicting the conditions which precede flow instability was developed by Saha and Zuber. It is based on the local fluid conditions where the void activity becomes significant.

$$Nu = \frac{\phi D_e}{k_f \Delta T_\lambda} = 455 \quad \text{if } Pe \leq 70,000 \quad (2)$$

$$St = \frac{\phi}{G c_{pf} \Delta T_\lambda} = 0.0065 \quad \text{if } Pe > 70,000 \quad (3)$$

where:

$$Pe = \frac{Nu}{St} = \frac{G D_e c_{pf}}{k_f} \quad (4)$$

Saha and Zuber developed this correlation based on vapor bubble behavior for a variety of fluids (water, Freon-22, Freon-114). The method predicted the Onset of Significant Void (OSV) which has been found to precede a flow excursion. Two criteria must be met to achieve the OSV: (1) The bubbles must detach from the wall. (2) The evaporation rate at the wall (vapor formed at and leaving wall) must be greater than the condensation rate in the liquid core (vapor condensing in core). Under different flow conditions one of these two criteria will be controlling. It has been found that vapor bubbles detach from the wall at a local roughness number of about 0.02. This corresponds to a Stanton number of 0.0065. The condensation and evaporation relationship can be evaluated based on the local Nusselt number. When the Nusselt number exceeds 455 the condensation rate of vapor entering the liquid core will no longer exceed the evaporation rate. This may be restated as: For OSV to occur the Nusselt number must be greater than 455 and the Stanton number must be greater than 0.0065. The Nusselt number represents the relationship between the evaporation and condensation rates and the Stanton number represents the bubble detachment phenomena criterion.

## **2.2 Purpose of Task**

There are two significant points which this project will try to identify. The first is when vapor first forms on the channel surface. This might be designated as the Nucleate Vapor Transition. (Steady state equivalent is ONB.) The second is when the vapor formation rate is large enough to lead to flow instability and thermal excursion. This point might be designated as the Significant Vapor Transition. (Steady state equivalent is OSV.) A correlation will be developed to relate established steady state relations with the behavior of transient systems.

For all flow conditions (steady state and transient) the nominal wall temperature will exceed the liquid core coolant temperature. At the interface between the wall and the fluid, the temperature will lie between these two values. At steady state conditions if the wall temperature is less than the saturation temperature there will be no vapor generation in the channel. For most subcooled conditions, if the flow is marginally reduced there should still be no vapor generation. When the change in flow is great enough, vapor will be generated at the trailing portion of the channel (Figure 2a). For a larger flow transient the point of vapor generation is expected to move upstream (Figure 2b). A still larger flow transient will allow the formation of larger vapor pockets, some of which may break away from the heated surface (Figure 2c). At some magnitude of flow transient, flow will be impeded (Figure 2d). Larger flow transients should result in the formation of large vapor bubbles which significantly impair flow leading to flow instability and a thermal excursion.

## **3.0 DESCRIPTION OF TASK**

### **3.1 Customer's Requirements**

Bankoff, Lee and Knaani have completed a literature review on Forced-Convection Subcooled Nucleate Boiling. The review documented 4 ONB models, 11 OSV models, 3 bubble boundary layer models and 8 void fraction models. All of the works are based on steady-state forced-convection, subcooled nucleate boiling. No experimental studies were identified which address transient forced-convection, subcooled nucleate boiling. The next step in their program will be to use the literature review as a basis to develop a theoretical model for transient downflow instability. This task will provide data to be used to benchmark and verify the theoretical model.

### **3.2. Test Description**

The test will be performed in the Heat Transfer Laboratory, Building 786-A. The test rig will consist of a vertical flat channel rig which has a heated section about 4 feet long and a nominal flow area of 0.125" x 3". The transient flows will be produced using a positive displacement pump. In the later stages of

the testing, transients may be produced using a bypass around the heated channel.

### 3.3. Theoretical Basis and Limitations

Figures 3 and 4 show a variety of thermal hydraulic correlations<sup>4</sup>. All of these correlations are based on steady state fluid behavior. The information presented in these figures can be used to evaluate what flow instability milestones can be expected to occur during any given flow or power transient.

If the heat flux and mass flux can be presented as parametric relations:

$$\phi = \psi_1(t) \quad (5)$$

$$G = \psi_2(t) \quad (6)$$

then the transient trajectory can be imposed on the heat flux, mass flux flow instability milestone plots. At each location where the trajectory intercepts a flow instability milestone the potential exists for flow instability behavior.

To demonstrate this assume that the heat flux is constant at 1,000,000 Btu/hr-ft<sup>2</sup>, and the mass flux decreases with time from an initial condition of 2,900,000 #/hr-ft<sup>2</sup>. From Figure 5 it is apparent that none of the flow instability milestone criteria has been exceeded. As the mass flux decreases the first milestone is ONB. The theoretical time to ONB based on steady state behavior can be predicted from this intercept ( $G = 1,250,000$  #/hr-ft<sup>2</sup>) and equation 6. As the mass flux drops other milestones occur:

<u>Milestone</u>	<u>Mass Flux, G</u>
Minimum pressure drop	550,000
OSV	500,000
Quality = 0.0	400,000
CHF (soft system)	400,000
CHF (hard system)	50,000
Quality = 1.0	50,000

The time to each milestone can then be predicted from Equation 6. Figure 6 illustrates how the time to a milestone can be calculated for different flow transients.

A similar solution can also be completed for a constant mass flow and an increasing heat flux. For initial conditions: 700,000 Btu/hr-ft<sup>2</sup>, 1,250,000 #/hr-ft<sup>2</sup> (Figure 5) the milestones are:

4

ONB, Bergles and Rohsenow (Collier, pg. 150.); OSV, Saha and Zuber; Minimum Pressure Drop, Whittle and Forgan; CHF, Mishima and Nishihara; and CHF, Katto.

<u>Milestone</u>	<u>Heat Flux, <math>\phi</math></u>
ONB	100,000
Minimum pressure drop	112,000
OSV	114,000
Quality = 0.0	120,000
CHF (soft system)	120,000
CHF (hard system)	520,000
Quality = 1.0	1,250,000

The theoretical time to each flow instability milestone can be estimated from Equation 5.

A more realistic trajectory might be:

$$\phi = \begin{cases} 10^6 \frac{\text{Btu}}{\text{hr ft}^2} & t \leq 0.3 \text{ seconds} \\ 10^6 (0.9 e^{-4t} + 0.1) & t > 0.3 \text{ seconds} \end{cases}$$

$$G(t) = G_0 \left[ 0.18 e^{-2.78 t} \sin \left( 4.17 t + \frac{\pi}{2} \right) + 0.82 \right]$$

Where:

$$G_0 = 2,900,000 \frac{\#}{\text{hr ft}^2}$$

The parametric solutions are presented in Figure 7; the trajectory is shown in Figures 8 and 9. For this trajectory the milestones which are intercepted are:

ONB  
 Minimum pressure drop  
 OSV  
 Quality = 0.0  
 CHF (soft system)

The time to each milestone can be calculated from either equation 5 or 6 using the trajectory intercept data.

Several researchers<sup>5</sup> have observed a delay between the predicted time to the onset of flow instability (as defined by DNB or CHF) using steady state models and the experimentally observed time to flow instability. In some cases the predicted time was less than 20% of the observed time<sup>6</sup>. The data was correlated in a variety of ways. Most correlated the actual heat or mass

5 Moxon and Edwards; Celata, D'Annibale, Farello, Setaro and Cumo; Cumo, Fabrize and Palazzi; and Lahey et al.

6 Celata, et al.

flux at instability with the predicted heat or mass flux at instability as a function of physical parameters and transient quickness.

### **3.4 Range of Test Conditions**

#### **3.4.1 Identification of Variables**

The data, theoretical relations, and correlations on two-phase flow exhibit wide ranges of uncertainty; in many cases standard deviations of 25 to 50% are considered acceptable. This wide variation makes it imperative that the rig be characterized. This process will entail characterizing the apparatus for the following conditions.

1. Subcooled, isothermal, steady-state water flow,
2. Saturated, isothermal, steady-state steam flow,
3. Saturated, isothermal, transient water flow,
4. Steady-state, water flow S-curves (heated)

Significant parameters for transient boiling behavior which should be evaluated can be predicted based on the previously discussed steady state correlations.

Variables from Equation 1 include, the coolant temperature supplied to the flow channel, the heated length and the heated hydraulic diameter. The two variables which are expected to be most readily adjusted are the coolant temperature and the hydraulic diameter (channel thickness).

Variables from Equations 2, 3, and 4 include, the heat flux, the hydraulic diameter, and the mass flow rate. This introduces two additional variables which can be readily varied: The heat flux and the coolant flow.

Another significant variable which should be evaluated is the flow direction. The behavior of the transient response could be significantly impacted by a change from down-flow to an up-flow configuration. Since the two-phase flow regimes for downward and upward flow are very different<sup>7</sup>, it is possible that the flow direction impacts the transient response behavior.

The application of transients introduces an additional variable which should be evaluated. The most significant is the rate of the flow transient. It is expected that very slow transients will exhibit a strong similarity to steady state data. More rapid transients could result in a situation where it is possible to pass through a normally unstable state and achieve an alternative steady state condition. Possible variations of transient conditions could include a step change and a ramp function (Figure 10).

The variables to be evaluated during this task are listed in Table 1. The heated length will remain constant for the task; the remaining variables will be evaluated.

### **3.4.2 Evaluation of Variables**

It is unknown which variables will have a significant impact on transient flow phenomena. For this reason it is not possible to describe all of the task test conditions. As a minimum each test variable will be evaluated at two test conditions to determine if a relationship exists. The preliminary principle nominal operation conditions are listed in Table 2. The primary conditions will be evaluated for flow transient changes (measured as the ratio of final mass flux and initial mass flux) of 0.05 to 1.0. The primary conditions will serve as a baseline of comparison for the effect of the secondary condition evaluation. Each secondary condition will be evaluated individually. Those test conditions found to have a significant effect may be evaluated at additional test conditions.

### **3.4.3 Test Condition Discussion**

**Channel depth** - The flow passage depth has been selected to minimize the necessary flow rate but still provide adequate area to allow observation of vapor bubbles leaving the heated surface. The channel depth also is similar to the channel depth used by Whittle and Forgan. The secondary depth approaches that used in SRS reactor assemblies.

**Channel exit pressure** - The SRS reactors operate at atmospheric conditions. The selected pressure allows a nominal pressure gradient from the exit of the test section.

**Channel length** - An extremely long flow channel would make it difficult to inspect the channel at all flow points. A short flow channel would require extremely high power densities. A heated length of 4 feet is expected to be manageable. The unheated inlet will be two feet (100 hydraulic diameters) and the exit will be one foot (50 hydraulic diameters). The exit was kept shorter because of the significant two-phase pressure drop in this section. The overall length of the test channel with end connections will be about nine feet.

**Channel width** - The channel width should be kept as narrow as possible to reduce flow and allow better edge visualization. The channel width must be wide enough to reduce edge effects and allow visualization from the front. The edge effects are thought to be significant if the channel depth is larger than 10 percent of the channel width (proposed design:  $0.125/3 = 4\%$ ). Small channel widths may not allow for adequate visualization (See Figure 9.) For initial design efforts a channel width of three inches has been selected. This

width will be iterated during the design effort based on scoping evaluations and design detail information. It is desirable to minimize the width.

**Flow direction** - The present SRS reactors operate in an downflow mode. It is desirable to obtain data based on this arrangement. The proposed New Production Reactor and selected components in the existing reactor (septifoil cooling) operate with upflow. Data should be obtained to support efforts related to these second two conditions.

**Heat flux** - The heat flux will be selected based on the amount of water flow. The water flow is a function of the Reynolds number. The initial water flow prior to the transient will be 120% of the flow estimated by equation 1 at the critical temperature.

**Imposed flow transient** - The primary transient flow curve will be a step function. This shape was chosen since it is expected to create the largest effect. The transient will be induced by varying the pump speed. Data will be evaluated based on the actual flow transient. The second test condition will be selected based on the transient flow characteristics of the test rig. Other flow transients such as a ramp change may also be evaluated.

**Inlet temperature** - For this task the inlet flow will always be subcooled. The 60°C temperature is considered easy to achieve and representative of the conditions at SRS. It also provides a good variation for the secondary condition.

**Reynolds number** - The Reynolds number will be based on the initial conditions prior to the transient. The values selected include both laminar and turbulent flow. It is expected that the pressure drop during two-phase flow will be significant, and it will be necessary to characterize the curve for at least one heat flux in the upper higher quality flow region (~30%). If the rig design pressure is limited to 45 psig and the operation range to 30 psig, the flow with  $Re=60,000$  will probably exceed the rig design pressure before reaching 3% quality. (The uncertainty on the calculation is very high.) For  $Re=10,000$  it should be possible to achieve high quality flow without exceeding the rig design pressure. The selected flow rates will be adjusted to provide good variable separation and allow operation within the rig design limits.

### **3.5 Sources of Input Data**

None

### **3.6 Tasks and Estimated Schedule**

3.6.1 Write Task Experimental Plan -D. A. Coutts - 8/31/91

3.6.2 Obtain approvals for Task Plan - D. A. Coutts - 8/31/91

- 3.6.3 Write operating procedure - D. A. Coutts - 10/31/91
- 3.6.4 Design test rig - T. J. Steeper - 10/20/91
- 3.6.5 Fabricate test rig - T. J. Steeper - 11/30/91
- 3.6.6 Finish testing - D. A. Coutts - 4/30/92
- 3.6.7 Document results - D. A. Coutts - 12/31/92

### **3.7 Purchases**

The operation of this rig will require some specialized instruments to measure flow profile effects near the heated plate. This equipment may not be available before 12/91 therefore some testing will be done prior to receiving this equipment.

### **3.8 Training**

D. A. Coutts or his designate will train the technicians in specialized activities associated with this task.

## **4.0 TEST APPARATUS**

**4.1 Test Apparatus Description** - The test apparatus is shown in Figure 11. The test channel will have a flow area which is nominally 0.125" X 3". The heated surface will be 4' long and 3" wide. Heating of this surface will be accomplished by electric resistance effects. The heated surface will be visible since vision panels will be provided as shown in Figures 12 and 13. A positive displacement pump will be used to allow steady-state operation on the negative slope portion of the S-curve. The discharge from the pump will be damped and moderately throttled. The throttling should reduce density wave effects. The discharge from the heated channel will be cooled in a heat exchanger supplied from the Building 786-A water system.

### **4.2 Instrumentation**

- 4.2.1 Pressure Gages, 2, 0 to 60 psig, Category 1
- 4.2.2 Pressure Gages, 4, 0 to 60 psig, Category 1
- 4.2.3 Pressure Gages, 4, 0 to 10 psid, Category 1
- 4.2.4 Pressure Gages, 2, 0 to 5 psid, Category 1
- 4.2.5 Water Flowmeter (electric), 1, 0 to 11 gpm, Category 1
- 4.2.6 Water Flowmeter (rotometer), 1, 0 to 11 gpm, Category 1
- 4.2.7 Water Flowmeter (electric), 1, 0 to 3 gpm, Category 1
- 4.2.8 Water Flowmeter (rotometer), 1, 0 to 2.7 gpm, Category 1
- 4.2.9 Thermocouples, Standard Type E, 22, 0 to 300°C, Category 1

4.2.10 Thermocouples, Test Response Type E, 6, 0 to 300°C, Category 1

4.2.11 Thermometer, 1, 0 to 120°C, Category 1

## 5.0 INVESTIGATION AND TEST PROGRAM

The test rig will be characterized for a variety of steady-state and transient flow conditions. Pressure drop characterizations will be developed for:

- Steady-state, isothermal, subcooled water, 20 and 60°C, 0 to 11 gpm
- Steady-state, isothermal, saturated steam, maximum flow will be based on test apparatus design pressure
- Transient isothermal, subcooled water, 20 and 60°C, Re, step and range conditions stated in Section 3.4.3
- Steady-state, S-curves as stated in Section 3.4.3 (2 or 3 power levels)
- Two phase transient tests as stated in Section 3.4.3 (2 or 3 power levels)

## 6.0 DATA ACQUISITION, REDUCTION AND EVALUATION OF DATA

6.1 **Data Acquisition** - Data will be recorded using Workbench software on Macintosh computers.

6.2 **Data Reduction** - Transient pressure and temperature data will be plotted with respect to time. Pressure data will also be normalized using isothermal data. Tabular and graphical data will be recorded.

6.3 **Data Evaluation** - Steady state data will be evaluated by comparison with known established relations. Single phase data will be evaluated using:

$$f \equiv \frac{\Delta p}{4(L/D)(\rho V^2/2)}$$

where:

$$f = 16/Re \quad \text{laminar}$$

$$f = \frac{0.0791}{Re^{0.25}} \quad 3 \times 10^3 < Re < 2 \times 10^4 \quad \text{turbulent}$$

$$f = \frac{0.046}{Re^{0.20}} \quad 2 \times 10^4 < Re < 5 \times 10^5 \quad \text{turbulent}$$

Two-phase steady state data will be evaluated using Friedel's (1979) correlation. (See Figure 15.)

Single-phase transient effects will be evaluated using a variety of curve fits proposed in the available literature.

Two-phase data will be evaluated by developing a comparison with single-phase data.

## **7.0 REFERENCES**

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## 8.0 NOMENCLATURE

### 8.1 General

A	Flow area of the heated channel
a	Heated channel width
b	Heated channel depth
$c_{pf}$	Specific heat at constant pressure for the fluid
$D_e$	Hydraulic diameter of the heated channel, $\frac{4A}{P}$
$D_H$	Heated hydraulic diameter of the channel, $\frac{4A}{a}$
f	Friction factor as defined in section 6.3
G	Mass flux rate
g	acceleration due to gravity
$k_f$	Thermal conductivity of the fluid
L	Channel length
$L_H$	Heated length of the channel
P	Wetted perimeter of the heated channel
$\Delta p$	Pressure drop
R	Temperature ratio as defined in equation 1
Re	Reynolds number
$t_0$	Time that the flow transient starts
$t_1$	Time when steady state is achieved after a flow transient
$\Delta T_\lambda$	$(T_{sat} - T_{local})$ at the excursion
$T_{sat}$	Saturation temperature of the fluid
V	Mean velocity
$\phi$	Heat flux into the channel
$\rho$	density

**8.2 Subscripts:**

f	Return to a steady state condition after a transient
o	Start of a transient
ONB	Onset of Nucleate Boiling
OSV	Onset of Significant Void
L	Liquid property
G	Vapor (gas)

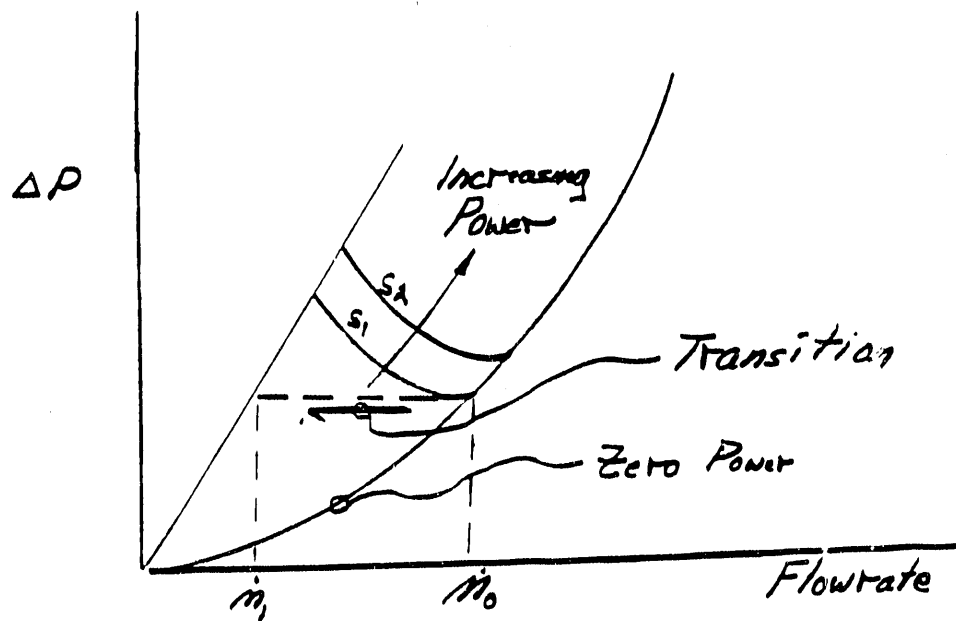


Figure 1, S Curve

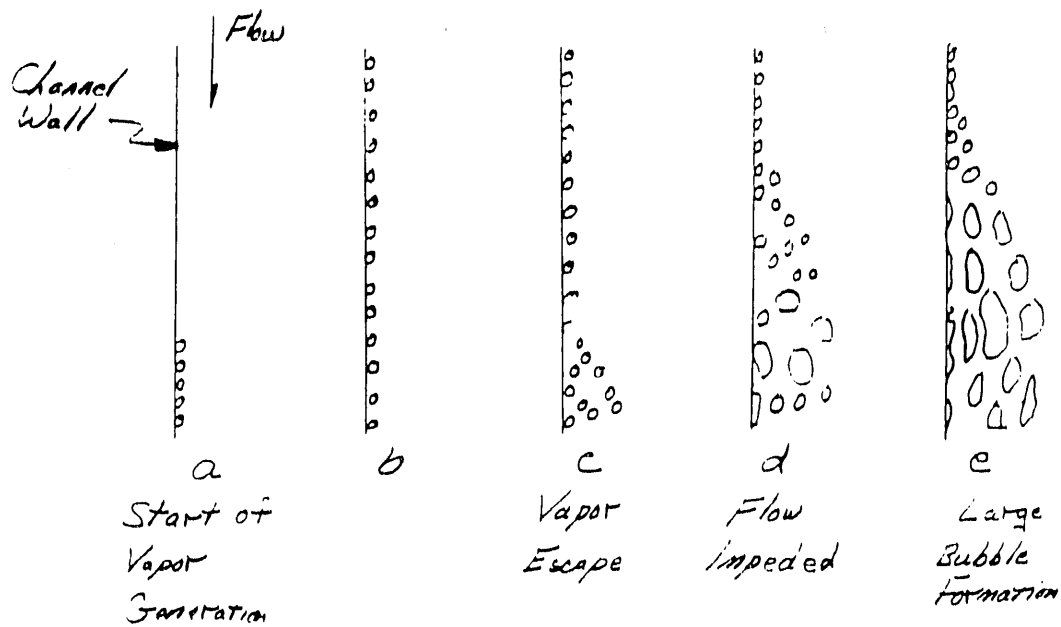


Figure 2, Vapor Generation Patterns

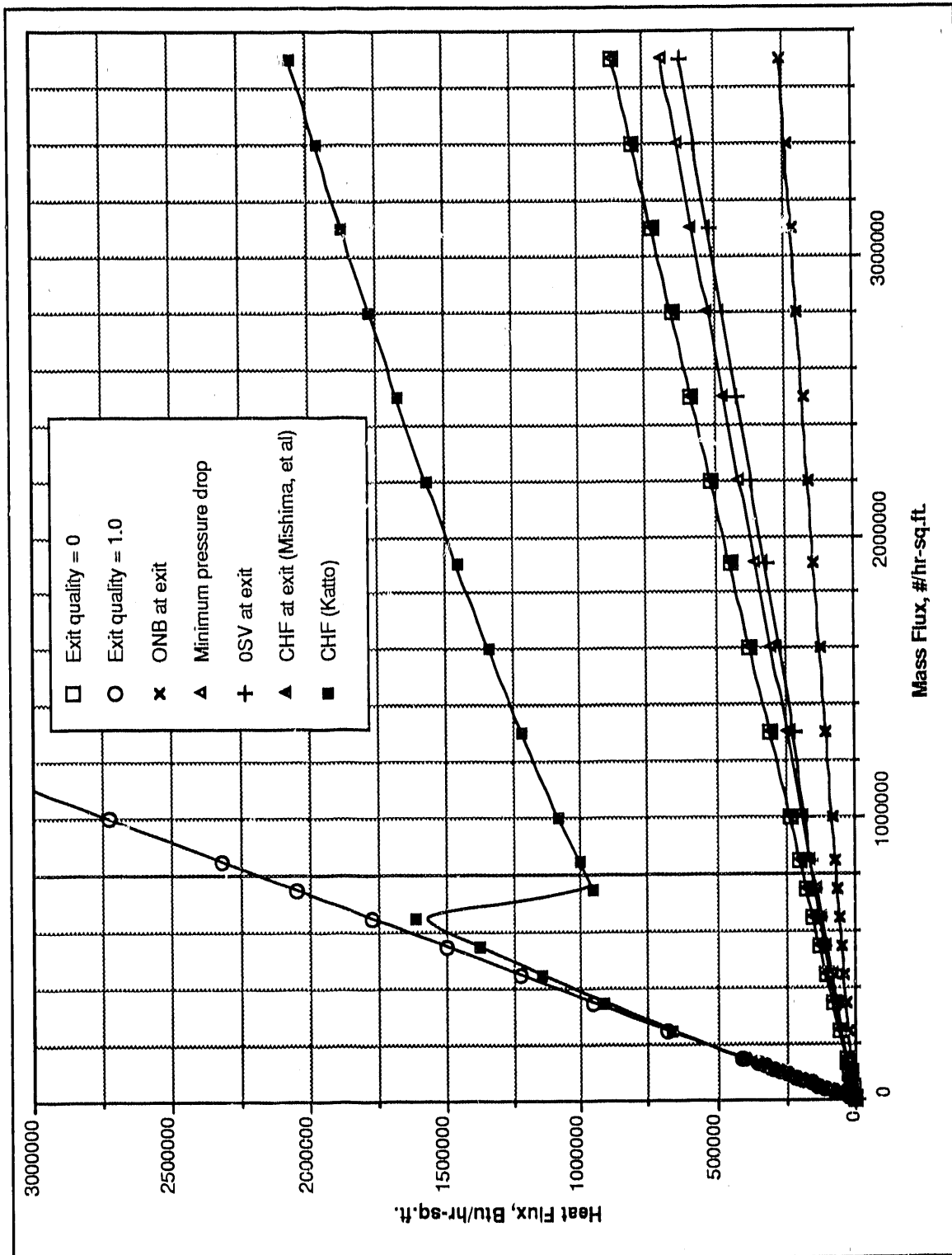


Figure 3, Flow Instability Milestones (Inlet Temperature of 140°F, high flows)

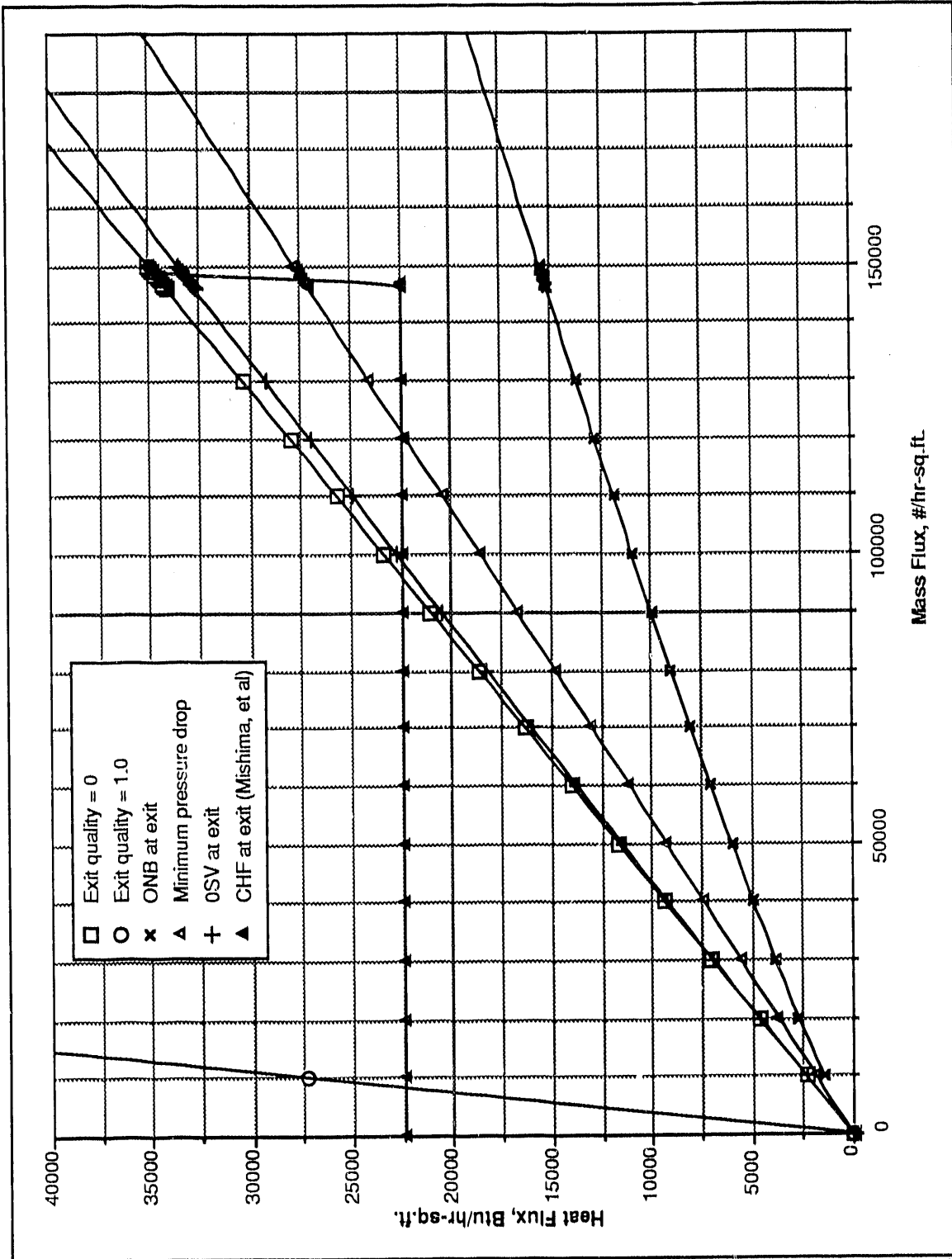


Figure 4, Flow Instability Milestones (Inlet Temperature of 140°F, low flows)

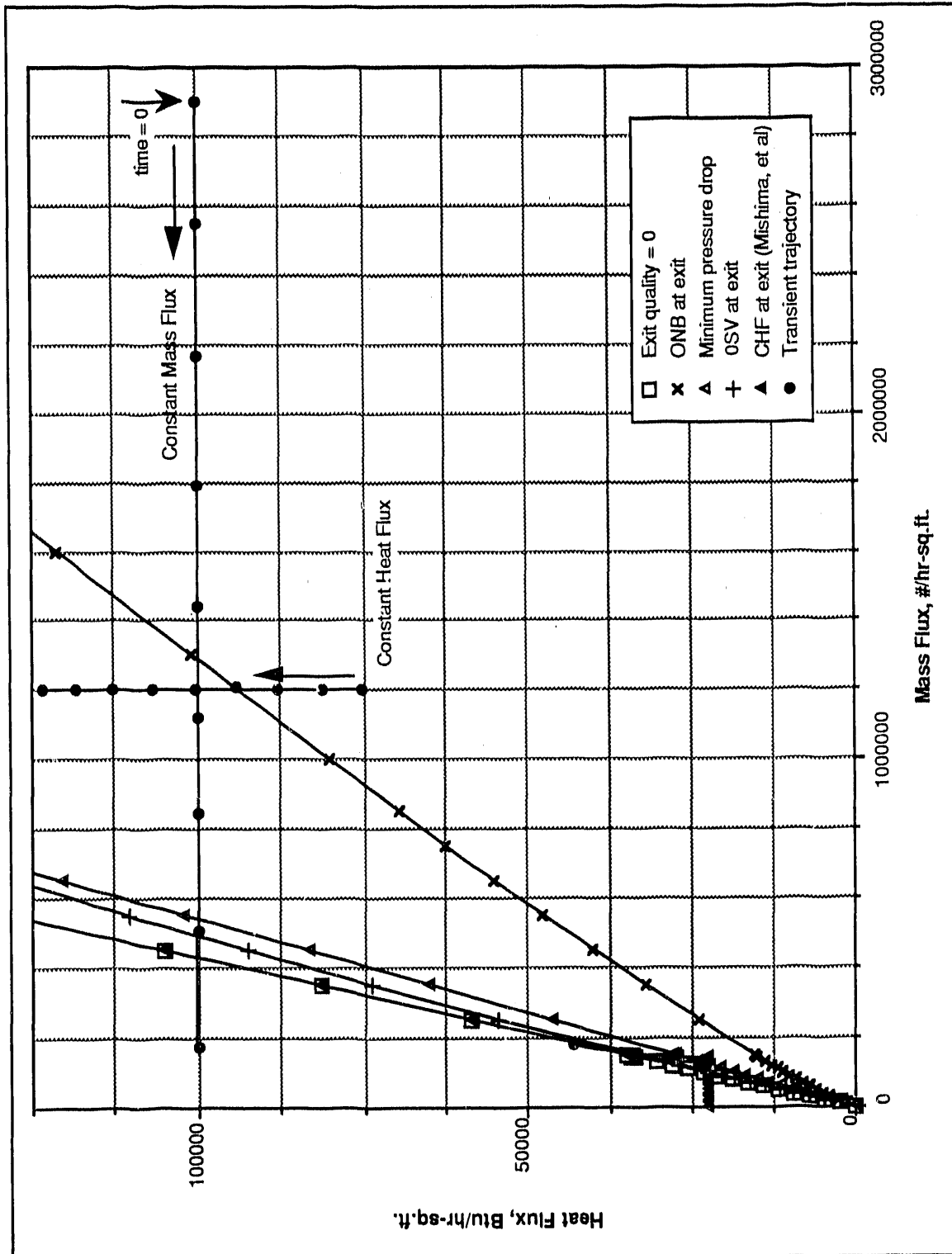


Figure 5, Flow Transient Trajectories

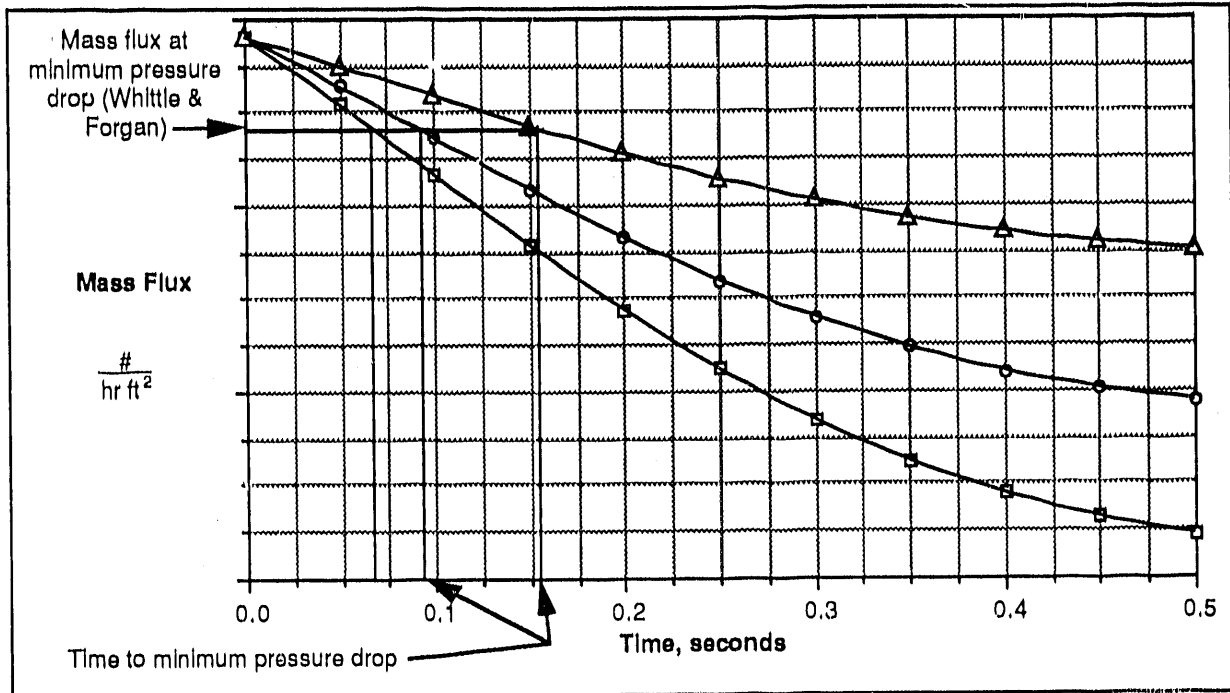


Figure 6, Time to Minimum Pressure Drop

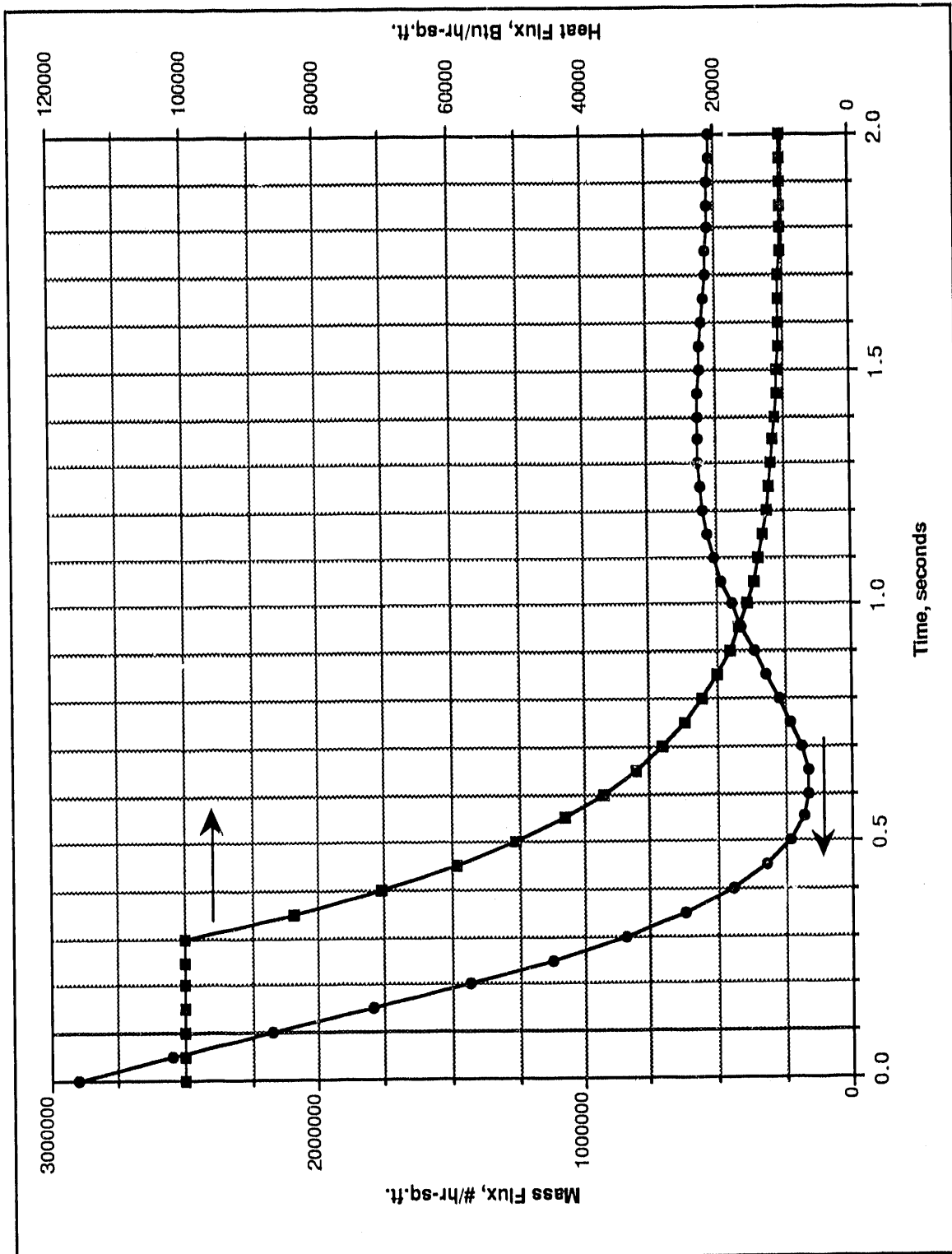
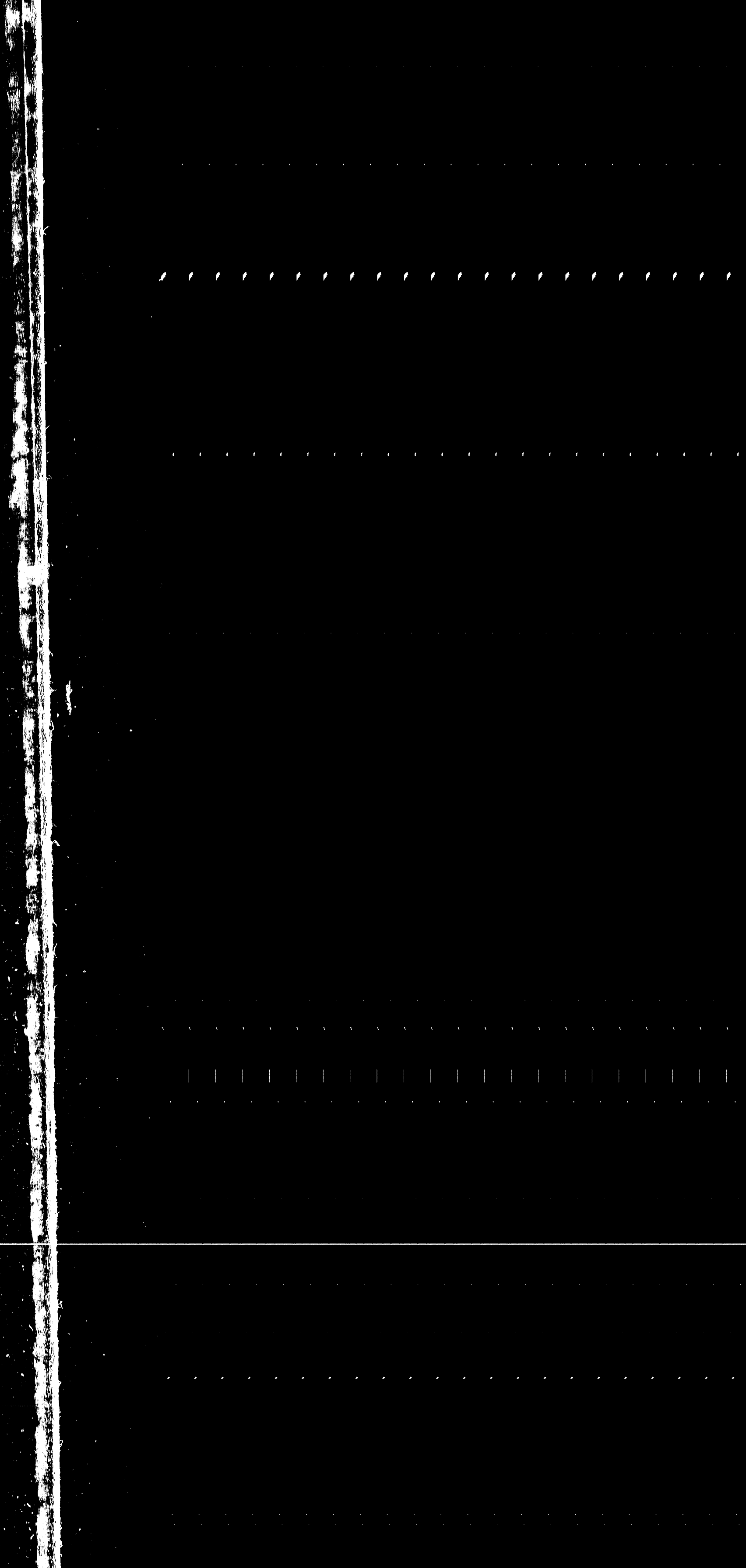


Figure 7, Example Parametric Mass Flux and Heat Flux Relations



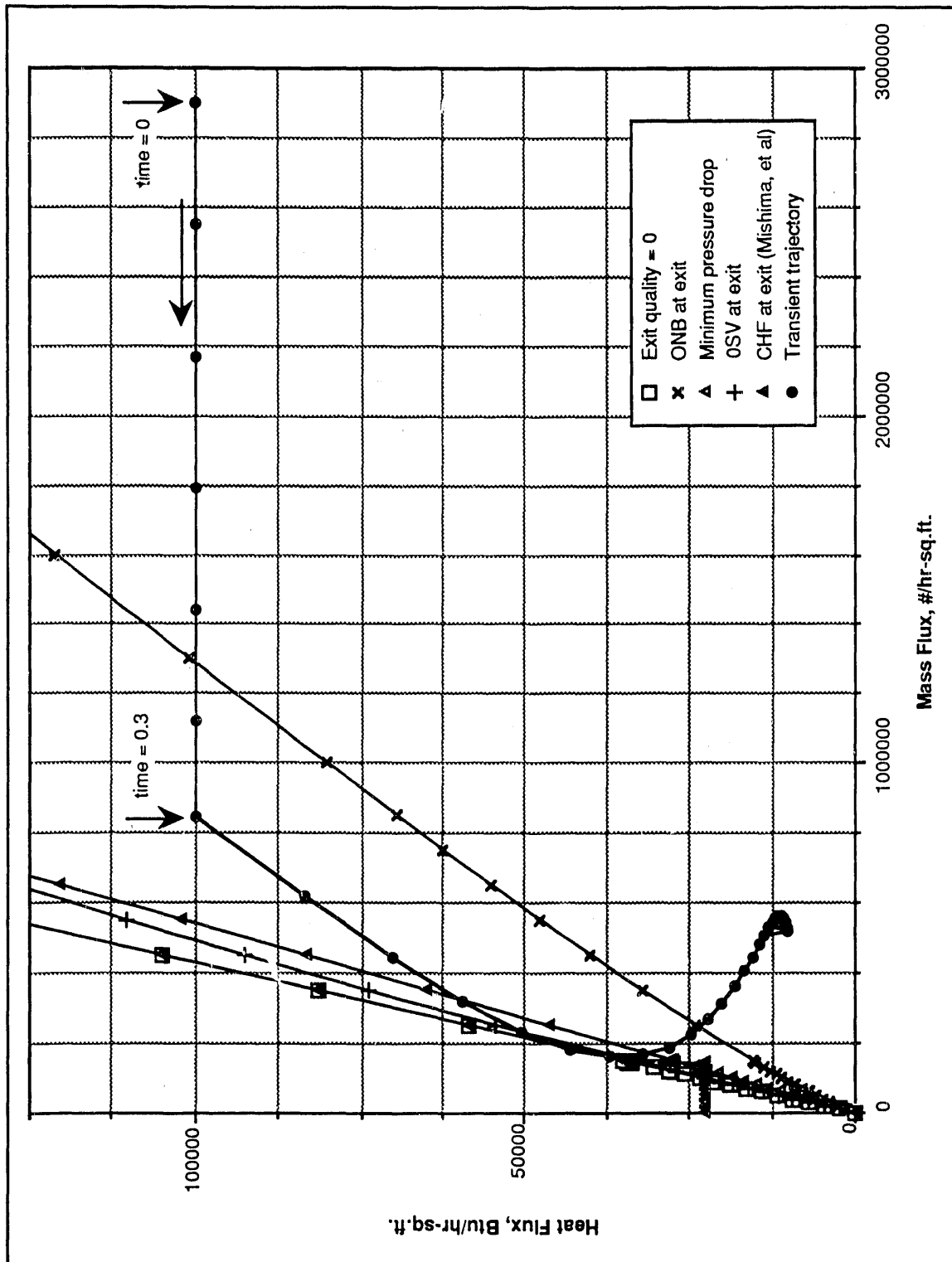


Figure 8, Compound Heat and Mass Flux Trajectory for an Inlet Temperature of 140°F

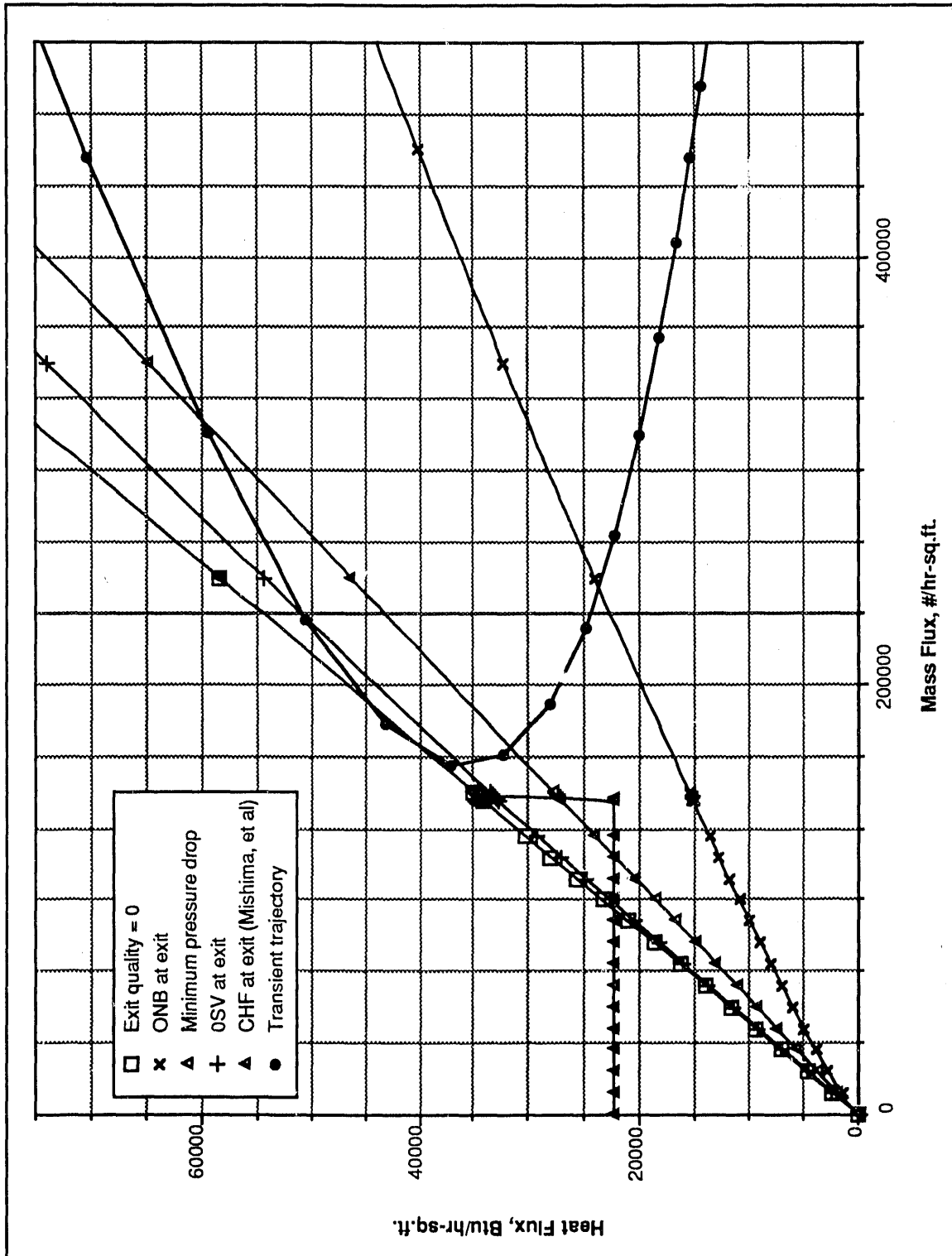


Figure 9, Compound Heat and Mass Flux Trajectory for an Inlet Temperature of 140°F (detail of intercepts)

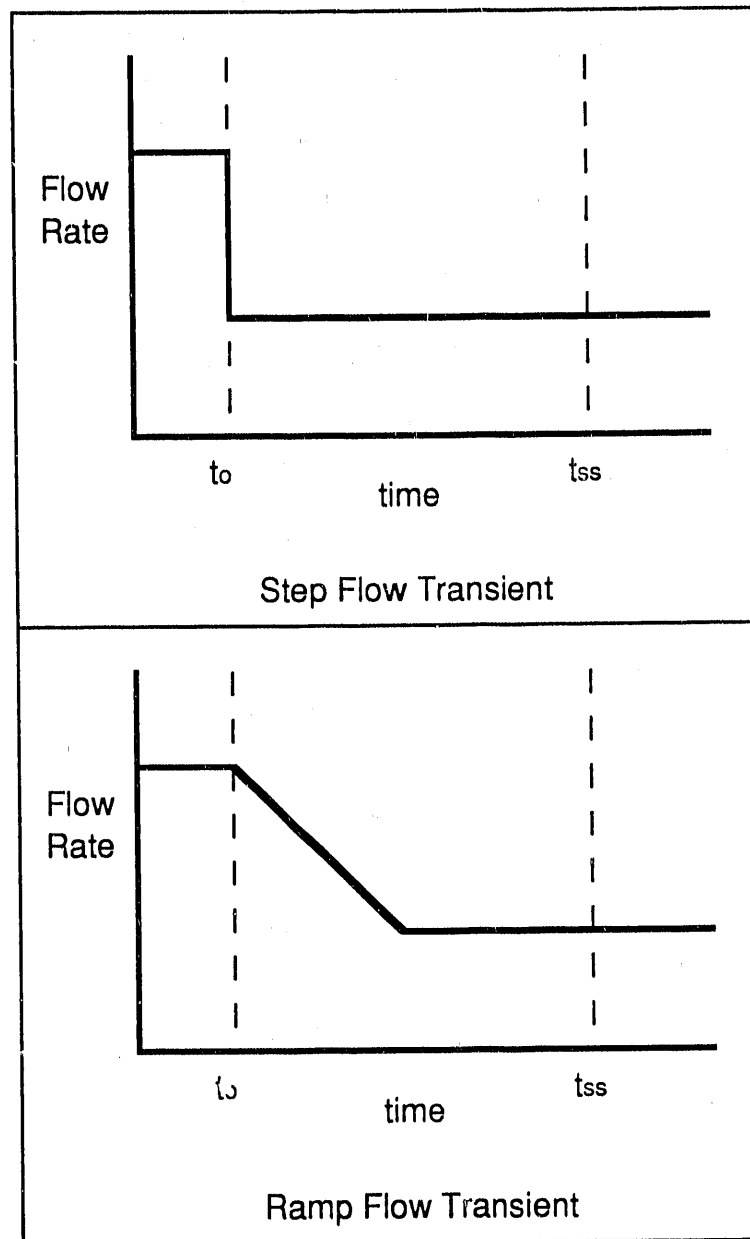


Figure 10, Imposed Flow Transients

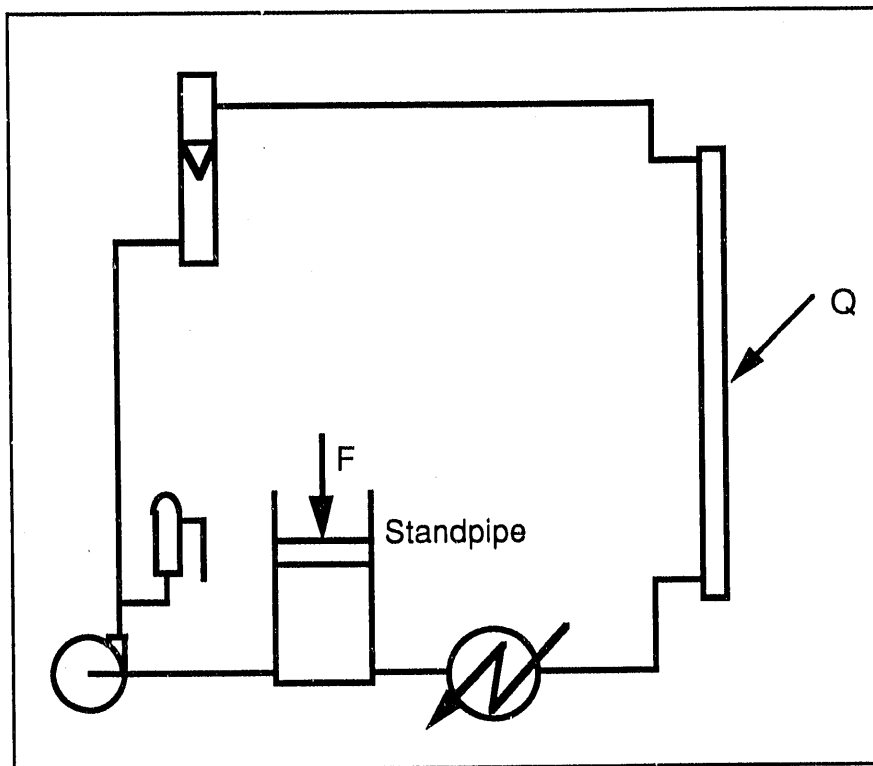


Figure 11, Rig Schematic

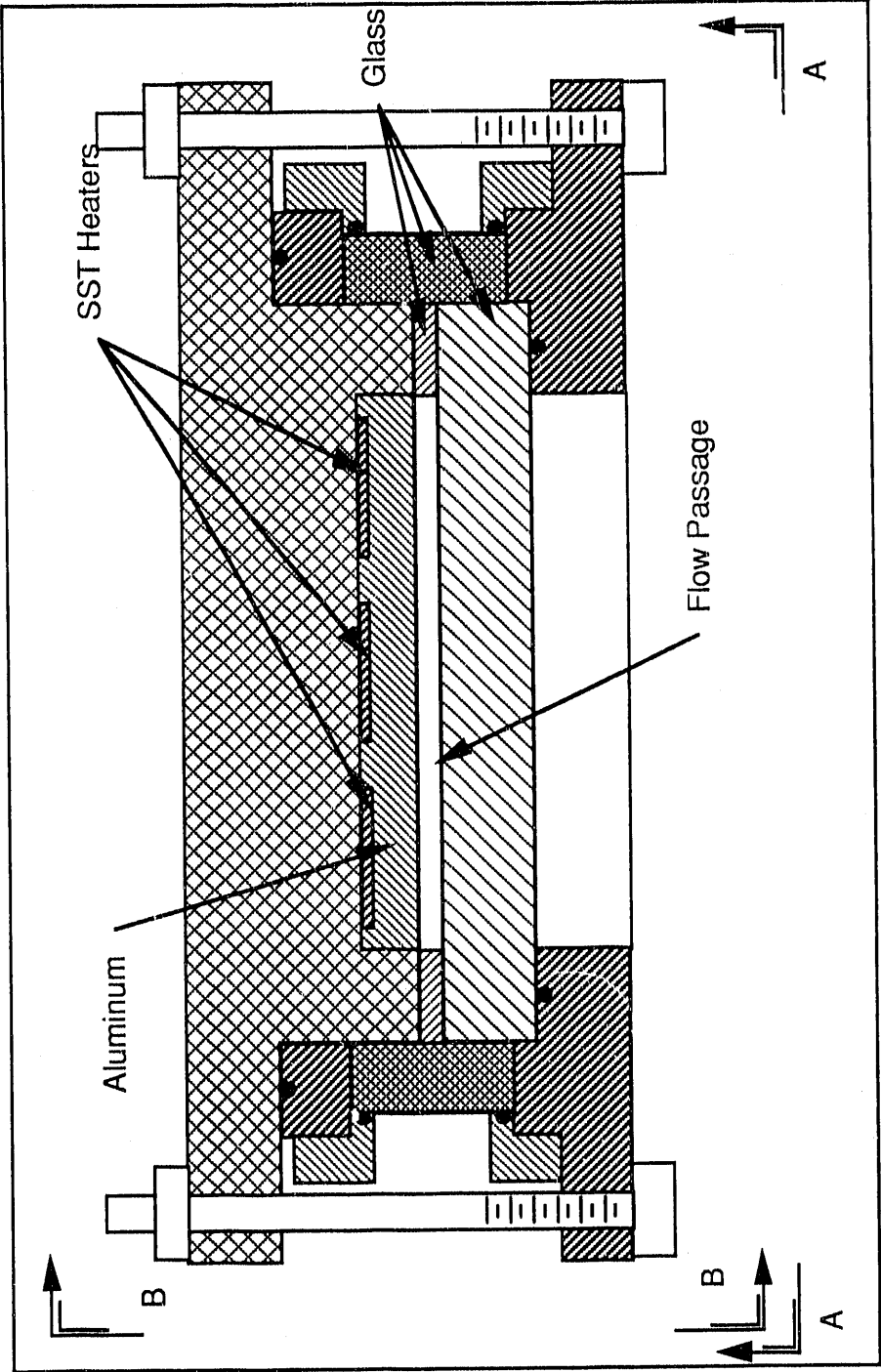


Figure 12, Flow Channel Section

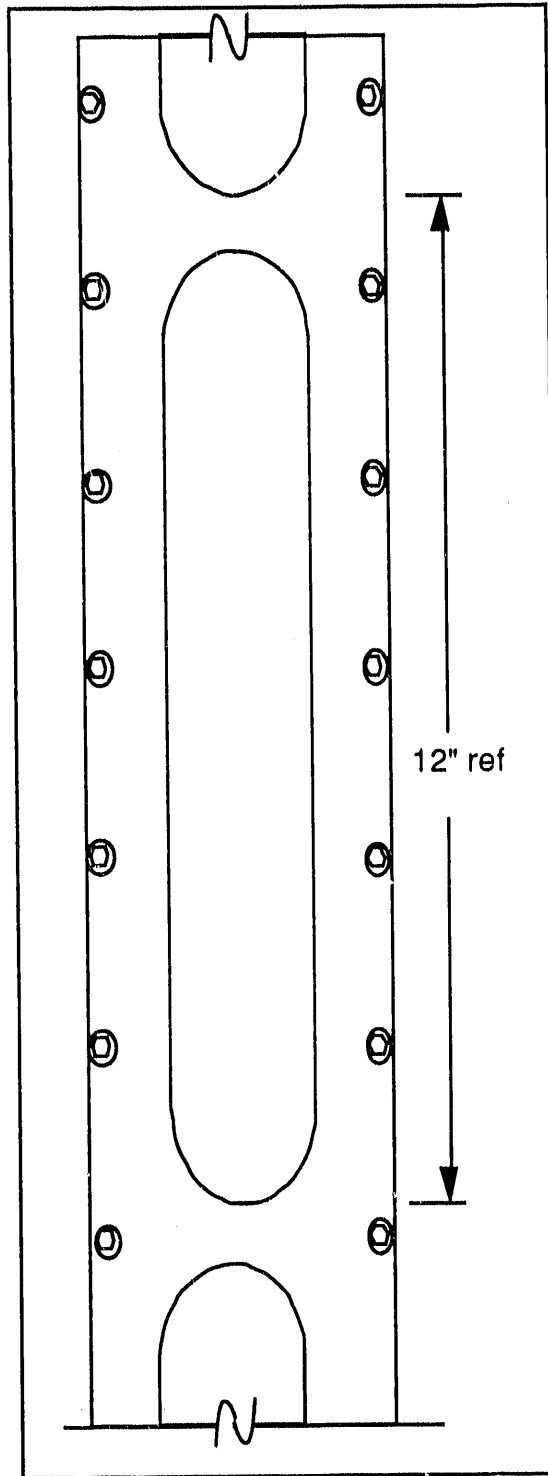


Figure 13, Section AA

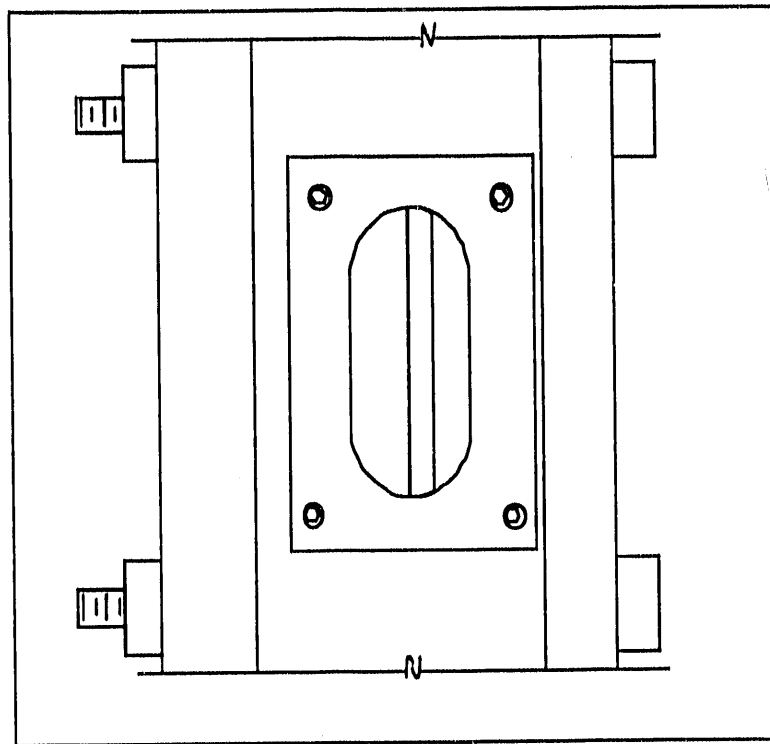


Figure 14, Section BB

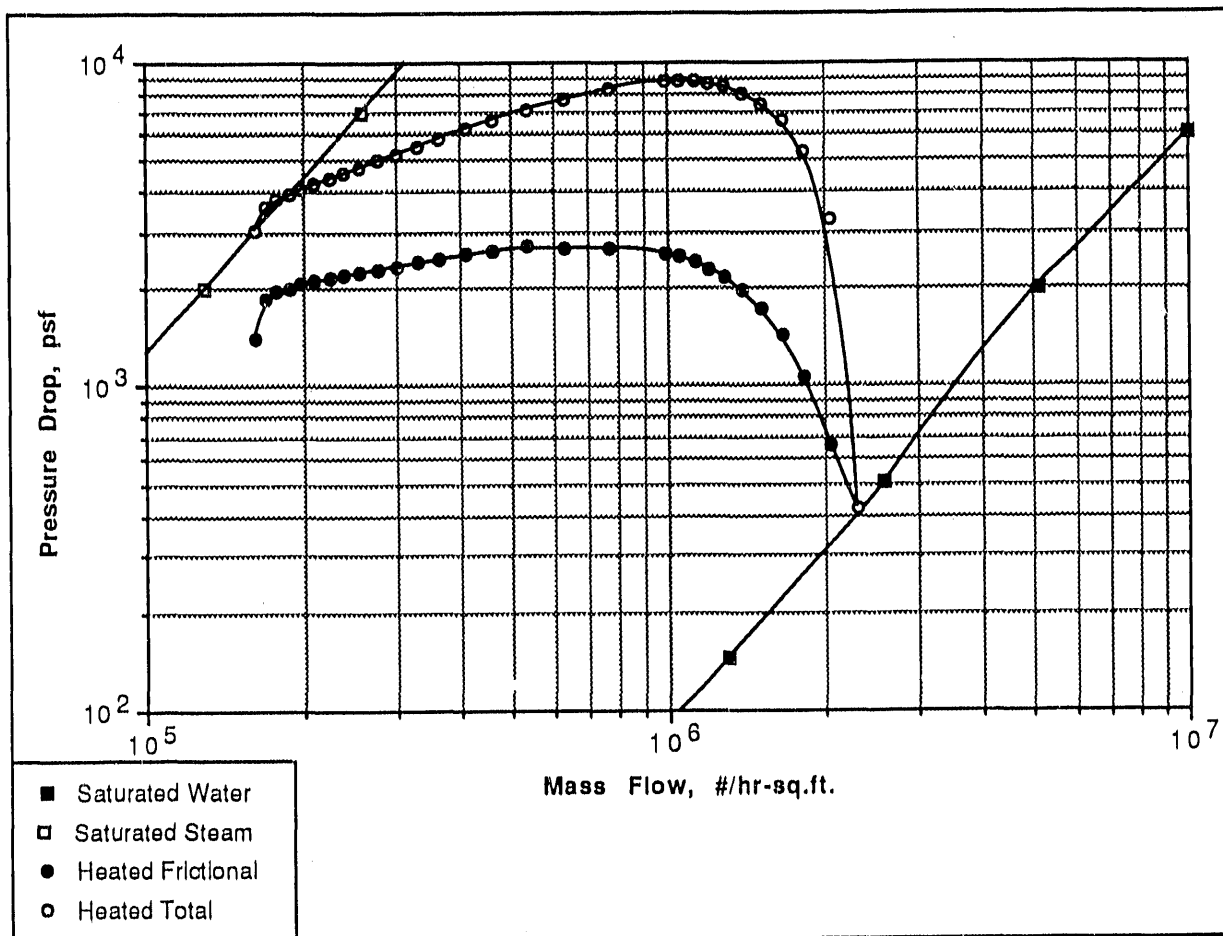


Figure 15, Typical Demand Curve for a Single Power Level

**TABLE 1**

**Independent Test Variables**

Flow Direction  
Heat Flux  
Heated Hydraulic Diameter  
Heated Length  
Hydraulic Diameter  
Imposed Flow Transient  
Initial Mass Flow Rate  
Inlet Temperature  
Mass Flow Rate Change

<b>TABLE 2</b>		
<b>Proposed Testing Conditions</b>		
<b>Test Conditions</b>	<b>Primary</b>	<b>Secondary</b>
Channel width	3"	NA
Channel depth	0.125"	0.25
Reynolds number (Inlet steady state)	10,000	1000, 60,000
Channel exit pressure	15 psia	NA
Heat flux	Based on equation to achieve $G_{initial} = 1.2G_{OSV}$	
Inlet temperature	60°C	85°C
Heated length	4 feet	NA
Flow direction	down	up
Imposed Flow Transient	Step	Ramp with 1/2 period for solid water step transient

**END**

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