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**MINET VALIDATION STUDY  
USING EBR-II TEST DATA**

**Gregory J. Van Tuyle**

**Date Published — November 1983**

**CODE DEVELOPMENT, VALIDATION AND APPLICATION GROUP**

**DEPARTMENT OF NUCLEAR ENERGY, BROOKHAVEN NATIONAL LABORATORY  
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# MINET VALIDATION STUDY USING EBR-II TEST DATA

Gregory J. Van Tuyle

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## Abstract

A natural circulation test transient performed at the EBR-II facility is simulated using the MINET computer code, and calculated results are compared against data from the plant. The MINET EBR-II representation includes much of the intermediate loop and the steam generator system, and corresponds to the portion of the plant usually represented by MINET when it is executed with SSC, the Super System Code. MINET calculations agreed well with the plant transient data, with discrepancies well within uncertainties in thermocouple time constants and boundary conditions.

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Thanks also go to BNL people who helped with the MINET code and this report. Mr. Thomas Nepsee wrote the input processor and several data management routines for MINET. Mr. Robert Kennett helped plot the results, and prepared the camera ready figures for this report. Mr. Jaime Guillen, a student intern from the Massachusetts Institute of Technology (MIT), aided in developing the input data deck and performed some of the early testing of the stand-alone MINET. The report was typed by our excellent secretary, Mrs. Carmen Falkenbach.

## 1. INTRODUCTION

MINET is a computer code designed for the transient analysis of fluid flow and heat transfer networks. The underlying methodology is well suited for the analysis of complex systems, such as are found in the balance of plant of power generating facilities. Models for balance of plant components, such as turbines and condensers are currently being added to the code.

Two versions of MINET are currently in use, one that executes with the SSC code [1], designated Version 0, and one that executes in stand-alone mode, designated Version 1. Version 1 was created from Version 0, and currently has far greater flexibility than Version 0.

The principal utilization of SSC/MINET has been in the analysis of a generation of LMFBR plants entering the construction phase, including the Clinch River Breeder Reactor (CRBR), the German SNR-300, and the Japanese MONJU plants. It has also been applied by various external users for design studies, a role that could be expanded, depending on the future developments with CRBR and proposed commercial size plants.

In order to establish that the use of SSC/MINET for such analysis is justified and reliable, it is necessary to perform a series of validation studies. SSC and Version 0 of MINET have both passed various analytical checks and inter-code comparisons, establishing that the codes are performing as intended. In addition, SSC has been validated using a series of test transients from the Fast Flux Test Facility (FFTF) [2]. Since FFTF has no steam generator system, this validation study did not test Version 0 of MINET. Thus, prior to the EBR-II analysis, only the MINET heat exchanger module had been tested against experimental data [3].

This is the initial validation study for Version 1 of MINET, after a significant period of development. For the EBR-II representation used in this test, Versions 0 and 1 are nearly identical, which makes this an excellent test of the successful transition to the stand-alone MINET.

The Experimental Breeder Reactor II (EBR-II) is a 62.5 Mwt sodium cooled reactor and power plant that was completed in 1964. It has a steam generator system that resembles the one planned for CRBR. Thus, transient data from EBR-II is very useful in validating MINET for the analysis of CRBR.

The EBR-II test transient analyzed involved a coastdown to natural circulation from 36% full power and 39% full primary flow. This test was chosen because of its reliance on decay heat removal via the natural circulation mode, a type of transient of particular significance in LMFBR systems. Test data from this transient for comparison against computer code results were made available to us by ANL staff [5].

In the study detailed in this report, both versions of MINET were used to simulate the transient. The portion of the EBR-II system represented corresponds to the part that MINET represents when executed with the SSC code. In the test using Version 0, code updates were used to isolate MINET from SSC at the start of the transient. Thus, in both simulations, the intermediate loop flow and the intermediate heat exchanger (IHX) outlet temperature were inferred from experimental data and input as transient boundary conditions. Results from the stand-alone MINET are shown in the plots, although the two versions gave nearly identical results.

## 2. MINET

MINET (Momentum Integral NETWORK) is a computer code developed for the transient analysis of intricate fluid flow and heat transfer networks, such as those found in the balance of plant in power generating facilities. It can be utilized as a stand-alone code, or interfaced to another computer code for concurrent analysis. Through such coupling, a computer code currently limited by either the lack of required component models or poor computational speed can be extended to more fully represent the thermal hydraulic system, thereby reducing the need for estimating essential transient boundary conditions.

### 2.1 Momentum Integral Network Method

The method employed in the MINET code is a major extension of a momentum integral method developed by Meyer [6]. Meyer integrated the momentum equation over several linked nodes, called a segment, and used a segment average pressure, evaluated from the pressures at both ends. Nodal mass and energy conservation determined nodal flows and enthalpies, accounting for fluid compression and thermal expansion.

In MINET, a network structure was built around Meyer's momentum integral model for the flow segment. In this extended method, a system is represented using one or more flow networks, connected to one another only through heat exchangers. Each network is composed of segments, accumulators, and boundaries. Segments contain one or more pipes, pumps, heat exchangers and valves, each of which is represented using one or more nodes. Accumulators represent voluminous components and significant flow junctions. Accumulators and boundaries are connected by segments.

In systems which can be represented by MINET, heat exchangers are frequently shared by segments in two networks, with the flow from one segment passing through the tubes and the flow from the other passing on the outside. In order to decouple these segments during a transient time step, the tube temperatures are treated explicitly in the heat transfer calculations, and are not advanced until the end of the step.

With the segments and networks thus decoupled, MINET transient calculations proceed in a three step process, repeated for each network. The initial step is to march through the network segments, loading the segment matrix equation

$$\underline{\underline{A}}_S \underline{x}_S = \underline{\underline{B}}_S \underline{y}_S \quad , \quad (1)$$

and solving for the segment response matrix,  $\underline{\underline{B}}_S'$  ( $=\underline{\underline{A}}_S^{-1} \cdot \underline{\underline{B}}_S$ ). For a segment  $s$  with  $N_S$  nodes,  $2N_S+2$  linearized equations are loaded, including  $N_S$  nodal mass conservation equations, a segment momentum equation, and a total of  $N_S+1$  donor-cell differenced nodal energy equations and segment inlet enthalpy boundary conditions. Vector  $\underline{x}_S$  contains nodal interface enthalpies and flows, and vector  $\underline{y}_S$  includes changes in enthalpy and pressure in the modules at the segment ends.

The second step is to march through the network accumulators, loading the network matrix equation

$$\underline{\underline{C}}_n \underline{v}_n = \underline{D}_n \quad , \quad (2)$$

and solving to advance accumulator enthalpies and pressures. For a network  $n$  with  $N_n$  accumulators,  $N_n$  conservation of mass and  $N_n$  conservation of energy equations are loaded. The terms for the mass and energy entering and exiting the accumulators are evaluated using the segment response matrices,  $\underline{\underline{B}}_S'$ , thereby linking the accumulators.

The final step is to march through the network segments, using the solution from Eq. 2 to determine vector  $\underline{y}_S$ . The segment response matrix,  $\underline{\underline{B}}_S'$ , is then multiplied by  $\underline{y}_S$ , and the nodal interface enthalpies and flows are advanced. After segment conditions are advanced in all networks, the heat exchanger tube temperatures are advanced.

Two features of the method account for the flexibility and speed of MINET. First, segment nodes connect only to immediately adjacent nodes, causing matrix  $\underline{\underline{A}}_S$  to be banded, except for the momentum equation. This allows the storage of matrix  $\underline{\underline{A}}_S$ , and the solution of Eq. 1, in close-packed form, i.e., with large blocks of zeroes suppressed. Thus, the complexity of

the flow network is absorbed entirely in Eq. 2, where the matrices are lower order. Second, because a segment average pressure is used, saturation properties are evaluated only once per segment per step.

## 2.2 Component Models

While the momentum integral network method forms the basis for the MINET code, several component models, called "modules", are used to determine key parameters in the basic conservation equations. These parameters include the heating term in the energy equation and the pressure loss term in the momentum equation.

### Segment Components

Segment components include pipes, pumps, heat exchangers, and valves. Each representative module contributes pressure "losses" to the segment momentum equation.

Pipes. Pipes are the simplest component to represent. Pressure losses due to friction, gravity, acceleration, and form (i.e., obstructions) are calculated. Module heating or cooling is user-input as a function of time.

Pumps. Pumps are essentially one node pipes with an additional pressure "loss" term due to the pump head. Coefficients for the pump head as a fourth order polynomial fitted function of the pump flow rate, at a reference pump speed, are input by the user. A family of curves is implied for all pump speeds, based on the assumption that the head varies with the square of the pump speed. The pump speed is presently determined in one of three ways: 1) a user-input value vs. time table, 2) a simple coastdown model, or 3) a control system calculation.

Valves. Valves are basically one node pipes, with an additional pressure loss term due to the drop across the valve opening. The user has the option of ignoring the possibility of critical flow at the valve orifice, or using critical flow models by Henry-Fauske or Moody to place an upper bound on the flow passing through the valve. If critical flow is anticipated, the valve must be isolated in a segment by itself, as the imposition of a local choked flow limit is in conflict with the segment integral momentum equation.

The valve position can be: 1) user-input as a function of time, 2) calculated in response to pressure (safety/relief) or flow (check), or 3) determined by a control system calculation.

Heat Exchangers. Heat exchangers are treated as two pipes linked via heat transfer through the tube wall. The heat transfer from the tube to the fluid is calculated at each time step and used in the nodal energy equations. A fixed mesh nodalization is used, with any change in heat transfer regime within nodes factored into the nodal heat flux calculation, i.e., heat flux is piecewise averaged.

There are several heat exchanger designs in use, particularly if one includes the experimental units, which provide much of the transient data needed for code validation. A number of options are available in MINET, including parallel- and counter-flow; straight and helical tubes; and coaxial, square, and hex (triangular pitch) tube configurations. Another important design, the U-tube is being studied, and improvements will be incorporated to allow representation of these units.

Accumulators. Accumulator computational modules are used to represent voluminous system components, as well as locations in a network where pressure must be accurately monitored, e.g., significant flow junctions. For example, one would use one or more accumulators (connected by short, wide pipes) to represent a pressurizer or steam drum, or for a header between flow paths of unequal resistance. Currently, one can specify the geometry as a box shape, a vertical or horizontal drum, or a partial box or drum, as well as the operating conditions, i.e., whether the contents are distributed homogeneously or, if saturated, divided into liquid and vapor regions.

Boundaries. External interfaces to the MINET system representation are provided through the boundary modules. At each boundary, two conditions are required: 1) pressure or flow, and 2) temperature, enthalpy, or quality (if saturated). These are supplied by the user or by another computer code. Generally, the temperature parameter will be used in the MINET calculations only when flow is entering the system. The exception to this rule is that the user can fix the temperature at an outlet boundary during the steady state, provided that some heating source is available for adjustment by MINET. MINET will always calculate the unspecified flow/pressure parameter and the temperature

of the flow exiting the system, save for the one exception where the temperature is fixed by the user. With regard to pressure and flow, the user must provide the pressure at outlet boundaries and the flow at inlet boundaries for the steady state calculations. There is no restriction as to which parameter is specified for the transient calculations. The steady state restriction may be relaxed in future versions of MINET.

Turbines. There is no turbine model currently in MINET, but one is planned for incorporation in the near future.

### 2.3 Constitutive Relations

In addition to the basic MINET method and the supporting component models, various constitutive relations are needed for fluid properties and heat transfer. Currently MINET contains properties and correlations for water/steam, air, sodium, and eutectic NaK.

Because of the complexity introduced by phase changes, this package of functions for water and steam is the most extensive. The property functions are based on polynomial fits of the 1967 ASME steam tables. The heat transfer correlations include those for subcooled convection, subcooled nucleate boiling, forced convection vaporization, film boiling, superheated convection, and filmwise condensation.

Air is treated as an ideal gas, but the property functions are programmed to parallel the functions for water/steam. A heat transfer correlation for air crossing heated tubes is available in MINET, and other correlations can easily be added as they are needed.

Sodium and NaK are assumed to be subcooled, and in that state they are essentially incompressible. Both are treated as thermally expandable, i.e., the density changes with temperature. The property functions are programmed to parallel those for water/steam and air. Heat transfer correlations are available for both fluids, whether passing inside or outside of tubes. In principle, MINET could analyze boiling or superheating in either fluid, once appropriate properties and correlations have been added.

## 2.4 The MINET Code

The MINET code is relatively small and fast running, due to modular programming, careful data structuring, and an underlying numerical method that allows a large problem to be broken down into several small ones. In addition, steps have been taken to maximize the range of problems that can be analyzed, as well as the potential for concurrent analysis, i.e., with another computer code.

### Data Structure

MINET is variably dimensioned, with nearly all of the principal data residing in a large "container" array. Pointers are defined for each variable, which indicate the position in the container array where the values for the variable are located. The contents of, and pointers for, the container array are carefully preserved throughout the calculations.

Most of the storage space used for calculations is accessed through data abstractions. The data abstraction package of functions manages a container array and the accessing of the array, through pointers similar to those used in the principal container. Through the data abstractions, MINET can create storage for a matrix equation, perform the matrix calculations, and de-allocate the storage space, so that it is available for other calculations. Thus, the data abstractions facilitate the efficient use and re-use of storage space, while masking the details of container management from high level MINET subroutines.

### Input Processor.

The MINET input processor reads in a deck of free-format input records, and temporarily stores the data using data abstractions. It then processes the data, linking the various components into segments and networks. The data is then organized according to computational module number, segment number, and network number, and loaded into the principal container.

### Steady State Calculations

At the beginning of the steady state calculations, the system configuration, and component geometries and performance are known, as are the flow rates and temperatures at inlet boundaries and pressures at outlet boundaries. The temperature at an outlet boundary is also known when it has been "fixed"

by the user. In addition, the form loss factors for each segment component, the valve positions, the pump speeds, and the initial level in any accumulator with separated (saturated) contents are all known. The user's estimates of the energy transferred into or across (heat exchangers) components are treated as "known" if possible, but are subject to change if they contradict the boundary conditions. The user's estimates of the initial flows out of the accumulator ports and the network pressures are used only to initialize the iterative process.

The steady state calculation is a four step iterative process. First, energy transfer rates throughout the system are checked against boundary conditions, and any required changes will be made through energy adjustment factors. Second, the adjusted energy transfer rates will be used to determine segment, accumulator, and boundary enthalpies in each network. Third, pressure losses will be evaluated for every segment in each network, for current flows and enthalpies. During this step, the heat exchangers must be initialized, with an area correction factor used to resolve any discrepancies between the required energy transfer rate and that indicated by the heat transfer correlations. Fourth, the segment flow rates and accumulator and inlet boundary pressures are adjusted. At this point, if all the system enthalpies are not converged (from Step 2), the process is repeated, starting again at the first step.

Any adjustment factors for energy or heat transfer will be printed as part of the steady state calculations. Should any of these factors be significantly different than 1.0, the user is expected to review the input data for inconsistencies.

### MINET Transient Calculations

The transient calculations are based on the momentum integral network method described earlier. Adjustment factors determined during the steady state calculations are applied consistently in the transient computations. Transients are driven by changes at the boundaries, via the pump speeds or valve positions, and through the heat sink term in non-heat exchanger modules. All of these parameters can be controlled through user-input value vs. time tables. Alternately, pumps can be tripped and coasted down and valves can be

tripped open and closed in response to pressure (safety/relief) or flow (check). A compatible generic control system is planned, although not currently available.

### 3. EBR-II [4]

The Experimental Breeder Reactor II (EBR-II) is an unmoderated, heterogeneous, sodium-cooled reactor and power plant with a power output of 62.5 megawatts (MW) of heat. The energy produced in the reactor is converted to 20 MW of electricity through a conventional steam cycle. The reactor is fueled with  $U^{235}$  or plutonium, and the plant includes an integral fuel processing facility where the irradiated fuel is processed, fabricated, and assembled for return to the reactor.

The EBR-II is primarily an engineering facility to determine the feasibility of this type of reactor for central station power plant application. Major emphasis has been placed on achieving high thermal performance at high temperatures, and high fuel burnup with a fast and economical fuel processing system. The thermal performance of the reactor and the size of the system components are such as to permit direct extrapolation to central station application. The plant has been designed to permit a maximum of experimental operational flexibility by separation of the plant systems, and yet permit extrapolation to a commercial plant which would not require the same degree of separation.

Heat is removed from the reactor by the primary sodium coolant system and transferred to the secondary sodium system in a shell-and-tube heat exchanger. The secondary system transfers the heat to the steam generator where superheated steam is produced to drive a conventional turbine-generator (See Figure 1).

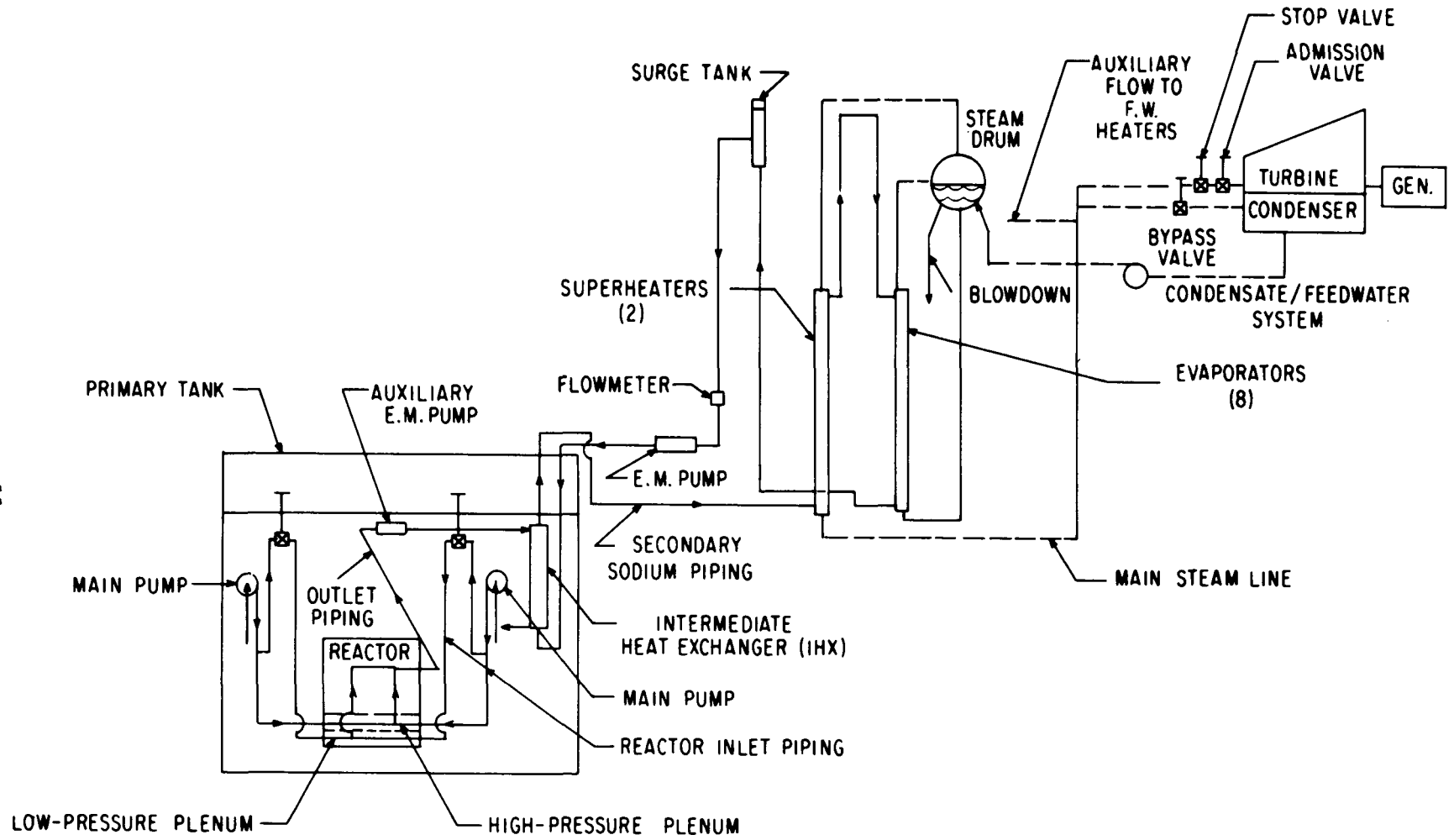


Fig. 1 - Schematic of EBR-II Plant

#### 4. MINET REPRESENTATION OF EBR-II

MINET was originally designed to analyze the steam generator system and part of the secondary system (intermediate loop) of an LMFBR, as part of the SSC analysis of the entire system. This is the case for our analysis of EBR-II, although here MINET represents a relatively larger portion of the intermediate loop because of the intricate branching therein.

The MINET representation is shown schematically in Figure 2. "MINET Standard Deck E1" is the name of the input deck that creates the component configuration as shown. The intermediate heat exchanger (IHX) shown at the left side of the drawing is not represented by MINET, but is included in the drawing as a reference point. The dashed line extending from the IHX represents a pipe that is included in MINET when it is executed in stand-alone mode so we can drive the transient with the IHX outlet temperature. When MINET is run with SSC, in order to model the whole system, this pipe is removed from the MINET representation and is represented in the SSC calculations.

At the time this transient was conducted in EBR-II, there were 1 IHX, 2 superheaters, 8 evaporators (later reduced to 7), 1 steam drum, and a number of headers. The MINET intermediate loop flow path represents 1 path from the IHX (dashed line), 2 paths to the superheater, 2 to 1 to 2 to 8 paths between the superheater and the evaporator and 8 to 2 to 1 paths from the evaporator to the point in the intermediate loop where SSC picks up the calculations.

In the steam generator system, feedwater is added to the lower portion of the steam drum, mixing with the saturated liquid directed downward from the steam separators. This is represented using two accumulator modules connected by a short, wide pipe. A portion of the flow from the lower portion of the drum, called the "blowdown", is drawn off for filtration treatment and use in feedwater heating. The remaining fluid passing out the lower part of the drum is drawn through 8 parallel recirculation loops. As the flow passes through the evaporators, it is heated to a quality somewhat less than 0.1. Because the vast majority of heat transfer takes place in the top part of the evaporator, we represented it using two heat exchanger modules, the lower one coarsely noded and the upper one with fine nodalization.

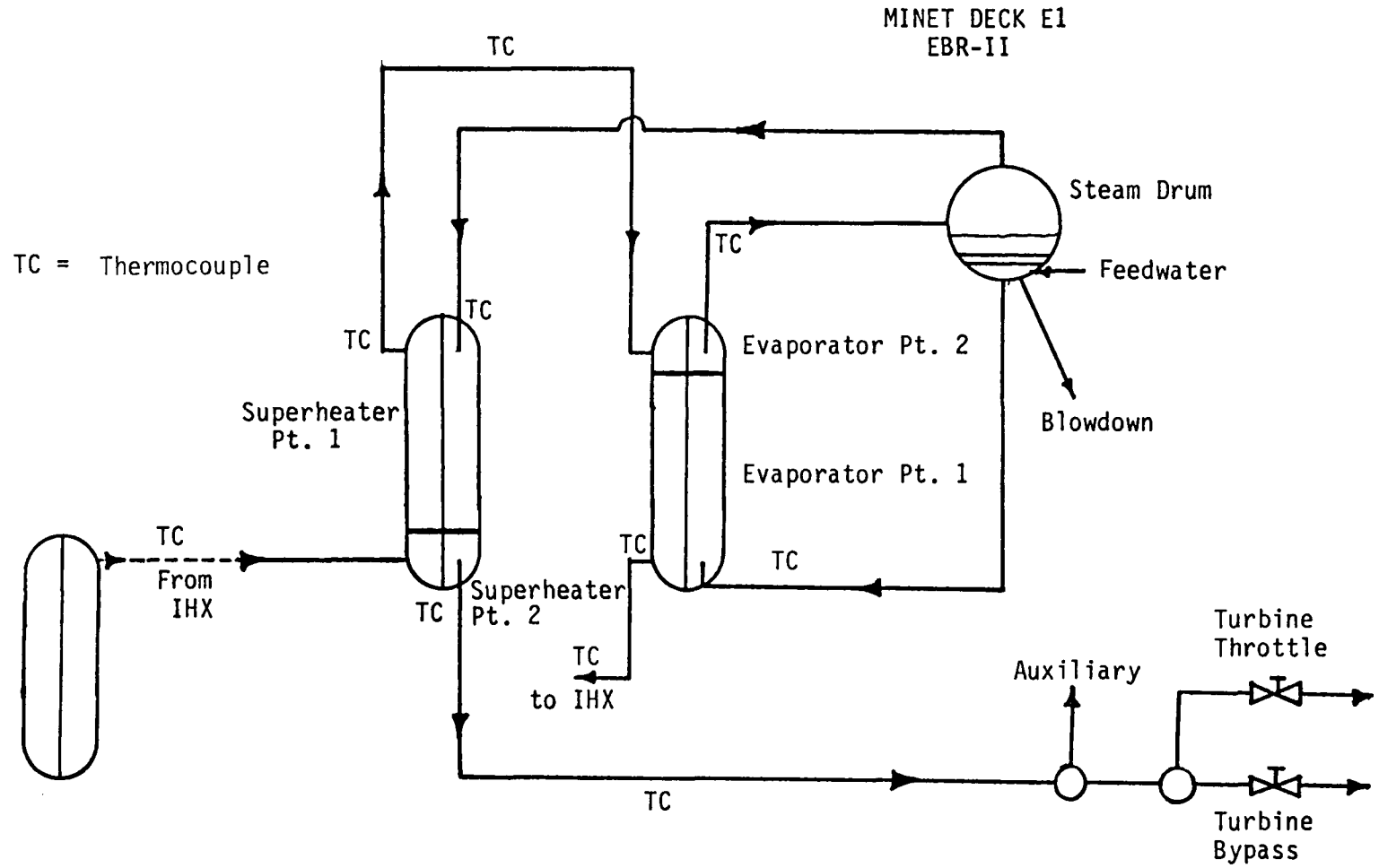


Figure 2 - MINET Standard Deck E1. A One Loop EBR-II Deck.

Steam is drawn from the upper part of the drum and passed through two parallel superheater lines. The superheater tubing is twice modified, once by core tubes that are inserted to create a faster (annular) steam flow, and again by shroud tubes sleeved over the regular tubes near the hot sodium inlet to reduce thermal shock problems. Again, we needed to use two MINET heat exchanger modules to represent the superheater units, because of the change in tube thickness in the lowest 1 meter, where the shroud tubes are located.

Superheated steam is passed on toward the turbine header, with two locations (represented as one in the calculations) where steam is bled off to the auxiliary lines, i.e., the feedwater heaters. (In this particular transient, information regarding the rate at which steam is removed in this manner was not available, and is a major problem in simulating the system.) At the turbine header, flow exits to either the turbine or turbine bypass lines, and on to the condenser.

For the most part, the EBR-II steam generator system and the MINET portion of the intermediate loop could be represented using options and features currently available in MINET. The only significant exception was that the turbine bypass valve position had to be controlled in response to the turbine header pressure, which required a minor code modification.

## 5. INITIALIZATION

Prior to transient analysis it is necessary to initialize conditions in the system. The goal is to start with initial conditions as close as possible to the actual conditions in the system before the transient. If necessary, the calculated flow and pressure distribution can be controlled through user-input loss coefficients. Heat transfer area correction factors are available for each heat exchanger, in order to resolve discrepancies between the heat transfer correlations and actual plant conditions. Thus, with a little effort, one can place the initial conditions at any configuration that is consistent with basic mass, energy, and momentum conservation.

In modeling the EBR-II system, one has to accept the fact that the plant has relatively old instrumentation, and much of that is concentrated in and around the reactor. Reportedly, this situation is currently being improved, but that does not help with the simulation of this transient. With regard to the initial conditions, it is the flow rates that are most uncertain, as these were either not measured, or are obviously somewhat in error. After a considerable amount of investigative effort, the initial conditions shown in Table 1 were determined, which are almost certainly close to being correct, at least for the important parameters.

In the intermediate loop, we wanted to drive the transient with the IHX outlet temperature, which was 3.6<sup>0</sup>K hotter than the superheater inlet temperature. Presumably this was due, in part, to heat losses in the piping. It is also likely that the thermocouples were not calibrated against each other. Therefore, we took the IHX outlet temperature plot and subtracted 3.6<sup>0</sup>K throughout the steady state and transient. Other than this parameter, the intermediate loop was not difficult to initialize. With regard to the sodium pressure, this parameter was not needed since the sodium is treated as sub-cooled and incompressible.

In the steam generator system, we were forced to use information provided by ANL staff who have modeled the system previously using the NATDEMO code [7]. Such information was used in setting the feedwater, recirculation, auxiliary, and bypass flows, and the initial position of the turbine bypass valve. Of these initial conditions, all have been confirmed either directly or indirectly, except for the recirculation loop flow rate.

Table 1. Initial Conditions

Fluid	Variable	EBR-II	Steady State Accuracy	MINET	Value
N <sub>a</sub>	Flow	124.0 kg/s	Good	124.0 kg/s	Input
N <sub>a</sub>	IHX Out Temp	711.4 K*	Good	711.6 K	Forced
N <sub>a</sub>	Pressure	? MPa	Unknown	.89 MPa	Input
N <sub>a</sub>	S.H. Out Temp	680.9 K	Good	679.5 K	Calculated
N <sub>a</sub>	Evap. Out Temp	574.0 K	Good	575.0 K	Forced
H <sub>2</sub> O	Feedwater Flow	13.58 kg/s	Off	13.615 kg/s	Input
H <sub>2</sub> O	Feedwater Temp	564.7 K	OK	564.7 K	Input
H <sub>2</sub> O	Blowdown Flow	2.27 kg/s	OK	2.27 kg/s	Forced
H <sub>2</sub> O	S.D. Pressure	8.89 MPa	Good	8.89 MPa	Forced
H <sub>2</sub> O	S.D. Level	.3542 Relative**	OK	.3563 Relative	Input
H <sub>2</sub> O	T Saturation (S.D.)	574.1 K	Good	575.4 K	Calculated
H <sub>2</sub> O	Recirc Flow	? kg/s	Unknown	225.3 kg/s	Forced
H <sub>2</sub> O	Superheater Flow	12.22 kg/s	Poor	11.35 kg/s	Forced
H <sub>2</sub> O	Superheater Out Temp	701.3 K	Good	702 K	Forced
H <sub>2</sub> O	Turb Hdr Press	8.74 MPa	Good	8.74 MPa	Forced
H <sub>2</sub> O	Bypass Valve Position	.254 Relative	Unknown	.254 Relative	Input
H <sub>2</sub> O	Throttle Valve Position	Closed	OK	10 <sup>-6</sup> Relative	Input
H <sub>2</sub> O	Auxiliary Flow	? kg/s	Unknown	2.5 kg/s	Forced
H <sub>2</sub> O	Bypass Flow	? kg/s	Unknown	8.85 kg/s	Forced

\*Temp Shifted Down to S.H. Inlet Temp by Subtracting 3.6<sup>0</sup>K

\*\*To the Height of the Drum

All of the input loss coefficients and calculated heat transfer area correction factors were reasonable and consistent. Except for the uncertainty in the recirculation loop flow rate, the calculated initial conditions are, very probably, quite close to those at the start of the transient.

## 6. TRANSIENT BOUNDARY CONDITIONS

The transient boundary conditions are summarized in Table 2, and the various figures, tables, and equation referenced therein. These boundary conditions were obtained from plant data or calculations by ANL staff [5].

The IHX outlet temperature was fairly well known, although it had to be shifted down as described in Section 5. Of the flow rates, the one for the intermediate loop seems to be measured the most accurately, perhaps because it is relatively significant when one is focusing on the reactor heat removal. The feedwater temperature and the blowdown flow seem to be known fairly accurately, and are not terribly critical in simulating the transient, anyway.

The remaining three boundary conditions were more difficult to determine because of inaccuracies in the plots of the feedwater flow and the flow rate at the steam header, superheater outlet. The steam flow rate was shown as dropping to zero at one minute and staying there for the remainder of the transient, which is highly unlikely. Since this plot was the only direct means of evaluating the flows out the auxiliaries and the bypass, the ANL staff had to be consulted for an alternate approach [5]. Furthermore, it was determined that the plotted feedwater flow rate was too high at steady state. This was determined using an energy balance and the feed and steam temperatures, which are known better than the flows.

At our request, ANL staff provided BNL with three additional, essential pieces of information [5]:

- 1) ANL provided the mass flow rate used in their NATDEMO simulation, as the auxiliary flow was unknown. This flow rate (vs. time), which lead to relatively accurate pressure calculations in the NATDEMO analysis, is given in Table 3.
- 2) The instrument measuring the feedwater flow rate was less reliable than another that was available. BNL was provided with data from the alternate instrument, which had inadvertently been left out of the test results. This flow is plotted in Figure 6.

Table 2. Transient Boundary Conditions

Parameter	Input	Accuracy
IHX Outlet Temp*	Figure 3	Good
Intermediate Loop Flow	Figure 4	Good
Feedwater Flow	Figure 6	Doubtful
Feedwater Temp	Figure 5	Good
Auxiliary Flow	Table 3	Poor
Blowdown Flow	Figure 6	Good
Bypass Valve Position	Equation 3	OK

\*Temperature Shifted Down by 3.6<sup>0</sup>K to Match Superheater Inlet Value

Table 3. Auxiliary Flow Rate[5]

t (s)	W (kg/s)
0	2.5
90	2.5
190	2.27
260	1.68
600	1.68

- 3) The turbine bypass valve is 0.254 (relative) open at the start of the transient, and the turbine throttle valve is closed. The bypass valve is closed at 70s.

With regard to the auxiliary flow, two choices were available, 1) use the one from the NATDEMO run, or 2) drive with a pressure boundary condition. As NATDEMO does not fully represent the compression and thermal expansion of water and steam, the back-fitted boundary condition would not provide the correct pressure in the MINET calculations, as MINET does represent these effects. However, to use a pressure boundary condition would compromise the validation study, as it virtually assures agreement on several key parameters. Furthermore, a pressure boundary condition is nearly impossible to specify in pre-test analysis, i.e., if it is not known a priori. Thus, we chose to use the NATDEMO boundary condition.

With regard to the feedwater flow rate, we had to accept the alternate data as more accurate. (As it turns out, a flow rate in-between those indicated by the two instruments would have provided the best drum level.)

The turbine bypass valve position information allowed us to infer a controller, based on the header pressure at 0 and 70 seconds.

$$S(\text{rel}) = 4.305 \cdot (P \text{ (MPa)} - 8.676), \tag{3}$$
$$10^{-6} \leq S(\text{rel}) \leq 1.2$$

While this is undoubtedly a simplification of the true control system, we judged it to be sufficient and could not dispute the results it provided.

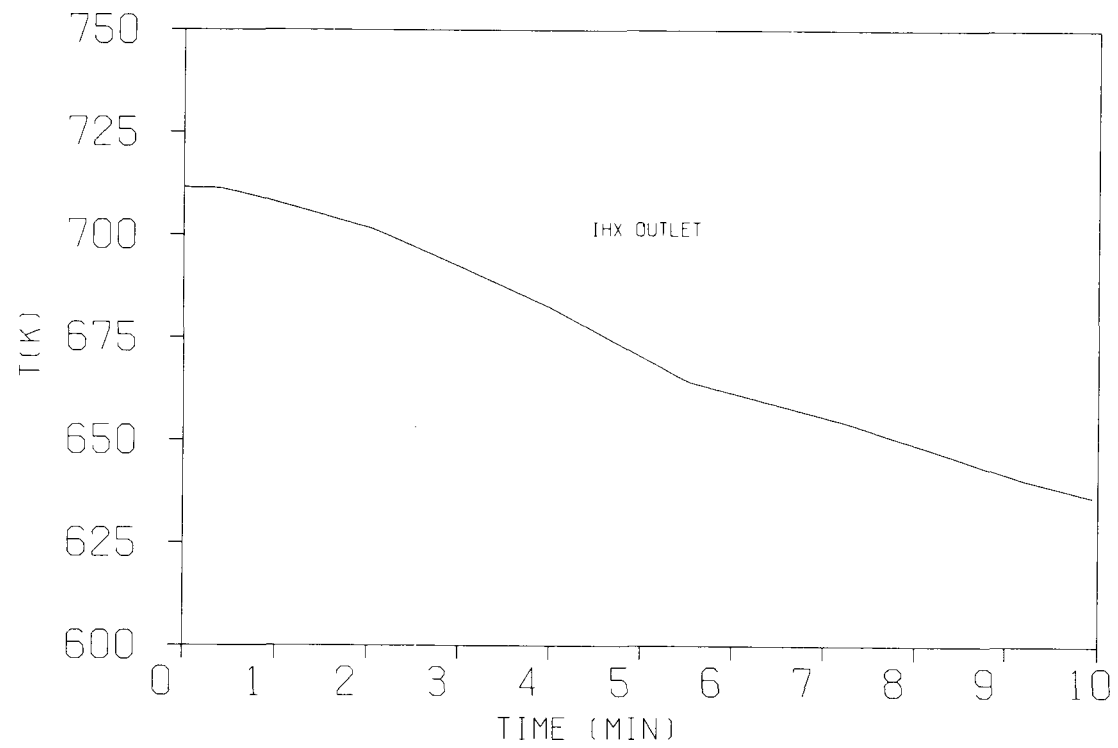


Fig. 3 - Secondary Side Intermediate Heat Exchanger Outlet Temperature

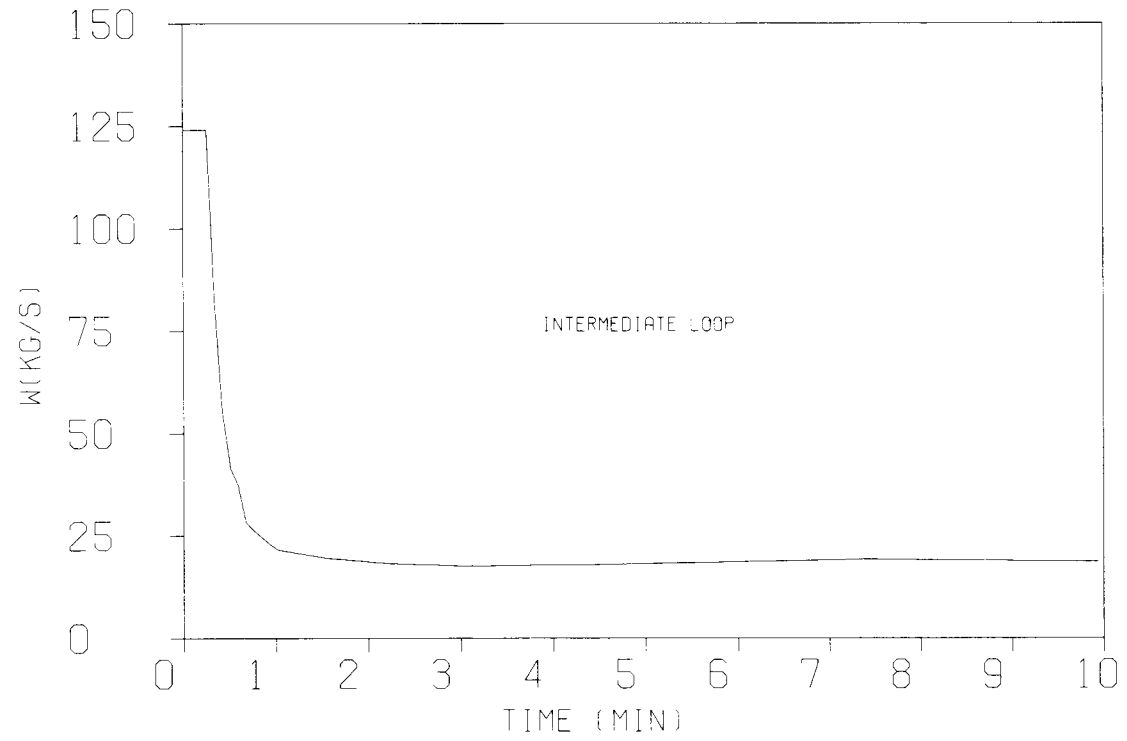


Fig. 4 - Intermediate Loop Mass Flow Rate

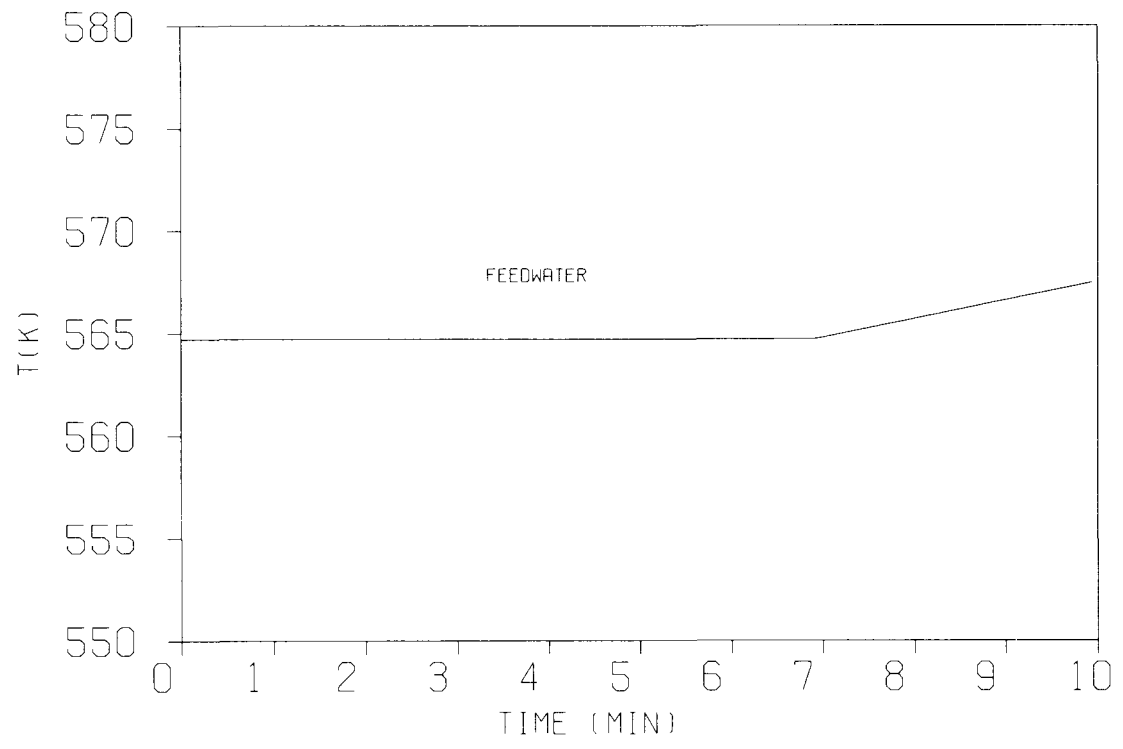


Fig. 5 - Feedwater Temperature

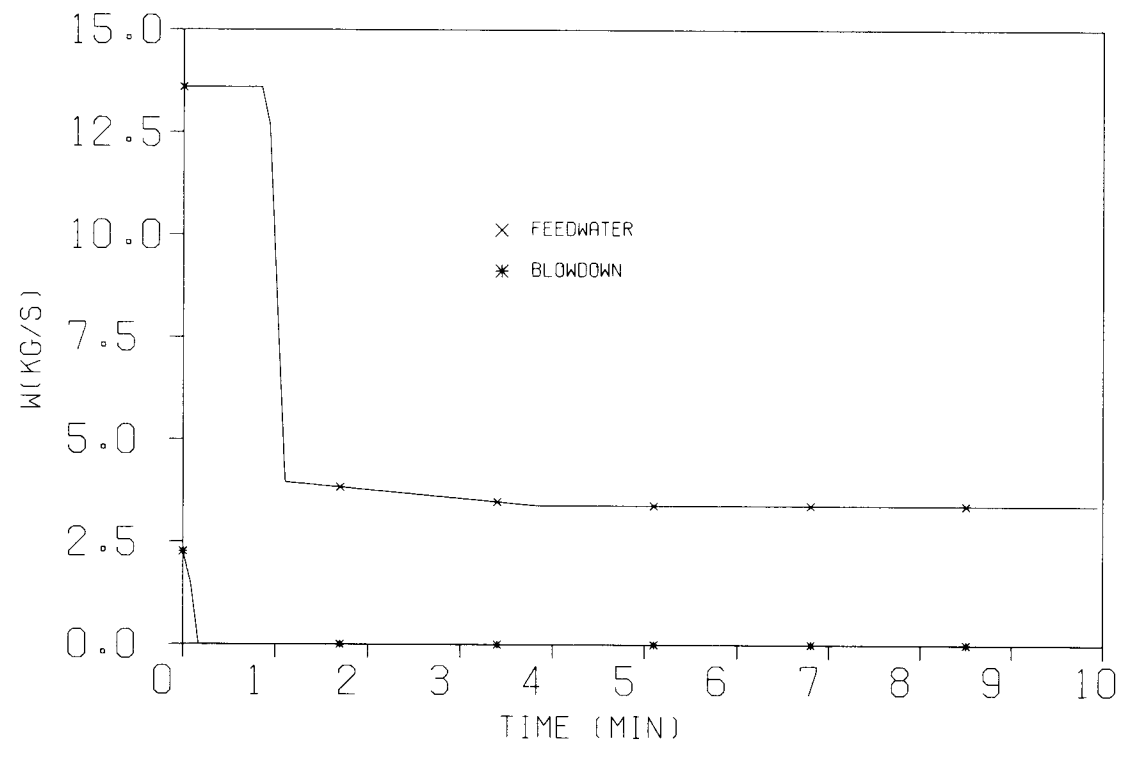


Fig. 6 - Feedwater and Blowdown Mass Flow Rates

## 7. TRANSIENT CALCULATIONS

The first 10 minutes of this 44 minute test transient were simulated. This timeframe was deemed sufficient to adequately compare all parameters of interest over a substantial range. When SSC and MINET are used together to simulate the whole system, we will follow the transient further, using a transient restart capability.

The results of the MINET calculations, vs. EBR-II measured results, are shown in Figures 7 through 14. It should be noted that thermocouple time constants of between 10 and 60 seconds effectively delay the EBR-II data [5], i.e., MINET calculated temperatures will lead the EBR-II thermocouple data. A discussion of each Figure follows.

Figure 7. Superheater Temperatures, Intermediate Loop

Once the delay from the thermocouple time constants is taken into account, MINET calculates the sodium inlet and outlet temperatures nearly exactly. The accuracy of these temperatures indicates that the steam flow rate must be reasonably close, at least for the first 5 or 6 minutes.

Figure 8. Evaporator Temperatures, Intermediate Loop

We have double checked the position of the evaporator inlet thermocouple, as well as the transport delay from the superheater outlet, and have found no errors. It appears that this thermocouple is one with a long time constant, in which case the MINET calculations are again correct. The temperatures at the evaporator outlet and outlet header are closely tied to the water side saturation temperature, and the agreement is not unexpected.

Figure 9. Evaporator Temperatures, Steam Side

The steam side evaporator inlet and outlet temperatures are essentially the same, whether calculated or measured. Because the evaporator operates at or near the saturation point throughout the transient, this plot has little significance.

#### Figure 10. Steam Side Pressures

The agreement of the calculated steam drum and turbine header pressures and those measured at EBR-II are about as close as possible, given the uncertainties in the feedwater and auxiliary flows. The difference in the two measured pressures does seem a little high, given the low flow rate through the superheater.

#### Figure 11. Steam Header Superheater Outlet Flow

The flow through the steam header superheater outlet is equal to the sum of the auxiliary and the bypass flows. The flow rate measured in this test is not really possible because, if it were correct, the steam system pressure would be increasing steeply rather than decreasing. The trend shown in the MINET calculation is more likely, but the amount of flow after the first minute of the transient is very much in doubt.

#### Figure 12. Steam Drum Water Level

Because of the uncertainty in the feedwater flow rate and the fact that the drum level is highly dependent on the amount of feedwater dumped into the drum, the discrepancy between the calculated and measured drum level is not significant. This can be illustrated using Table 4, where the two possibilities for the flow rate are compared. Note that by the end of ten minutes, the measured flow, as plotted, indicates the insertion of additional water into the drum equal to 19% of the total drum volume. This additional mass would be enough to raise the drum level (at ten minutes) from 0.39 to 0.54 (relative to total drum height), as compared to a measured value of 0.45.

#### Figure 13. Superheater Steam Temperatures

The calculated steam inlet temperature and, for the first 5 minutes, the steam outlet temperature agree well with the experimental results. At around 5 minutes the superheater inlet sodium temperature begins to decrease, as shown in Fig. 7. MINET indicates that the steam outlet begins decreasing within 100 seconds. The steam outlet temperature in the experiment drops off

somewhat later, although this does not show on the ten minute plot in Fig. 13. Essentially, MINET calculated temperatures lead the experimental ones by about three minutes. Given the accuracy of the other heat exchanger temperature calculations, and the excellent results in a previous test [3], it seems highly unlikely that this discrepancy is due to an error in the MINET calculations. It is more likely that the disagreement comes from three areas:

- 1) The thermocouple time constant. With the relatively poor heat transfer from moderate speed superheater steam, this time constant could easily be one minute or longer.
- 2) The heat capacity of the structure. We have only partially compensated for this effect, which could be significant given the smaller amount of steam to be heated.
- 3) The flow rate to the auxiliary lines. If the flow rate is actually lower than we are assuming, this will increase the steam outlet temperature.

Of the three sources of error, a long thermocouple time constant is likely to be the most significant. It is difficult to justify that the steam outlet temperature can remain above  $700^{\circ}\text{K}$  for nearly 4 minutes after the sodium inlet temperature drops below  $700^{\circ}\text{K}$ .

#### Figure 14. Steam Header Superheater Outlet Temperature

This temperature very closely corresponds to the superheater outlet temperature shown in Figure 13. The discrepancy between calculated and experimental values is again about 3 minutes, although the drop-off in the experimental temperature does not really begin until nearly 10 minutes into the transient, and does not show on this ten minute plot. Taken with the response shown in Figure 13, it appears that these thermocouples in the superheated steam part of the plant are very slow to respond.

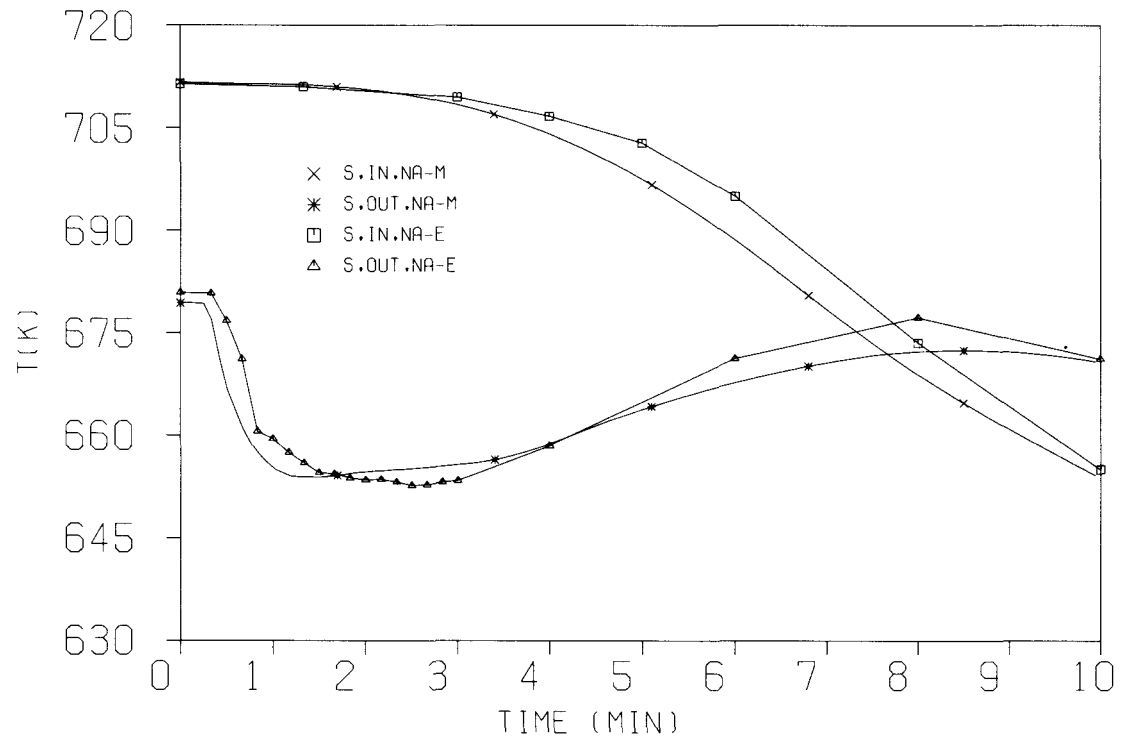


Fig. 7 - Superheater Sodium Temperatures, Inlet & Outlet, EBR-II and MINET

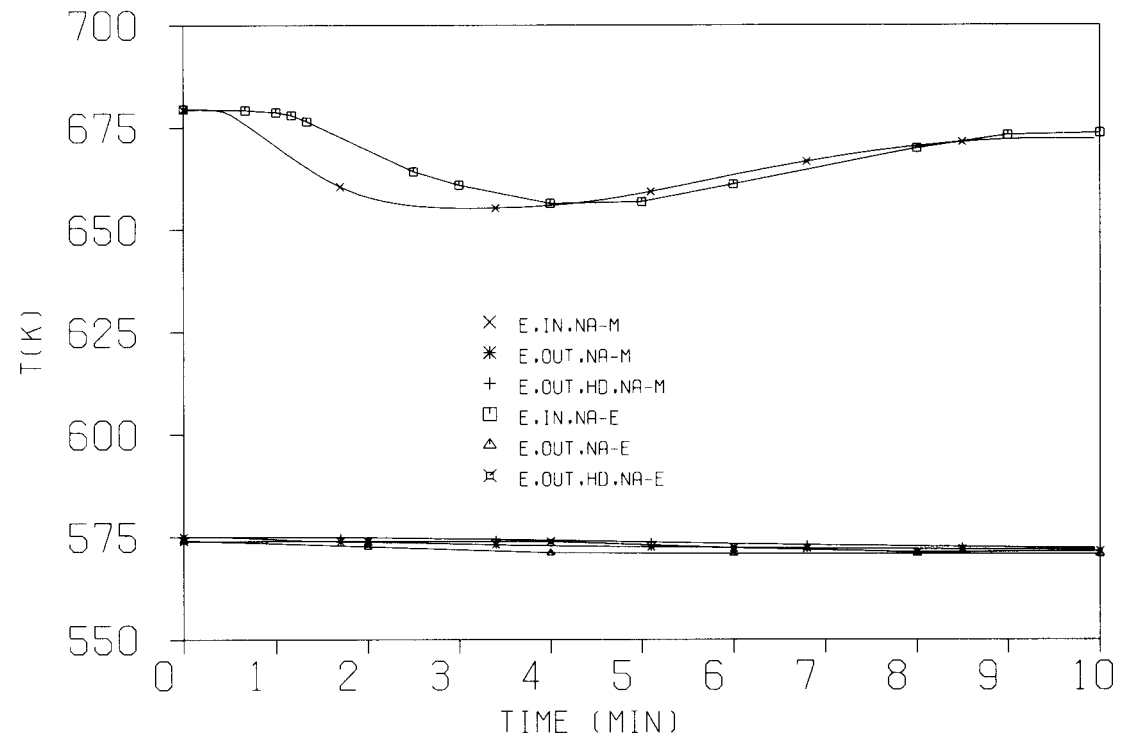


Fig. 8 - Evaporator Sodium Temperatures, Inlet, Outlet, Outlet Header, EBR-II and MINET

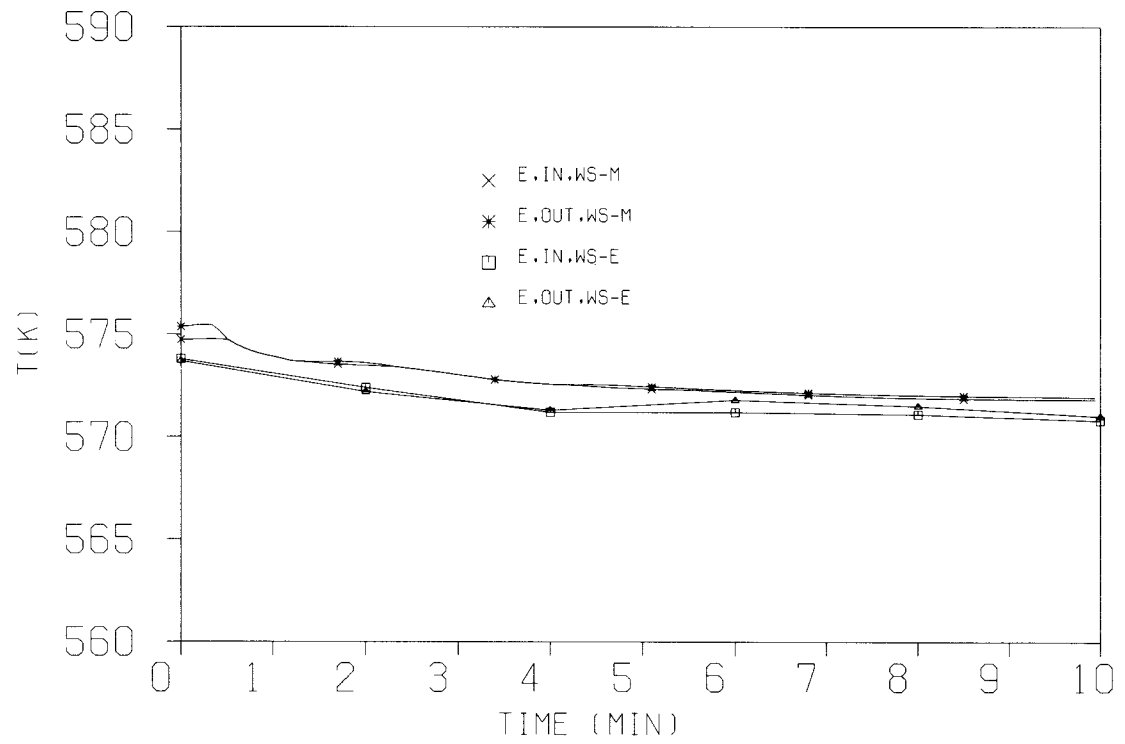


Fig. 9 - Evaporator Water Temperatures, In & Out,  
EBR-II and MINET

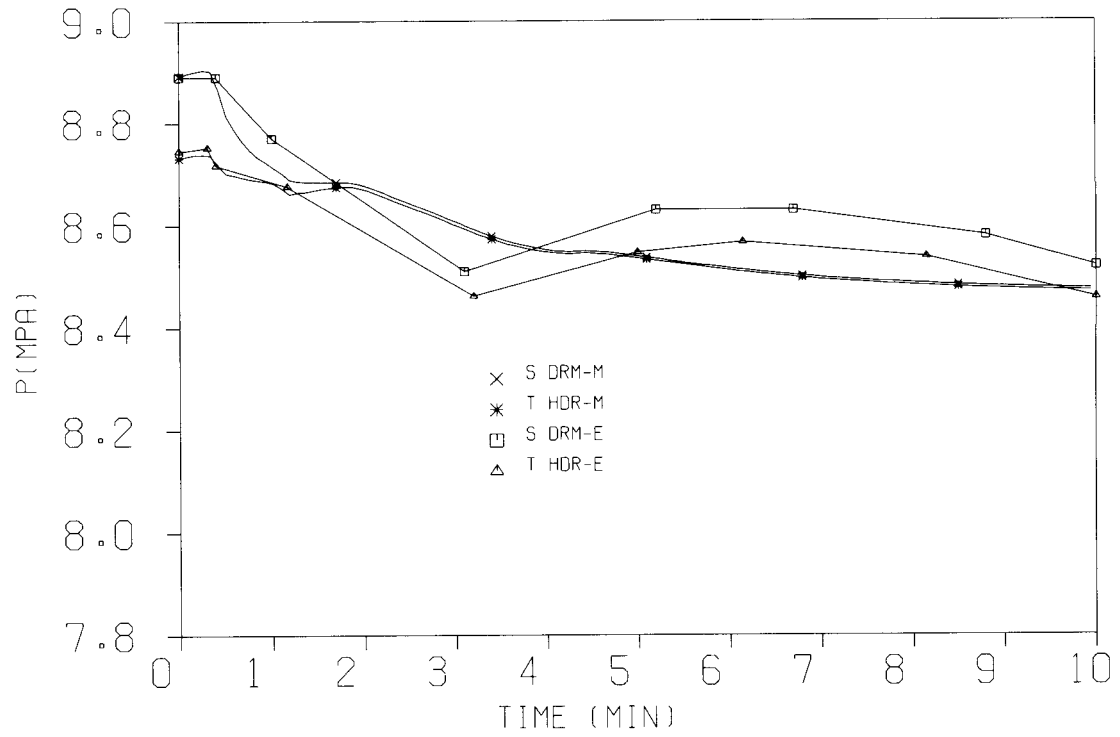


Fig. 10 - Steam Generator System Pressures, Steam Drum and Turbine Header, EBR-II and MINET

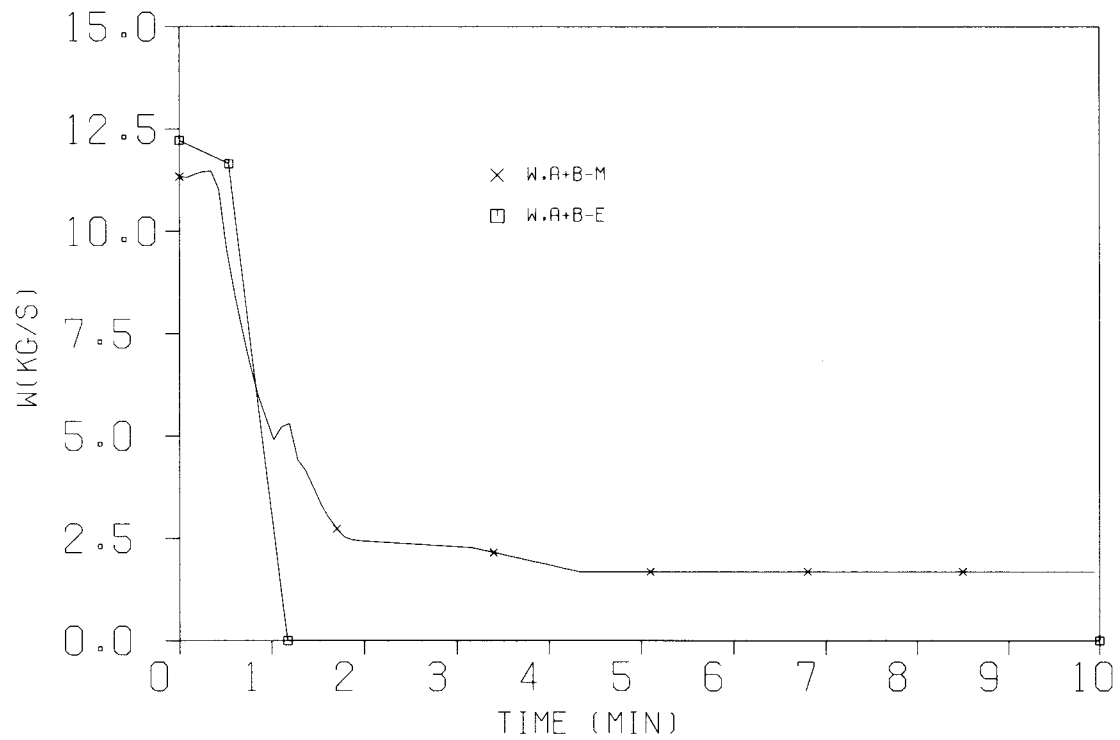


Fig. 11 - Steam Header Superheater Outlet Flow Rate  
(= Auxiliary + Bypass Flows), EBR-II and MINET

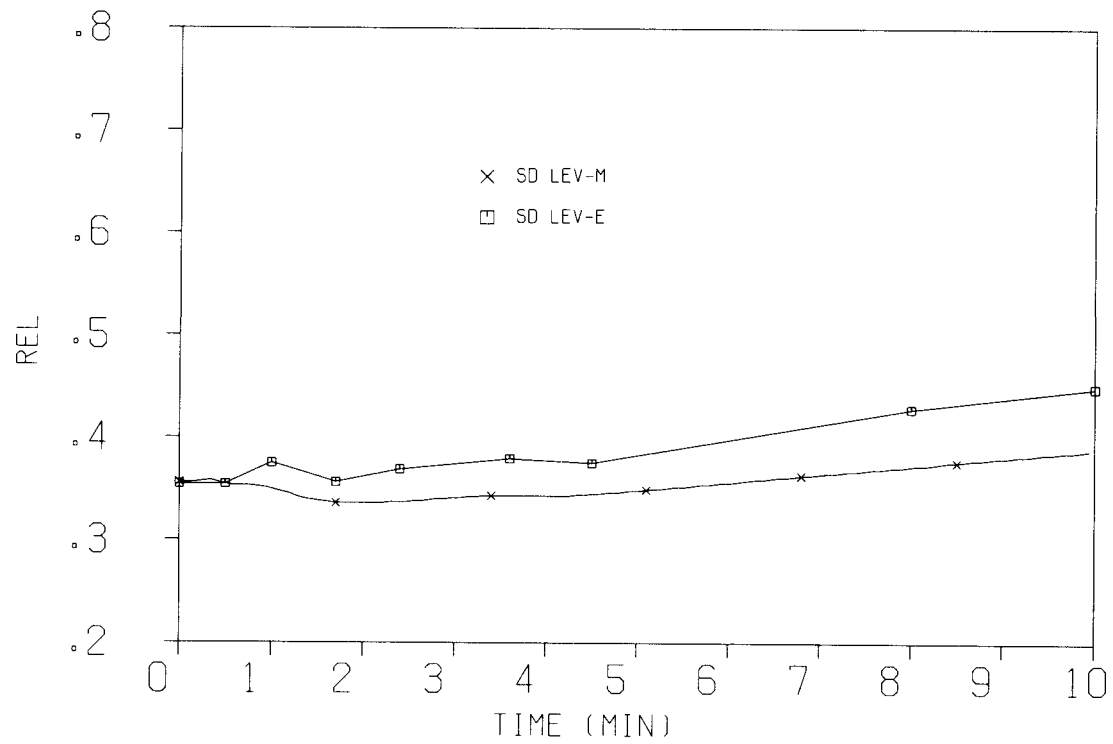


Fig. 12 - Steam Drum Water Level, EBR-II and MINET

Table 4. FW Flow Alternatives

Measured Data As Plotted (Advised Not to Use)				Alternate Data [5] (Used in MINET run)			Difference (Drum Vol = 15m <sup>3</sup> )			
t(s)	W <sub>FW</sub> (kg/s)	Norm W <sub>FW</sub> (kg/s)	$\int_0^t W dt$ (kg)	t	W <sub>FW</sub> (kg/s)	$\int_0^t W dt$ (kg)	t	$\Delta$ Mass (kg)	$\Delta$ Vol (m <sup>3</sup> )*	$\Delta V/V$
0	14.45	13.63	0	0	13.615	0	60	11.9	.02	.001
54	14.82	13.98	736	55	13.615	748.0	120	288.2	.41	.027
78	9.44	8.90	1010.6	66	3.96	845.5	180	527.1	.71	.047
234	6.80	6.41	2205.	230	3.39	1448.2	240	764.0	1.08	.072
264	7.75	7.31	2410.6	600	3.39	2702.5	300	978.5	1.38	.092
348	7.18	6.77	3001.9				360	1196.1	1.68	.112
372	7.50	7.07	3168.0				420	1402.3	1.98	.132
438	6.93	6.54	3617.1				480	1596.1	2.25	.150
600	6.93	6.54	4676.6				540	1785.1	2.51	.167
							600	1974.1	2.78	.19

\* -  $\rho = 710 \text{ kg/m}^3$  used

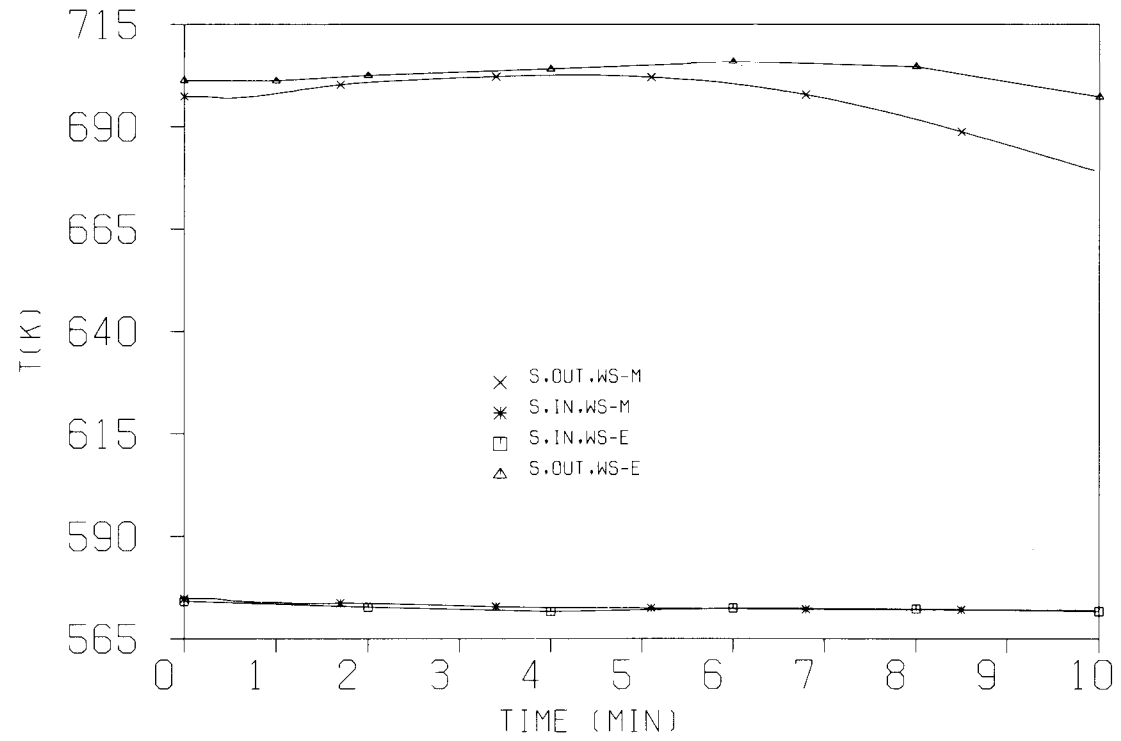


Fig. 13 - Superheater Steam Temperatures, Inlet & Outlet  
EBR-II and MINET

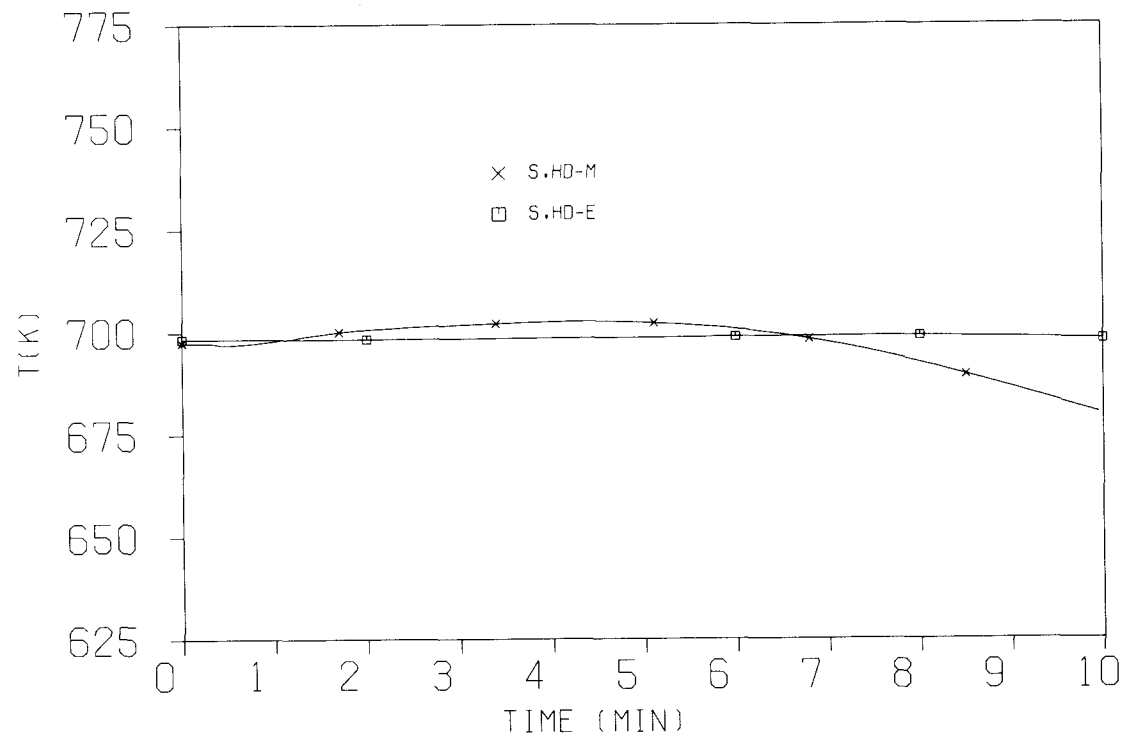


Fig. 14 - Steam Header Superheater Outlet Temperature,  
EBR-II and MINET

## 8. CONCLUSIONS

MINET did a very good job simulating the behavior of the EBR-II steam generator system, and much of the intermediate loop, during the first ten minutes of this natural circulation transient. Some of the calculations were very accurate indeed, and increase the probability that the relatively small discrepancies in other parameters are due to uncertainties in the transient boundary conditions and thermocouple time constants.

EBR-II is potentially a very useful source of plant transient data, and could be valuable in computer code validation efforts. Some of the instrumentation problems we encountered in simulating this test have since been addressed, and further improvements are being considered for implementation before the upcoming test series. While most of the EBR-II test transients performed thus far have centered around the reactor, a series focusing on the balance of plant is currently in the planning stages.

With respect to the use of MINET with SSC to analyze CRBR, this validation study strongly supports this because of the similarity of the systems. In addition, because of the control systems that are planned for CRBR, the transient boundary conditions are far more easily determined, which alleviates some of the difficulties we encountered in simulating the EBR-II system.

## 9. FUTURE PLANS

This simulation of the EBR-II test results is the starting point for three related efforts. Each will begin within the next several months.

1. The use of SSC and MINET, Version 0 to simulate the entire plant response for this test. In this study, MINET will be used in a supportive role, exchanging transient boundary conditions with SSC.
2. The use of SSC and MINET, Version 0 to perform pre-test predictions for a major EBR-II test series to commence in 1984. We have not as yet determined which tests to analyze, or whether we will perform another validation study first.
3. Further validation studies of MINET, utilizing some of the expanded capabilities and, new modules. This test series will probably involve simulating the feedwater heaters, turbines, and condensers, and may extend over several test transients.

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