CHAPTER 4

INTRODUCTION TO SAFETY ANALYSIS

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ABSTRACT

This chapter describes the thermohydraulics part of CANDU safety analysis for a selection of non-LOCA scenarios. These include overpower, loss of pumping and loss of heat sink scenarios. Trip coverage is covered and, in many cases, long term heat removal is by thermosyphoning. The phenomenology of thermosyphoning is described.

4.1 Introduction

Safety analysis comprises reactor physics, thermohydraulics, core behaviour and containment studies. This lecture addresses the thermohydraulics part. Generally thermohydraulic studies require information from reactor physics and supply information to fuel behaviour and containment assessments. The end objective is to determine the release, if any, of radioactivity from fuel to primary heat transport system (PHTS) to containment to the public given each scenario as a starting point. Given reactor physics information, the thermohydraulics part is to evaluate system temperatures and pressures -- notably fuel temperatures.

The calculation of fuel temperature requires knowledge of the coolant condition at the fuel surface and this generally requires a prediction of coolant condition throughout the primary system. For CANDU the general approach is to do a system calculation to generate the coolant conditions in the headers which are used as boundary conditions for calculations of individual channels. The channel coolant condition is then used for further refinement of fuel and pressure-tube temperature at particular axial locations.

Theoretically one could use a multi-dimensional two-fluid transient computer code for these studies, however, such a tool is not yet available for practical use. Indeed even the one-dimensional (1D) two-fluid models still need development, see chapter 13.

To date the work horse has been the 1D 3-equation code, commonly called the homogeneous equilibrium code but, in fact, having substantial capability to model inhomogeneous and non-equilibrium two-fluid effects. For example non-uniform phase concentrations and velocities are modelled. Also the pressure calculation is adjusted to compensate for the underprediction by the homogeneous equilibrium model when cold water is mixed with steam. Also phase stratification in horizontal pipes is treated by identifying the flow regime change and then selecting appropriate coefficients for heat transfer from exposed surfaces. Most of these adjustments to "homogeneous equilibrium" are essential for accurate modelling of the fuel channel and its feeders. For CANDU we do full size testing to verify that the adjustments are appropriate.

In the following section, a sample of scenarios will be described. The focus will be on non-LOCA scenarios because LOCA analysis is discussed in detail in Chapter 16. For each case an outline of the method of analysis and its important features will be given. As a general rule, the reader is advised to keep a schematic diagram of the PHTS at his side when studying these scenarios. For example, he could use Figure 1.4 of Chapter 1.

4.2 Accident Scenarios

Accident scenarios can be categorized as overpower, loss of pumping, loss of coolant or loss of heat sink though combinations are also studied. Overpower is commonly called loss of regulation (LOR) which means a loss of control of neutron flux such that the core or core zone power levels are greater than normal. Loss of pumping (LOP) scenarios include a loss of one or more pumps. For example we study the seizure of a single pump and we study the loss of all pumps as would occur if the class IV electrical power supply were lost.

Combinations of LOC and LOP scenarios are studied. A reactor trip may conceivably cause a loss of class IV electrical supply so we study LOC with loss of class IV power coincident with the reactor trip. As another example, a loss of electrical power as the initial event may result in primary pressures high enough to activate relief valves. Then it could be postulated that the valves fail to close causing a small LOC.

Below we examine particular non-LOCA scenarios selected because of their significant impact on safety system design.

4.2.1 Overpower or Loss of Regulation

The LOR scenario is the basis for neutronic trip setpoints. The slow LOR sets the overpower (or high n) trip and in so doing puts a limit on reactor power (100% power is chosen to permit a comfortable operating margin below the overpower trip). At low power and for the faster LOR's, the overpower trips become less effective and a rate trip (high rate log n) is used.

The objective of thermohydraulic analysis for the LOR is to demonstrate heat transport system integrity over a range of reactivity insertion rates from zero to greater than the maximum credible. Integrity is ensured if

a) coolant overpressure is limited

and b) fuel melting is avoided. This may not be necessary but is a sufficient condition. Melting occurs when a fuel element has fully dried out, but we have conservatively used "departure from nucleate boiling (DNB)" as the criterion pending results from post DNB heat transfer tests.

The limiting scenario for the overpower trip is the LOR that takes a core region to a power level just below the trip setpoint, where it sits. Fuel centreline temperatures have time to reach equilibrium.

The thermohydraulic analysis is approached by considering particular channels in turn. Header pressures and enthalpy are held constant at the nominal full power condition as channel power is raised step by step in a series of steady-state calculations. The sequence is terminated when DNB is predicted. The power is called the critical channel power (CCP). The overpower trips are set such that the CCP is not exceeded in any channel with due allowance for uncertainties in doing the CCP calculation and in making in-core measurements.

Figures 1, 2 and 3 illustrate details of the CCP calulation. Figure 1 shows the reduction of channel flow that occurs with constant header conditions as power is increased. Figure 2 shows the critical heat flux as measured in a full size horizontal channel with a near-cosine axial heat flux. It is given as a function of steam quality and flow rate. Figure 3 shows the axial variation of steam quality, critical heat flux and actual heat flux at the point of dryout in a particular channel.

The above information is based on the first indication of DNB. Recent tests show that fully-developed film boiling does not occur without a substantial increase of power beyond this point. So DNB temperatures are modest and we have a good case for increasing high n trip setpoints.

The CCP calculation supports the special but important case of high n trip coverage for a slow LOR from 100% power. Further calculations are required to show general trip coverage for faster LOR's from powers of less than 100%. Steps in these calculations are as follows:

a) An initial power level and an input rate of increase of reactivity are assumed.

b) A point neutronics calculation gives neutron flux as a function of time.

c) A fuel calculation gives UO_2 temperature and power to coolant Q_c as a function of time for a high-power channel, assuming no dryout.

d) A PHTS calculation gives system pressure as a function of time.

Calculation b gives the times of the high n and rate log n trips. Calculation c gives the time τ_ϕ at which the UO_2 melts or Q_c = CCP whichever is least. Calculation d gives the time of the high pressure trip and the time τ_P at which the system pressure exceeds 1.1 (1.5) x design pressure (1.5 for low-probability events), coverage is credited if $\tau < \tau_\phi$ and $\tau < \tau_P$ for a particular trip at time τ. Figure 4 gives a typical LOR trip coverage map.

4.2.2 Loss of Pumping

Classical safety analysis includes the study of several scenarios involving an impairment of the forced circulation of primary coolant. The simplest and most probable is a loss of electrical supply to all the PHTS pumps but we also study the rundown of one or more pumps and the seizure of a pump. Also PHTS flow impairment is common to many postulated scenarios, in particular the primary and secondary LOC scenarios.

The PHTS pumps are supplied with flywheels that reduce the head loss in the short term prior to reactor trip and permit a gradual development of thermosyphoning forces in the longer term -- about 2 minutes after the loss of electrical power.

A flow reduction is readily sensed by several regulating and safety system measurements: low flow, low header-to-header pressure drop, high pressure. Thermohydraulic analysis is required to show that power is reduced before fuel cooling is unacceptably impaired. For the more probable events such as a simple loss of class IV power we ensure that fuel damage is avoided. For the improbable events such as a loss of class IV plus unavailability of shutdown system #1 (SDS1), we ensure that fuel channel integrity is maintained. This requires accurate or conservative calculation of primary system pressure and fuel post-dryout temperature.

Figure 5 gives the result of a PHTS calculation for a loss of class IV power event without trip. Two trips would be expected on each of the two shutdown systems in the first 6 seconds. Figure 6 gives the sheath and UO_2 temperatures calculated by taking credit for the last of the four trips. DNB was predicted and film boiling was assumed to generate the temperatures of Figure 6. Recent post DNB tests show that these temperatures are overpredicted. Even so, they are far from limiting. Figure 7 gives the PHTS pressure which again is within limits.

The above analysis is typical of trip coverage analysis for a loss of pumping event. The longer term analysis is simple if single-phase thermosyphoning can be demonstrated but for some low probability events, e.g., loss of class IV plus a failed open PHTS relief valve, the thermosyphoning is two-phase and analysis becomes more complicated. Two-phase thermosyphoning analysis is described in Section 4.2.4 below.

4.2.3 Loss of Heat Sink

Loss of heat sink scenarios range from a simple loss of feedwater to the most severe design-basis earthquake. They have no immediate effect on fuel cooling but a long-term heat sink must be provided. These scenarios invariably see an early trip, for example on low boiler level or on high primary pressure, so power is quickly reduced to decay power. Unless secondary inventory is lost, as in a large steam main break, the liquid remaining in the boiler is sufficient to remove decay heat for 30 minutes. If secondary inventory is lost an emergency water supply (EWS) is activated on depressurization of the steam generators. In the longer term a shutdown cooling system can be activated to provide an alternative heat sink to the steam generators.

The analysis of loss of feedwater is trivial. Forced circulation of the primary coolant provides good fuel cooling and sufficient boiler inventory provides good heat transfer from primary to secondary whilst an auxiliary flow of boiler feedwater is being activated.

The DBE is much more complex. The assumptions include a complete steam main severance plus a complete loss of all electrical power systems. It is analyzed by doing a PHTS system calculation to generate header conditions followed by calculations of individual channels. In the longer term the analysis is supported by extensive studies done to understand the phenomenology of two-phase thermosyphoning, see Section 4.2.4 below.

Figure 8 shows some results of the DBE analysis for a typical CANDU reactor. Figure 8a shows the rapid secondary side depressurization and Figure 8b shows the effect on primary flow of the pump rundown. The EWS under gravity, starts flowing to the steam generators during the pump rundown. The primary pressure decreases rapidly after the trip to about 7 MPa, Figure 8c, where it slows due to inflow from the pressurizer. When the pressurizer empties, the pressure drops to about 2 MPa where it slows again due to boiling in the PHTS, Figure 8d. The PHTS stabilizes at low pressure and 10% void, an example of two-phase thermosyphoning.

4.2.4 Thermosyphoning

From the above sections we see that there are a variety of scenarios in which the primary coolant flow is not forced but must be buoyancy induced. These range from

a) loss of electrical power where the PHTS pressure is high (i.e., above nominal secondary pressure of 4.5 MPa) and the extent of void is small, to

b) the DBE where the system pressure is near atmospheric and a significant degree of boiling is possible.

Generally it is expected that a flow will continue over the top of the boilers induced by the buoyancy force arising from differences in coolant density. This is called thermosyphoning. (Another possibility is a reflux mode of two-phase flow between headers and boilers: steam from the core rises to the boilers where it is condensed and falls back in a countercurrent flow. Within a core pass individual channels would see a buoyancy-induced flow both in the normal and reverse directions.)

Thermosyphoning is of interest over a range of PHTS coolant inventories and secondary-side pressures (or temperatures). Core power is invariably at decay power levels -- no more than 3%. Thermohydraulic analysis is required to evaluate fuel temperatures for conditions under which the coolant boils in the fuel channel and the flow is low enough for the phases to stratify, or even to determine if such conditions exist.

At low pressure, because of flashing, PHTS void is concentrated near the boiler inlet plenum. Very low inventories have to be reached to get boiling within the fuel channel. At high pressures void is more uniformly distributed from fuel channel to boiler, so small losses of inventory can cause boiling within the fuel channel. Also flows are smaller because void in a fuel channel contributes to friction but not to the buoyancy force.

Figures 9 and 10 show the header-to-header pressure drop ΔP and flow, as a function of system void and secondary temperature, calculated for steady thermosyphoning conditions in CANDU at 2% power. Both ΔP and flow reach a maximum at about 20% system void. Thereafter void penetrates past the top of the boiler reducing the buoyancy head. Figure 11 shows the degree of subcooling at the RIH. Void is predicted in the RIH at a system void of 20 to 30%. At this point phase separation in the RIH would be expected to cause steam to accumulate in and pressurize the header. Thermosyphoning would be unlikely to continue.

Steady boiling in the fuel channel is possible for scenarios at high secondary temperature. Of particular interest are the more probable low void scenarios. The conditions are required under which steady stratified flow can be expected.

Give ΔP and ΔT from the system calculation (Figures 9 and 11), the channel flow depends on feeder geometry and channel power. The upper channels with highly orificed feeders have the worst combination of buoyancy head and friction factor so we consider these. For given geometry the flow will decrease as power decreases. Of interest is the power that just reduces the flow to the stratification threshold because this gives the highest fuel temperature: for higher power the flow is not stratified; for lower power the exposed pins have a lower rating. For a high elevation channel this power turns out to be 117 kW which <u>is</u> in the range of decay power.

Given inlet temperature, flow and power, the boiling point in the channel can be determined. Assuming stratification at this point, the exposed fuel pins will have the maximum possible heat flux. For low void scenarios, the point is calculated to be in the second fuel bundle from the downstream end and the temperature is conservatively calculated to be 580°C, a rise of 280°C from saturation temperature. Fuel damage is not expected at this temperature.

For the conditions of interest, two types of flow oscillation (channel and/or system) are possible depending on coolant inventory and secondary temperature. Periods range from 1 to 3 minutes and are governed by fluid transport time in parts of the circuit, depending on the type of oscillation. Amplitudes reach limit cycles where the channel flow is subcooled during the high-flow part of a cycle but stratified during the low-flow part of a cycle. The temperature rise of exposed fuel is not large (about 200°C even with an adiabatic assumption). With channel flows that, on average, would stratify, oscillations give periodic rewetting and therefore provide good fuel cooling. Flow oscillations are described in detail in Chapter 15 below.

4.3 Conclusions

Safety analysis of CANDU covers a wide range of scenarios. This chapter has given examples of overpower, loss of pumping and loss of heat sink scenarios. LOCA scenarios are the subject of Chapter 16.

The scenarios divide into a front end where trip coverage is important and into a long term where, if pumping is lost, thermosyphoning is important.

Thermohydraulic analysis is complete for these scenarios and the phenomenology is well understood. This has been accomplished using a three-equation transient thermohydraulics code supported by a large experimental program, a key component of which is the full-size testing of fuel channels.

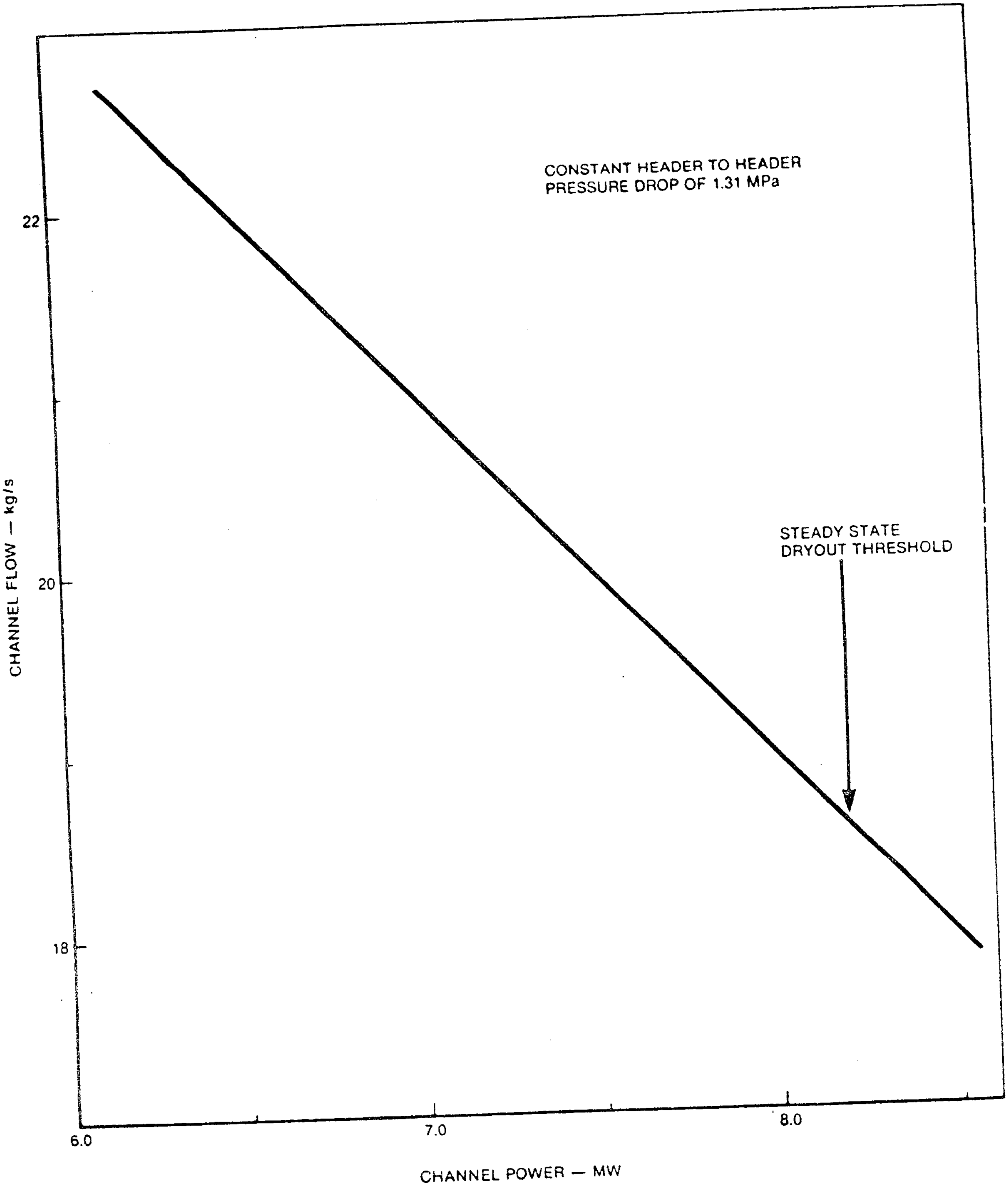

FIGURE 1 FLOW/POWER CHARACTERISTIC FOR CHANNEL L-11

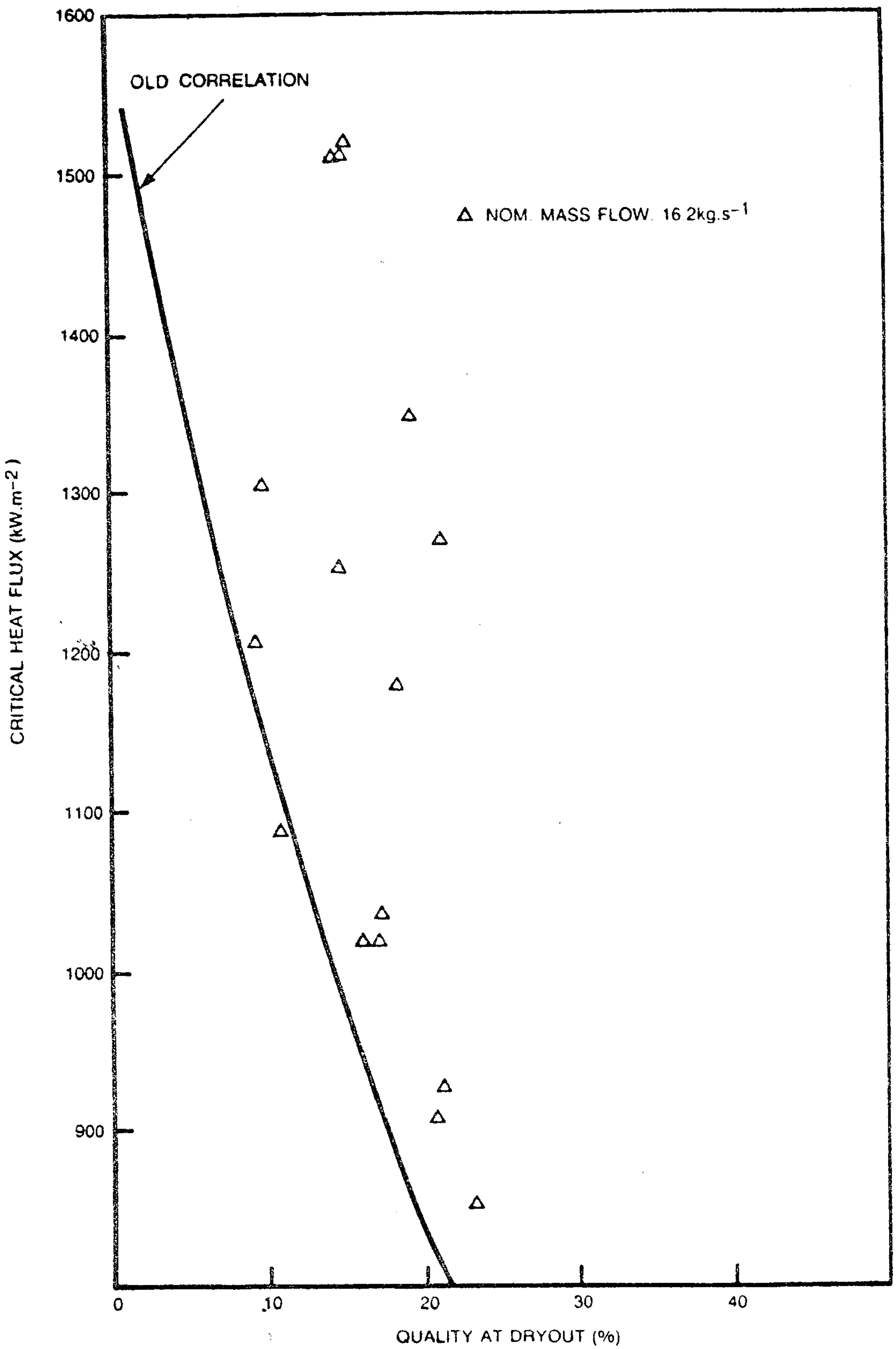

FIGURE 2 CRITICAL HEAT FLUX VS. QUALITY AT DRYOUT FOR NOMINAL OUTLET PRESSURE 9.65 MPa COSINE DATA

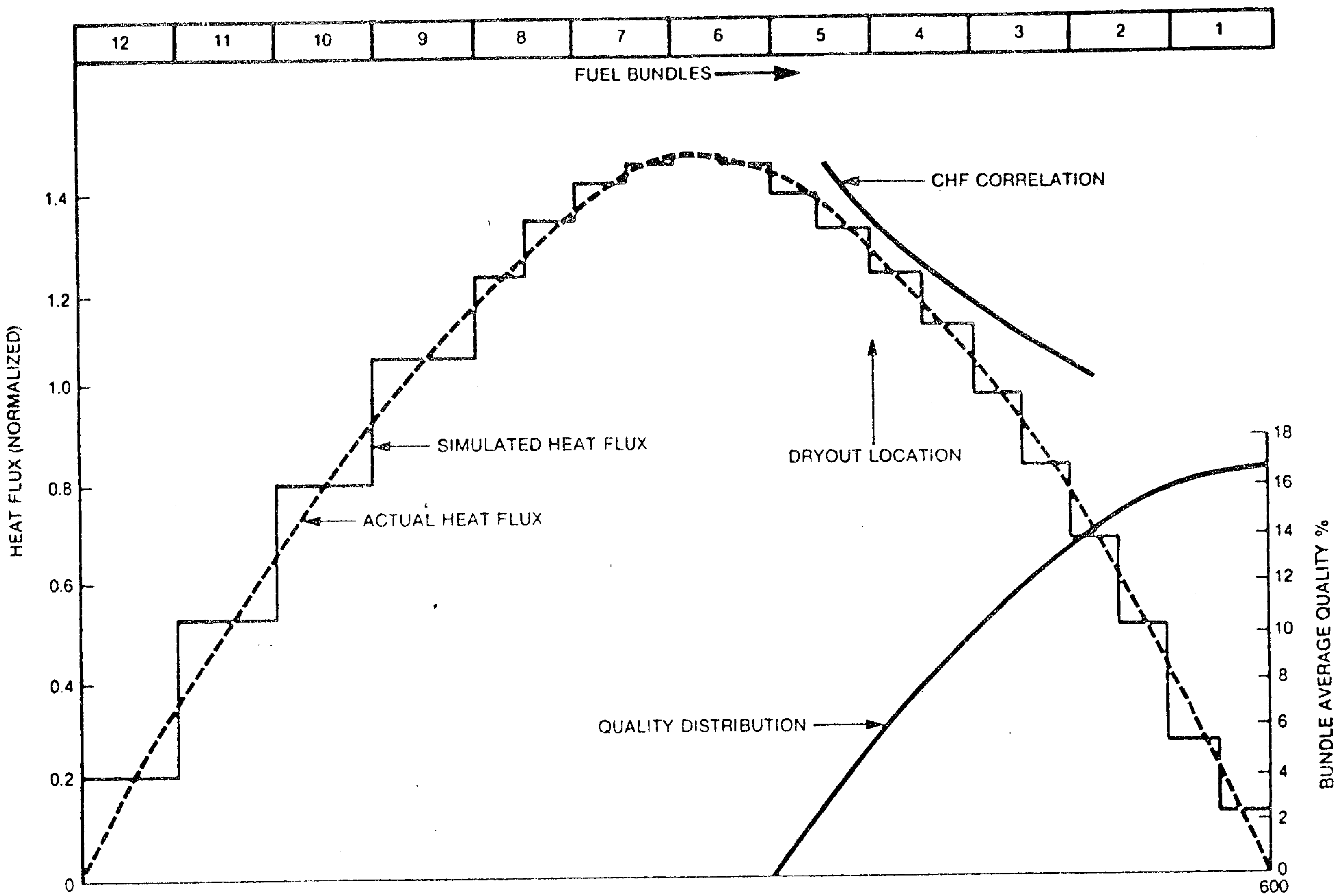

FIGURE 3 AXIAL FLUX AND QUALITY AT ONSET OF DRYOUT (SAMPLE CALCULATION)

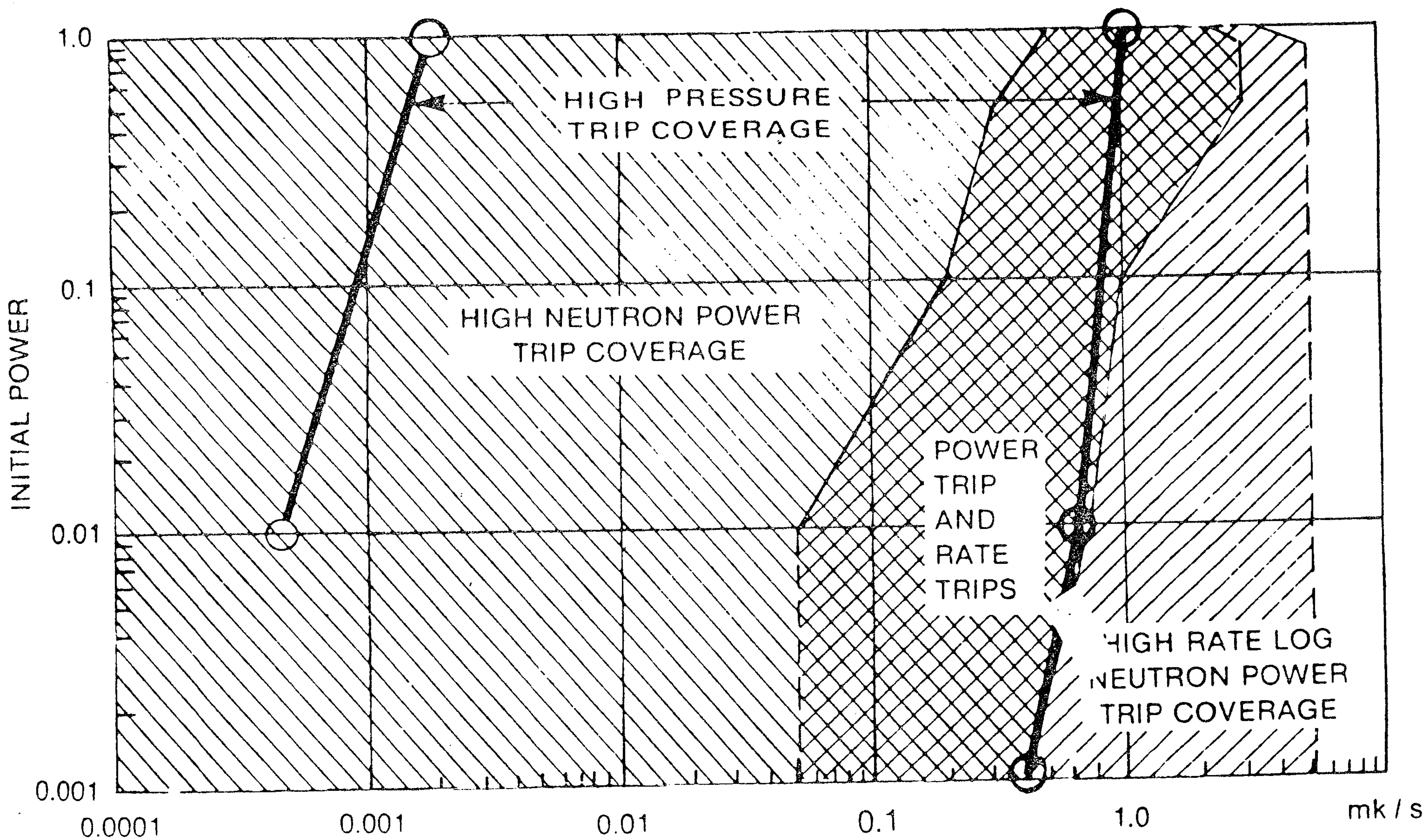

FIGURE 4 TYPICAL TRIP COVERAGE MAP

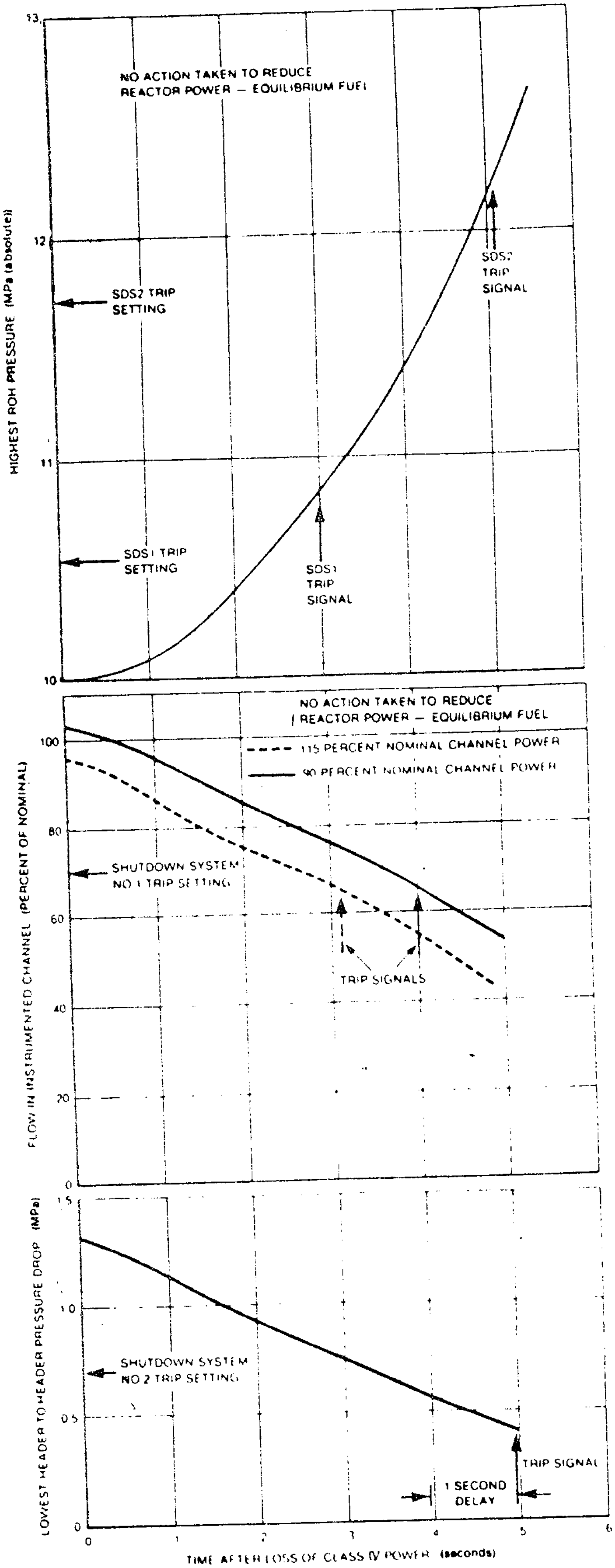

FIGURE 5 TRIP PARAMETER RESPONSE: LOSS OF CLASS IV

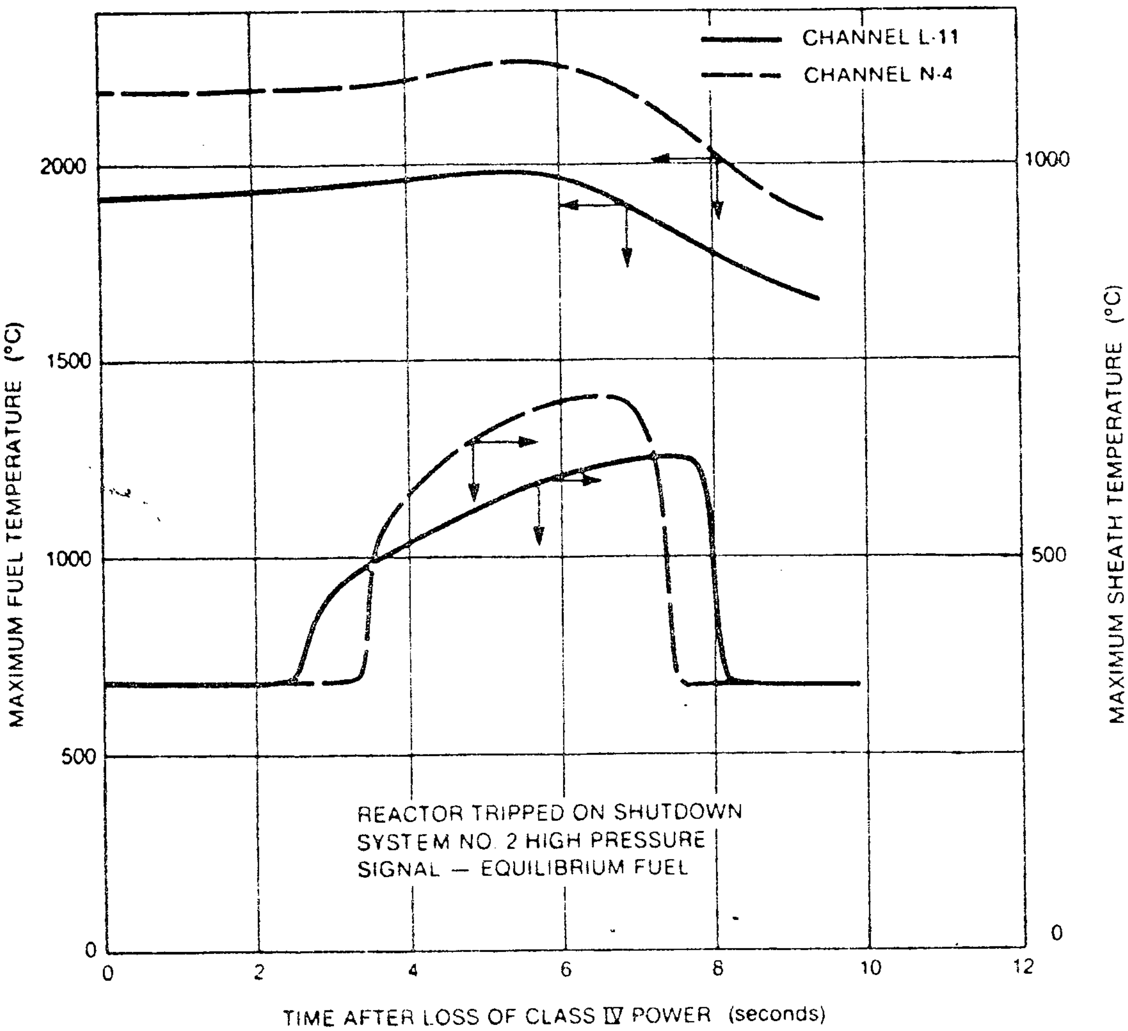

FIGURE 6 FUEL TEMPERATURE: LOSS OF CLASS IV

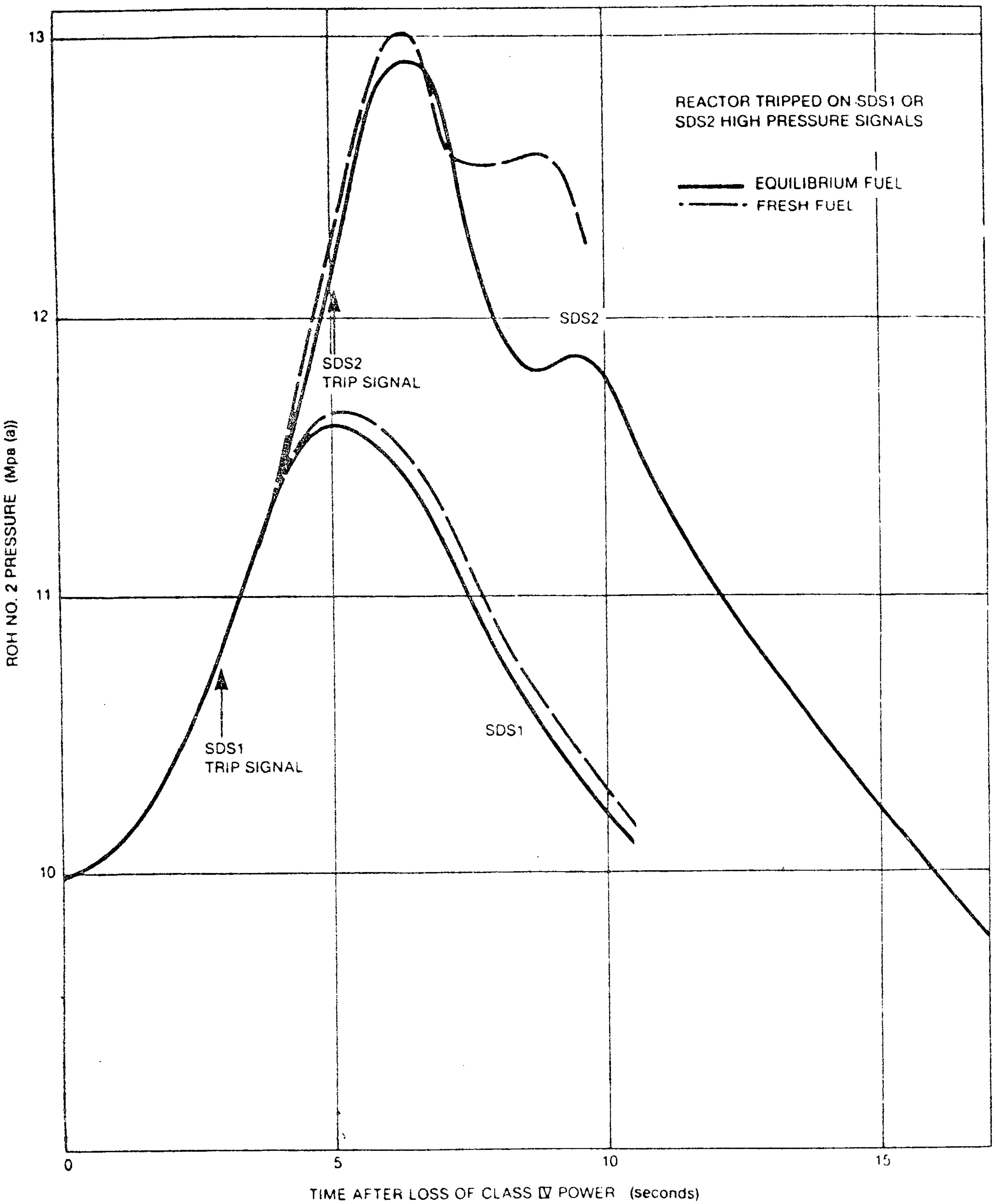

FIGURE 7 TRANSIENT PRESSURE FOLLOWNG LOSS OF CLASS IV POWER EVALUATION OF PEAK PRESSURE

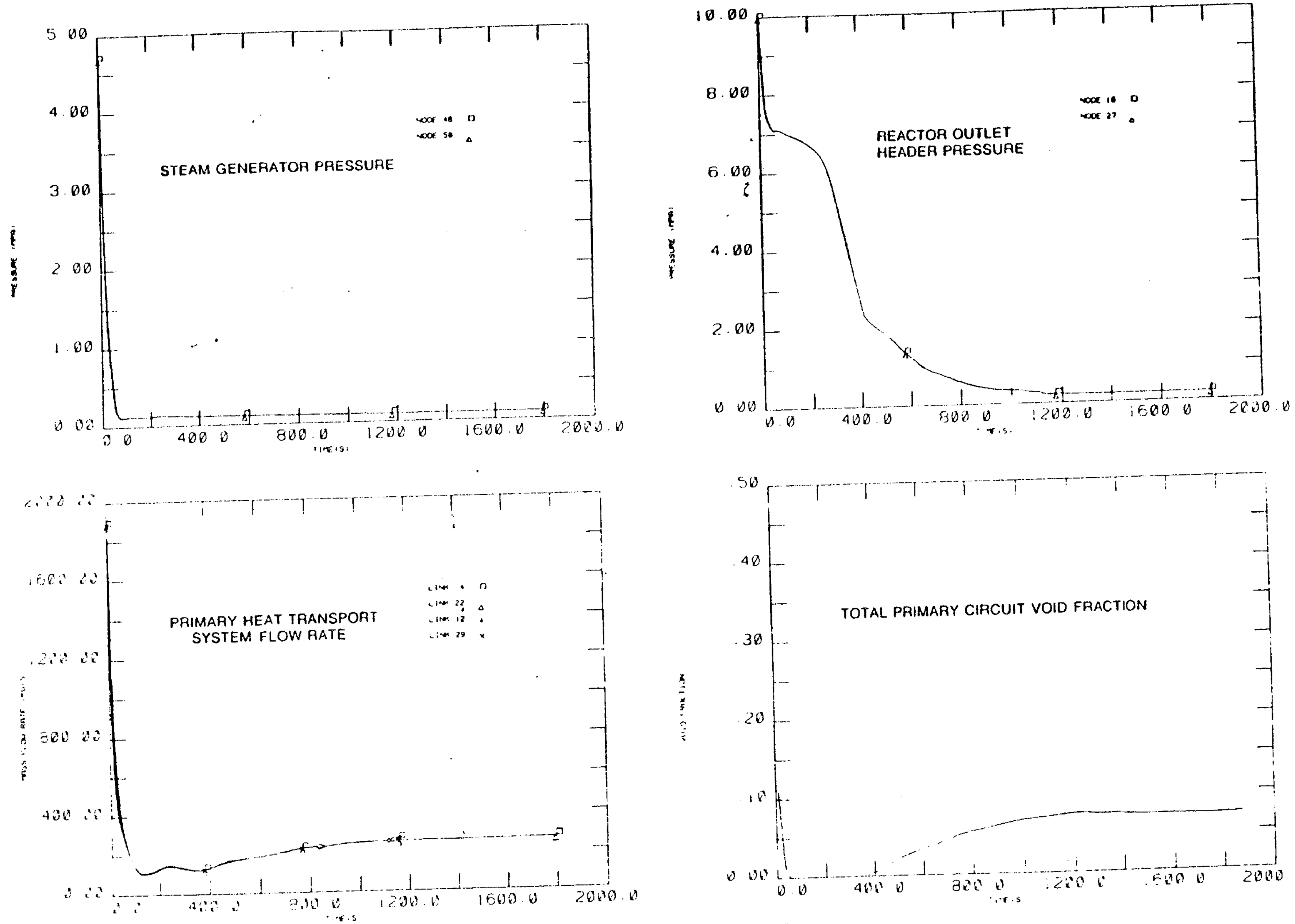

FIGURE 8 DBE ANALYSIS

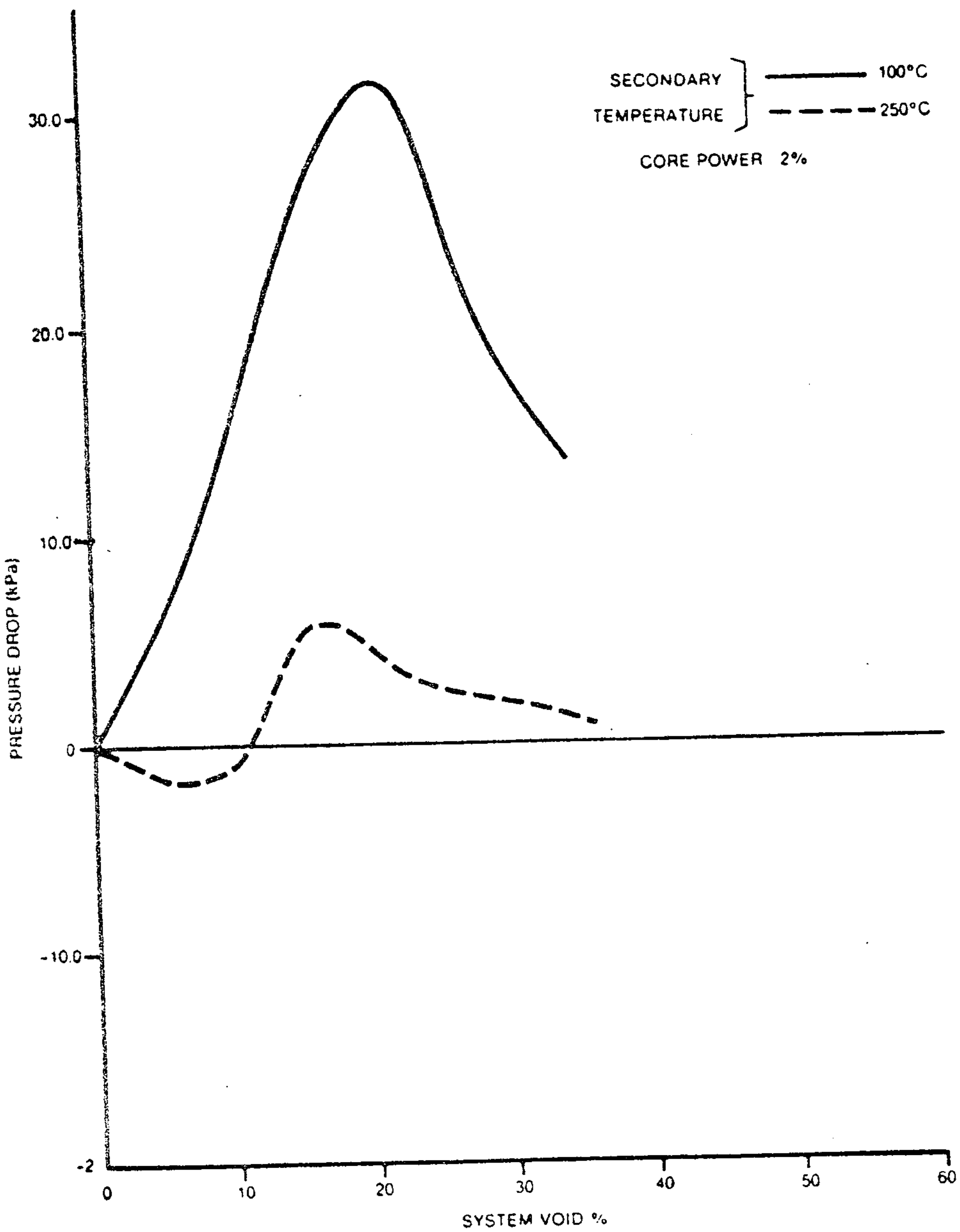

FIGURE 9 HEADER TO HEADER PRESSURE DROP IN TWO-PHASE THERMOSYPHONING

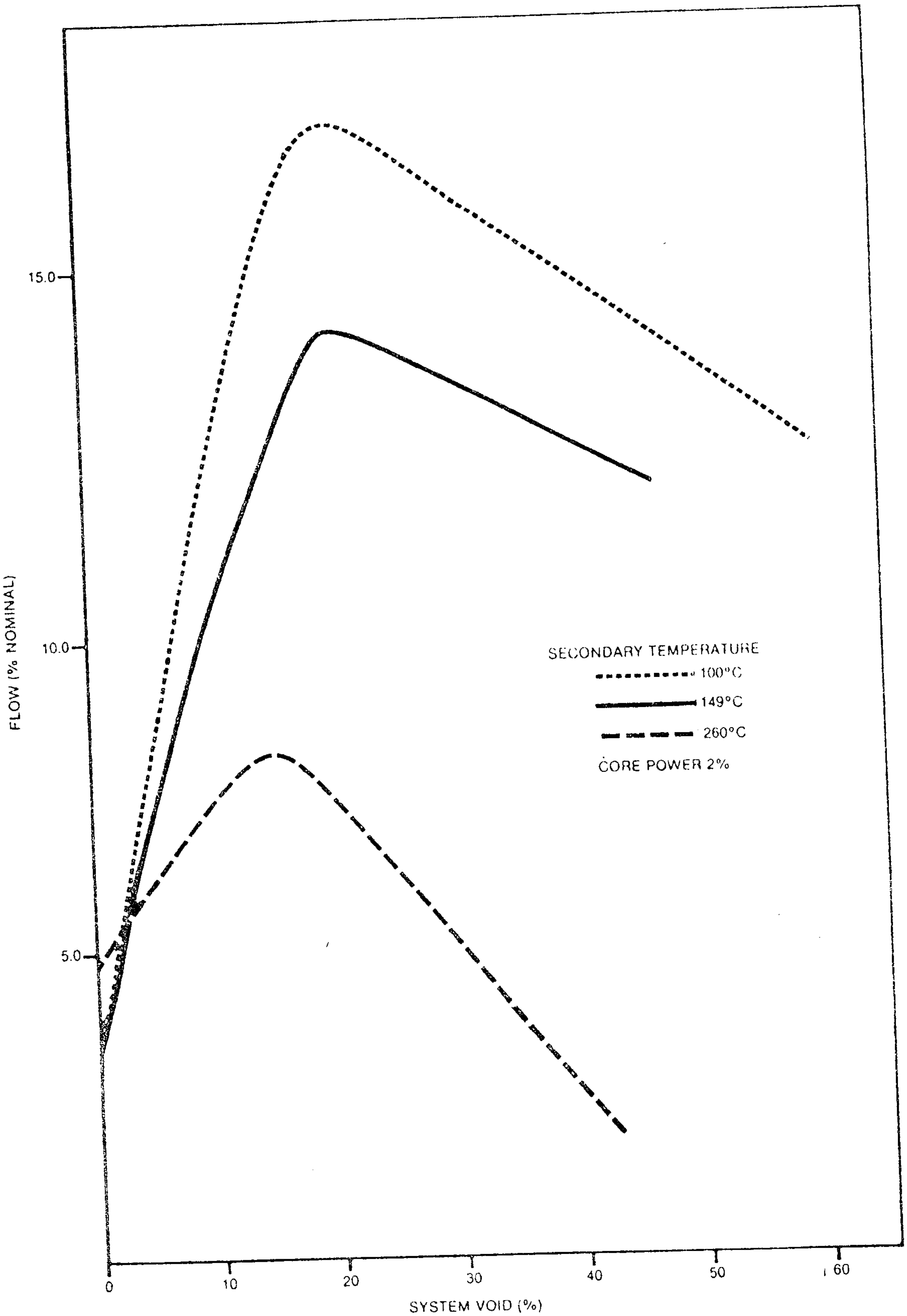

FIGURE 10 CANDU THERMOSYPHONING FLOW PREDICTIONS

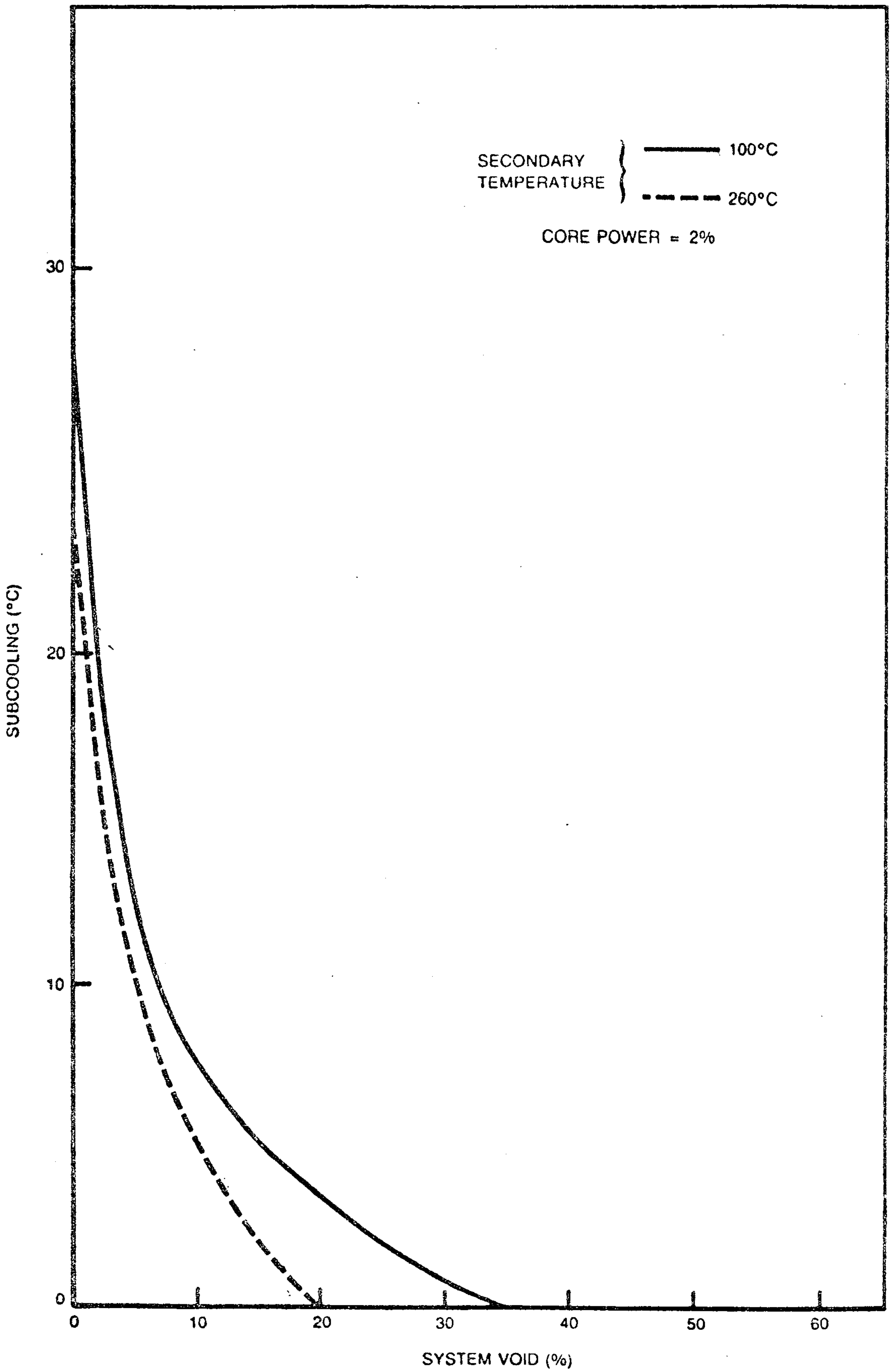

FIGURE 11 CANDU THERMOSYPHONING INLET SUBCOOLING