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ANALYSIS OF CRBRP STATION BLACKOUT USING SSC/MINET*

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DISCLAIMER

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ABSTRACT

A steam generator system transient analysis package (MINET), recently incorporated into the SSC code (a nuclear power plant systems analysis code), is reported. Essentially a code within a larger code, MINET is so named because it is based on a momentum integral network method.

After demonstrating good agreement with DEMO results for a transient where the capabilities of MINET had to be restricted, a transient will then be analyzed that more fully exercises its capabilities. This case is a station blackout transient with pony motors and auxiliary feedwater unavailable.

MODEL FUNDAMENTALS

Since the SSC code is being used extensively in the analysis of the Clinch River Breeder Reactor Plant (CRBRP), an analysis of the CRBRP steam generator system, using MINET, is reported. Plant transient data are generally unavailable for such advanced power plants, therefore, results from computer analysis of a CRBRP station blackout event, using the DEMO code, are shown. Comparable SSC/MINET analysis provided similar results, particularly when two specific DEMO assumptions were factored into the MINET calculations. A more extensive SSC/MINET analysis of a CRBRP station blackout event, with pony motors and auxiliary feedwater pumps unavailable, is also reported.

The MINET package interfaces with the SSC intermediate loop at points downstream of the IRX and upstream of the pumps, thus it includes the sodium side of the heat exchangers, as well as some connecting piping (see Figure 1). With few exceptions, the MINET representation is a closed system, accessed through the boundary modules. The exceptions are control system related components, e.g., pumps and valves. Boundary modules on the intermediate loop side interface only with the intermediate loop parameters and are inaccessible to the user.

INTRODUCTION

In MINET, a system is represented as a network of accumulators, segments, and boundaries. Accumulators are used to represent tanks and other voluminous components, as well as locations in the system where significant flow divisions or combinations occur. Segments are composed of one or more pipes, pumps, heat exchangers, and valves, each represented by one or more nodes. Boundaries are simply points where the network interfaces with the user or another part of the SSC code.

A new steam generator system transient analysis package (1), based on a momentum integral (2) network method, has been incorporated into the Super Systems Code (SSC)(3), a nuclear power plant systems analysis code. The principal features of the new SSC steam generator analysis package, named MINET (1), will be described in this paper.

Equations conserving mass and energy are used to calculate the pressure and enthalpy within accumulators. An integral momentum equation is used to calculate the segment average mass flow rate. In-segment distributions of mass flow rate and enthalpy are calculated using nodal mass and energy conservation equations. The segment pressure is taken to be the linear average of the pressure at both ends.

The SSC code was developed by Brookhaven National Laboratory (BNL) for the Nuclear Regulatory Commission (NRC), principally for the licensing analysis of liquid metal fast breeder reactor (LMFBR) plants. As the availability of transient data for LMFBR plants is quite limited, SSC code validation for steam generator systems currently depends largely on comparisons to results generated using other computer codes. The "data" against which SSC/MINET results are compared in this paper were generated using the DEMO code (4), which was developed specifically to represent the Clinch River Breeder Reactor Plant (CRBRP).

In MINET, the basic momentum integral network method is supplemented by generic models of the various component types. In the representation of the intricate relationship between the pump head, the relative

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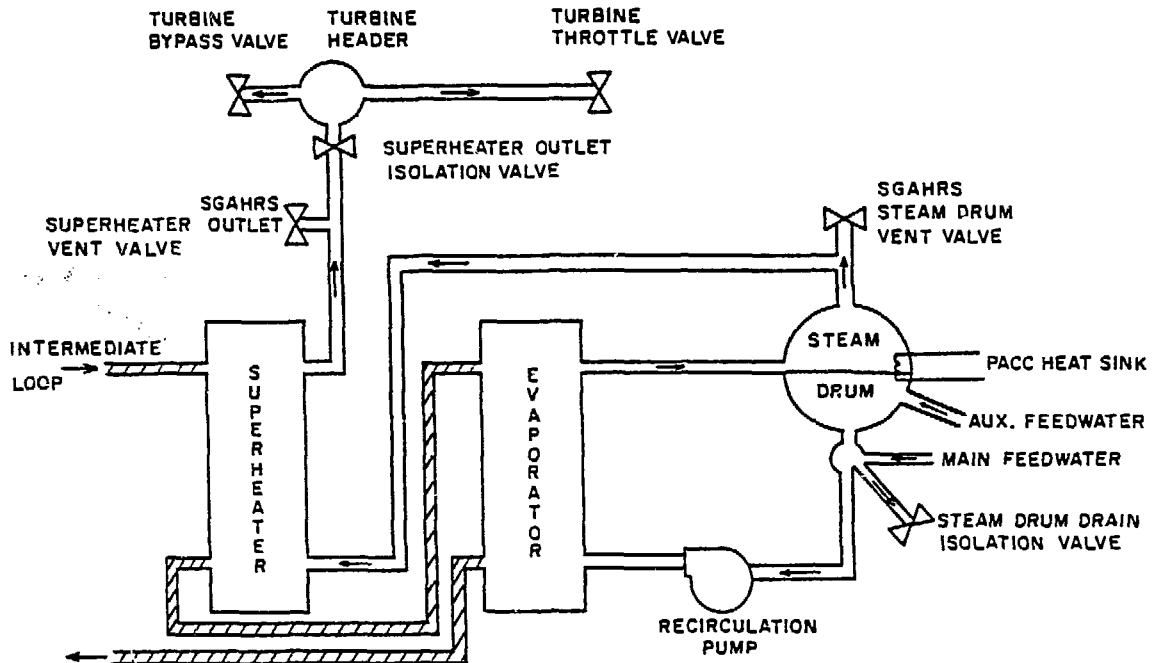


Figure 1. CRBRP Steam Generator System Used in SSC/MINET Analysis

pump speed, and relative mass flow rate, quadratic characteristics are assumed. Valves are represented using form losses if flow is unchoked, or by the Henry-Fauske (5) or Moody (6) choke flow models. Heat exchangers are analyzed using fixed length nodes and moving levels within the nodes to track the interfaces between water/steam side heat transfer regimes. Accumulator contents are assumed to be either homogeneously distributed or separated into saturated fluid and vapor regions, as indicated through user input.

STEADY STATE CALCULATIONS

Steady state calculations are performed largely by two new "network solvers", one for enthalpies and energy transfer, the other for pressures and mass flow rates. An outer level of iteration is used to insure consistency between the results of the two network solvers.

In preparation for the enthalpy and energy transfer network solver, the system is first divided into subsystems, each of which must transfer a given amount of energy for equilibrium to be maintained at current mass flow rates and pressures. This sub-system analysis, supplemented by the assumption that the total energy transferred across a heat exchanger is proportional to the available heat transfer area, determines the amount of energy to be transferred across each heat exchanger. In the enthalpy and energy transfer network solver, the accumulator enthalpies, segment inlet and outlet enthalpies, segment energy transfers, and sub-system energy transfers, are solved simultaneously.

The next step is to march through the segments, evaluating pressure losses. As the elevation heads in the heat exchangers depend on the enthalpy distribution, it is necessary to initialize those units at this

time. Discrepancies between the total energy transfer as indicated by heat transfer correlations, and that indicated by the enthalpy and energy transfer network solver, are resolved using a heat transfer area correction factor. Segment mass flow rate, inlet and outlet pressure, accumulator pressure, flow rate at outlet boundary modules, and pressure at inlet boundary modules, are then calculated in the second network solver.

TRANSIENT ANALYSIS

In MINET, transient analysis is performed at two levels, the segment level and the global (accumulator) level. First the response of each segment to potential changes in the bordering modules is determined and stored in the segment response matrices. These matrices are used in conjunction with the boundary conditions and current accumulator conditions to simultaneously advance enthalpies and pressure for all accumulators on one side of the network. Segment parameters are then advanced.

The first step in determining the segment response matrices is to march through the flow segment, loading the segment matrix equation. The equations loaded determine the response of the nodal interface enthalpies and mass flow rates to changes in enthalpy and pressure in the modules connecting to the inlet and outlet of the segment. Thus, for a segment with N nodes, and therefore $N+1$ nodal interfaces, a total of $2N+2$ equations are needed to constrain the mass flow rates and enthalpies. Of the $2N+2$ equations loaded, N nodal mass conservation equations and 1 momentum (or choked flow limit) equation are invariably loaded. The remaining equations are donor-cell differenced nodal energy equations and segment inlet boundary conditions, with the number of each dependent on flow conditions in the segment (1). The segment matrix equation is then

solved for the segment response matrix, which, when multiplied by changes in enthalpy and pressure in the modules bordering the segment, defines the enthalpies and mass flow rates for all nodal interfaces in the segment. Segment response matrices are determined for all segments on a network side before accumulator pressures and enthalpies can be determined.

Conservation equations for mass and energy in each of the accumulators on one side of the network are coupled in a matrix equation. The segment response matrices are used in the loading process to determine the mass flow rates and enthalpies entering and exiting the accumulators. The accumulator matrix equation is then solved for changes in accumulator enthalpies and pressures. Changes in pressures and enthalpies in the accumulator and boundary modules are then used to multiply through the segment response matrices and advance the nodal interface enthalpies and mass flow rates.

COMPARISON WITH DEMO FOR SIMPLE STATION BLACKOUT

The DEMO analysis of a CRBRP station blackout transient has been previously performed and reported by Perkins, et. al.(7). During the first second of this run, the pumps trip, the reactor scrams, and the turbine throttle valve closes. The turbine bypass valve opens at about 4 seconds, and the auxiliary feedwater comes on at about 44 seconds. There are no steam generator auxiliary heat removal systems (SGAHRs) vent valves, Protected Air Cooled Condensers (PACC), or superheater outlet isolation valves in this analysis. Results from this run are summarized in Figures 2a -2f.

As the principal goal in the SSC/MINET analysis of this transient was an inter-code comparison, efforts were made to match the DEMO input. Thus, the feedwater flow rate and temperature, the intermediate pump inertia, and recirculation pump ramp-down rates were matched, as were the initial conditions. Since some of the DEMO models in the turbine and turbine bypass areas had no equivalent in MINET, the turbine header pressure from the DEMO run was used as an input boundary condition for MINET.

When SSC/MINET was used to analyze the same transient, the results resembled those generated by DEMO, as can be seen in Figures 3a - 3f. The feedwater flow rate and temperature, the turbine header pressure, and the intermediate loop flow and superheater inlet temperature are effectively boundary conditions. Differences in steam drum pressure and level, superheater flow, and evaporator outlet temperature are due largely to the compression and thermal expansion in the evaporator, accounted for in MINET and neglected in DEMO. The differences in the water side evaporator inlet temperature and intermediate side evaporator outlet temperature result from the DEMO assumption that the feedwater mixes in at the evaporator inlet. The sources of these differences were verified by running MINET with incompressible flow in the pipes and heat exchangers and the feedwater injection at the evaporator inlet. Results from this run (9) were very similar to the DEMO results shown in Figures 2a-2f.

Even though true validation of one computer code using another is impossible, it can still reveal problems of a gross nature, such as coding errors. To this degree, it is clear that the new MINET package is unlikely to contain serious errors, and a reasonable level of credibility can be attached to its analysis.

SSC/MINET ANALYSIS OF STATION BLACKOUT WITHOUT AUXILIARY FEEDWATER

There have been several changes in the control systems for CRBRP since the release of DEMO, revision 4 (4). Many of these changes were included in the analysis of the first eight minutes of a CRBRP station blackout transient with auxiliary feedwater unavailable. The representation used in this analysis is as shown in Figure 1 and the results are summarized in Figures 4a - 4f.

The transient initiates with a loss of electric power, tripping the primary, intermediate, recirculation, and feedwater pumps, and scrambling the reactor. Soon thereafter, the turbine throttle valve closes, the steam generator auxiliary heat removal system (SGAHRs) activates the PACC system and SGAHRs vent valves, and closes the superheater and steam drum drain isolation valves, and the turbine bypass valve opens. It is assumed that pony motor driven pumps in the primary and intermediate loops, as well as the auxiliary feedwater pumps, are unavailable.

Mass flow rates (per loop) for the primary and intermediate loops are shown (Figure 4a) to be decreasing exponentially until the pump rotors lock at one minute. Core outlet temperatures (4b) decrease initially, and then increase until the three minute mark, when the power decreases to the point where natural circulation flow becomes sufficient to remove the heat. However, as can be seen in Figure 4c, due to transport delays, the superheater inlet temperature is not affected by the primary loop during the first eight minutes of the transient, except by its influence on the intermediate loop mass flow rate.

On the steam generator side, the system is largely isolated once the superheater outlet isolation valve closes (5 seconds). From this time on, essentially no flow is entering and the only flow exiting is through the SGAHRs vent valves. A limited amount of heat is also removed through the PACC, as simulated by a heat sink term in the steam drum. Notable periods in the transient occur at 30 seconds when the SGAHRs vent on the steam drum closes (Figure 4d), at two minutes when the reduced quality evaporator outlet flow, resulting from proportionately higher natural circulation flow on the water side, reaches the steam drum and drops the pressure, and at eight minutes when the steam drum water inventory is exhausted. It is noted that the control strategy according to the CRBR project office (9) is to use only the superheater outlet SGAHRs vent valve after the initial part of the transient. With respect to the steam drum going dry at 8 minutes, an approximate net of 22 metric tons of water/steam leaves the steam generator system during those 8 minutes, which is consistent with an initial inventory of 23 metric tons of liquid in the three steam drums. Furthermore, there are several similarities, between the SSC analysis and the DEMO analysis recently published (10) for a station blackout transient with auxiliary feedwater available.

SUMMARY AND CONCLUSIONS

A new steam generator system analysis package, called MINET, has been incorporated into the SSC code. The momentum integral network method employed is sufficiently flexible to allow the user to build the system representation required to adequately monitor a given transient. A simplified station blackout transient, as analyzed by DEMO, was replicated. It was

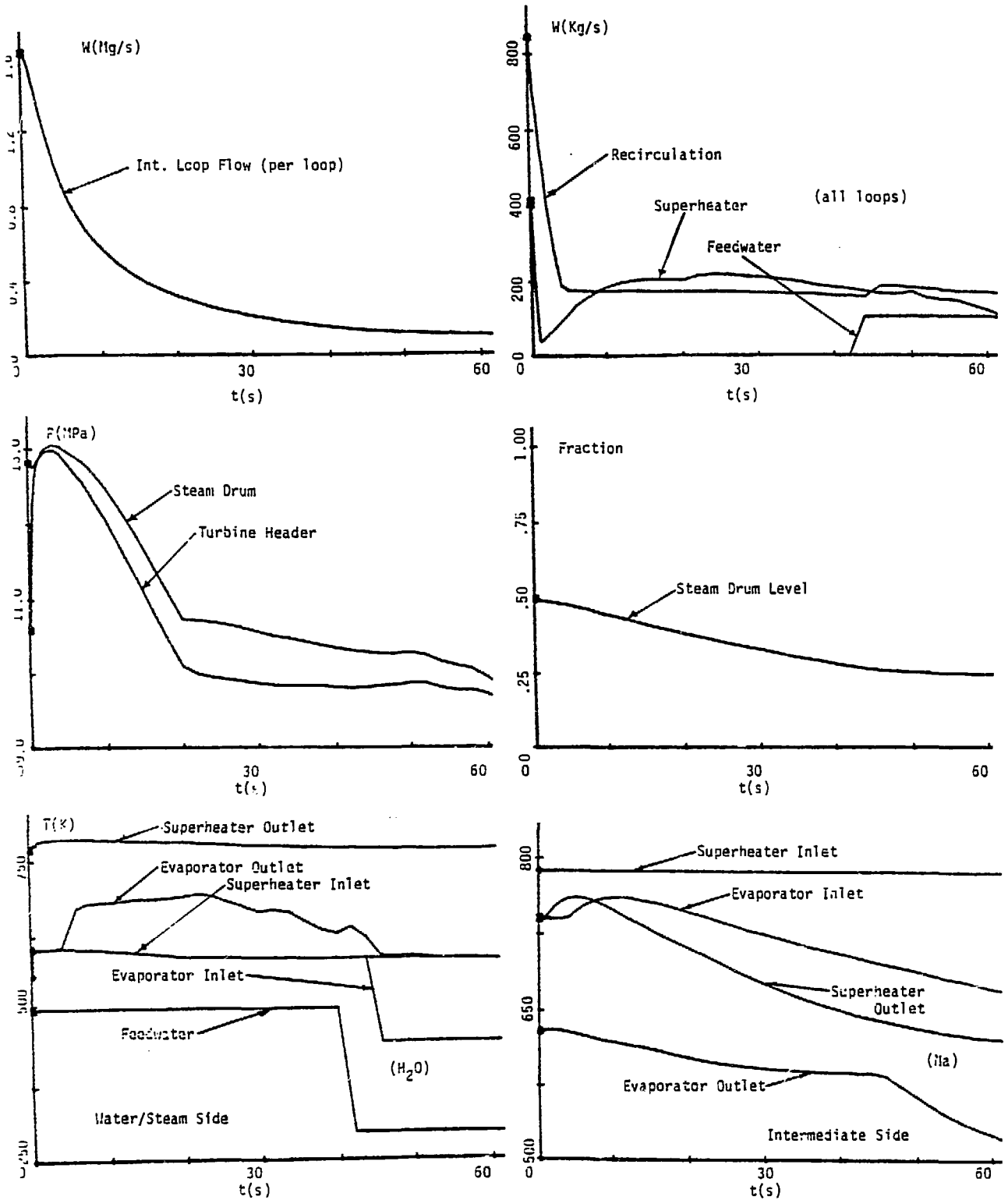


Figure 2. DEMO, Rev. 4 Analysis of CRBRP Station Blackout

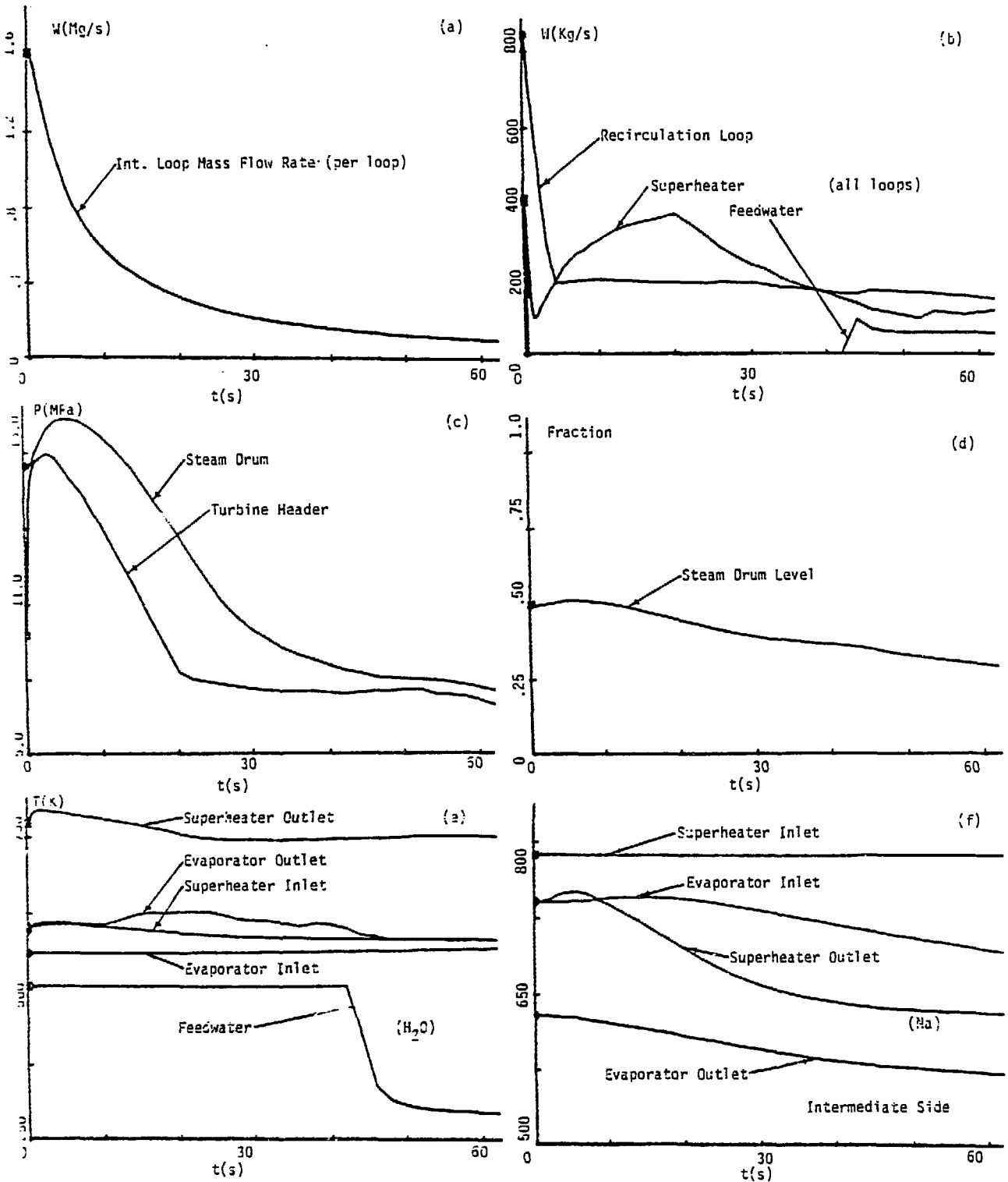


Figure 3. SSC/MINET Analysis of DEMO, Rev. 4 Version of CRBRP Station Blackout

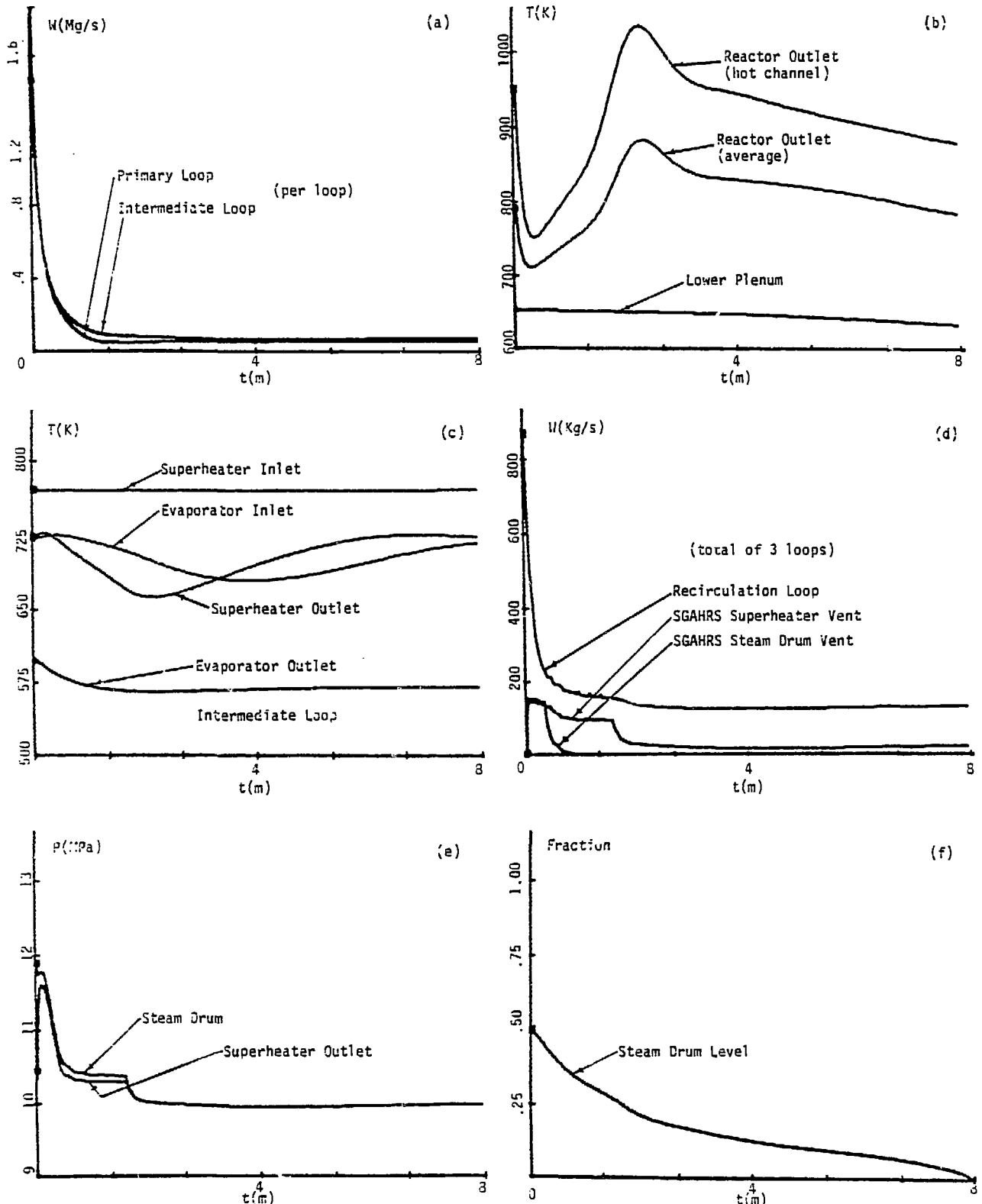


Figure 4. SSC/MINET Analysis of CRBRP Station Blackout Without Auxiliary Feedwater

found that differences in the results could be traced to two DEMO assumptions of marginal validity under the conditions simulated. These assumptions, namely incompressible flow in the recirculation loop and feedwater injection at the evaporator inlet, are quite acceptable for near equilibrium conditions, but clearly in error during active transients when examined in a short time frame. The SSC/MINET analysis of a related transient, factoring in current control systems and strategies, provide plausible results that tend to support some of the CRBRP project office calculations.

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