TITLE: CHAP: A COMPOSITE NUCLEAR PLANT SIMULATION PROGRAM APPLIED TO THE 3000 MW(T) HTGR

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CRAP: A Composite Nuclear Plant Simulation Program Applied to the 3000 MW(t) HTGR

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ABSTRACT

CRAP is a general systems analysis program which has been developed at LASL. The program is being used for simulating large HTGR nuclear power plant operation and accident transients. In this paper the general features and analytical methods of the CRAP program are discussed. Features of the large HTGR model and results of model transients are also presented.

INTRODUCTION

Development of a High-Temperature Gas-Cooled Reactor (HTGR) accident-simulation computer program for the Nuclear Regulatory Commission (NRC) has been in progress at the Los Alamos Scientific Laboratory (LASL) for nearly three years as part of a larger HTGR Safety Program. This paper describes the first version (CRAP-1) of the simulation program which we call CRAP (Composite HTGR Analysis Program).

The CRAP program has been developed around a general systems analysis framework. Features of the general CRAP program include a modular approach to reactor component modeling, a standardized module structure to facilitate modification of component models and incorporation of new models or components, steady-state and transient solution routines that are independent of system models, and a versatile input/output package. Steady-state solutions are obtained by Newton-Raphson iteration. A combined implicit-explicit-quasistatic predictor-corrector numerical integration method based on the optimal integrating factor solution of ODE's is used to calculate transients.

CRAP-1 contains specific models of a large 3000 MW(t) HTGR reactor and electrical generation plant components and controls. This program includes fifteen separate modules which are coupled through specified boundary conditions. In general the mathematical complexity of component modules has been minimized while maintaining an acceptably accurate representation of the static and dynamic characteristics of the component. Some of the transients that can be treated with CRAP-1 are control rod withdrawal at full or partial power, total or partial loss of the primary helium coolant flow or secondary feedwater flow, loss of one or more steam generator loops or core auxiliary cooling system (CACS) loops, loss of load.

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Two classes of digital solutions are performed: steady-state calculations and transient responses. The information required to obtain these solutions is the mathematical equations of the system written in terms of coupled, possibly nonlinear, ODE's with specified time dependent inputs. The main framework is independent of the coded model.

We have developed a modular approach for CHAP which allows system models to be represented by a set of subroutines, or modules, each representing a different component, feature, or subsystem of the overall plant. The user also codes a driver subroutine named MODEL which calls the individual component module subroutines in whatever order desired. If problem setup data is required for problem initialization, such as variable dimensioning, the user may recode subroutine SETUP for this purpose. A few simple rules have been developed for modularizing. The edit features of CHAP are based on the module approach such that data are summarized by module on the output listings. A binary file of plotting data for post processing with local plotting facilities. At the end of every steady-state and time-response calculation, CHAP also creates a file of restart variables.

The overall flow of execution through the CHAP program is shown in Fig. 1. CHAP is coded in standard FORTRAN-IV and generally follows guidelines established for exportable codes. Two versions of the code are available. For very large models a version is available which contains four overlays. For problems that are not too large a nonoverlay version is available.

A number of utility subroutines were developed for use in CHAP which broaden its usefulness for simulation. These include two linear system solver routines, a tabular-data linear-interpolation routine, and a nonlinear-network flow-resistance rebalance routine. Routines are also available for creating the state-variable derivative expressions associated with any general LaPlace transform representation of a component or a general proportional-plus-integral-plus differential controller.
STATE VARIABLES

Each component modeled is considered as a subsystem with specified inputs and outputs. The dynamic physical variables are described by a set of first-order, possibly nonlinear, ODE's. If the physical process is described by partial differential equations, numerical differencing techniques or lumped parameter techniques are invoked to create the necessary ODE's. The resultant set of equations can be described by

\[
\frac{dy_i(t)}{dt} = f_i(y_1, \ldots, y_i, \ldots, y_n, x_1, \ldots, x_k, \ldots, x_m); \quad i=1,n
\]

where \( y_i \) is the set of \( n \) integration or dynamic state variables, \( f_i \) is a set of \( n \) state-variable derivative relationships, \( x_k \) is a set of \( m \) time-dependent inputs, and \( t \) is the independent time variable. The equations contain physical descriptions of the thermal, fluid-flow, neutronic, after-beat and control processes of each component. They are based on physical laws and component design and attempt to represent accurately both the static and dynamic characteristics of the component.

![Flow Diagram](image)

Fig. 1. CHAP Logical Flow Diagram.
STEADY-STATE SOLUTIONS

A Newton-Raphson iteration is used to achieve a steady-state solution for the whole system of model equations. In vector notation Eq. (1) can be rewritten

\[ \dot{y}(t) = f(y(t), x(t)) \]  

(2)

Initial state variable values computed in the initialization region of each component module do not guarantee that \( \dot{y} \) will be null for the coupled system as required for a steady-state solution. The iterative procedure involves successively correcting \( \dot{y} \) according to

\[ y^{k+1} = y^k + \delta y^{k+1} \]  

(3)

so that

\[ y^{k+1} = f(y^{k+1}, x) = 0 \]  

(4)

where \( k \) is the iteration index.

The correction vector \( \delta y^{k+1} \) is computed from

\[ \delta y^{k+1} = - [J]^{-1}_k f^k \]  

(5)

where \([J]_k\) is the first order Jacobi matrix, evaluated at \( y^k \), whose elements \( J_{ij} \) given by

\[ J_{ij} = \frac{\partial f^k_i}{\partial y_j}, \quad i=1,n; \; j=1,n \]  

(6)

are numerically evaluated. Iteration continues until

\[ \begin{vmatrix} y^{k+1}_i \\ y^k_i \\ \end{vmatrix} \begin{vmatrix} -1 \\ \end{vmatrix} \leq \text{TEST} \]  

(7)

is satisfied for all state variables \( y_i \).

TRANSIENT SOLUTIONS

All of the state-variable derivative equations in CHAP are integrated with the same numerical integration technique. In general the ODE set may contain very fast and extremely slow response variables simultaneously. In addition some of the characteristic eigenvalues may be complex and the Jacobi matrix may be very sparse. For dynamic variables that are slowly responding or exhibit diagonal dominance in the Jacobi matrix an explicit integration technique works well. For very fast-response variables that do
not exhibit diagonal dominance implicit integration techniques are preferred. We have therefore developed a numerical integration technique which combines the aspects of both a semi-implicit (explicit) technique and a fully-implicit technique. The method is based on the optimum integrating factor solution of ODE's, is asymptotically stable, and the solution accuracy is controlled by adjusting the integration step size using a predictor-corrector convergence criterion.

The basic numerical integration algorithm is of the form

\[
y_{i}^{k+1} = y_{i}^{k} + \Delta t \left[ (1-\alpha_i) f_{i}^{k+1} + \alpha_i y_{i}^{k} \right] ; \quad i=1,n \tag{8}\]

where \( k \) is the time index, \( \Delta t = t^{k+1} - t^{k} \) the integration step size, and \( \alpha_i \) is a weighting factor evaluated to maximize the step size while maintaining numerical and asymptotic stability.

For \( \beta_i \) not equal to unity Eq. (8) is implicit and for \( \beta_i = 1 \) Eq. (8) is explicit. We assume that over the interval from \( t^k \) to \( t^{k+1} \) the solution \( y_{i}^{k+1} \) has the integrating factors form

\[
y_{i}^{k+1} = y_{i}^{k} e^{-\alpha_i \Delta t} ; \quad i=1,n \tag{9}\]

so that \( f_{i}^{k} = -\alpha_i y_{i}^{k} \) and \( f_{i}^{k+1} = -\alpha_i y_{i}^{k} e^{-\alpha_i \Delta t} \).

With these substitutions in Eq. (8), eliminating \( y_{i}^{k} \), the solution for \( \beta_i \) is

\[
\beta_i = \frac{e^{-\alpha_i \Delta t}(1+\alpha_i \Delta t) - 1}{\alpha_i \Delta t (e^{-\alpha_i \Delta t} - 1)} \tag{10}\]

Equation (8) is asymptotically stable for \( \alpha_i \) greater than zero. In CHAP \( \alpha_i \) is evaluated to maximize the integration step size. This is determined from the relationship

\[
\alpha_i = \sum_{j=1}^{n} \frac{f_{ij}^{k+1} f_{ij}^{k+1}}{f_{ij}^{k+1}} ; \quad i=1,n \tag{11}\]

A predictor-corrector algorithm for Eq. (8) is achieved by approximating \( f_{i}^{k+1} \) with a first order Taylor expansion about the predictor value. In vector notation

\[
f_{i}^{k+1} = f_{i}^{k+1} + [J] \Delta y_{i}^{k+1} \tag{12}\]
where $\delta y_{k+1} = y_{c}^{k+1} - y_{p}^{k+1}$.

Here the subscript "c" refers to corrector and the subscript "p" refers to predictor. For diagonally-dominant (explicit) equations we assume that $J_{ij} = 0$ for all $j \neq i$.

In matrix notation Eq. (8) can be rearranged to solve for $\delta y_{k+1}$ from the expression

$$\left[D_1 - D_2\right] \delta y_{k+1} = \left[D_1\right] (y^k - y_p^{k+1}) + \frac{f_p^{k+1}}{\beta} + \left[D_2\right] f^k$$

or equivalently,

$$[A] \delta y_{k+1} = \xi$$

(13)

where $D_1$ and $D_2$ are diagonal matrices whose typical elements are

$$d_{1i} = \frac{1}{\Delta t (1 - \beta_i)} \quad \text{and} \quad d_{2i} = \frac{\beta_i}{1 - \beta_i}.$$

The predicted value of $y_p^{k+1}$ is obtained as a special case of Eq. (13) by letting $\xi = \xi_k$, $f_{p}^{k+1} = f$, and $y_{c}^{k+1} = y_{p}^{k+1}$.

For the combined implicit/explicit algorithm the vector $\delta y_{k+1}$ is comprised of two components and denoted

$$\delta y_{k+1} = \begin{bmatrix} \delta y_{ex}^{k+1} \\ \delta y_{k+1} \\ \delta y_{im} \end{bmatrix}.$$  

(15)

Similarly the vector $\xi$ is denoted

$$\xi = \begin{bmatrix} \xi_{ex} \\ \xi_{im} \end{bmatrix}.$$  

(16)

and the matrix $[A]$ is composed of submatrices

$$[A] = \begin{bmatrix} [A_{ee}] & [A_{ei}] \\ [A_{ie}] & [A_{ii}] \end{bmatrix}.$$  

(17)
However, the explicit submatrix \([A_{ee}]\) is diagonal and the submatrix \([A_{ei}]\) is null. Therefore \([A]\) is rewritten

\[
[A] = \begin{bmatrix}
[D_{ex}] & [0] \\
[A_{ie}] & [A_{ii}]
\end{bmatrix}
\]  

(18)

The solution of the explicit variables are first obtained from

\[
\delta_{le}^{k+1} = [D_{ex}]^{-1} \delta_{ex}^k
\]  

(19)

The solution for the implicit variables are then obtained from the expression

\[
\delta_{li}^{k+1} = [A_{ii}]^{-1} [-A_{ie}] \delta_{le}^k + \delta_{im}^k
\]  

(20)

Jacobi information and solution convergence are used to select implicit and explicit variables.

A unique feature of the CHAP algorithm is the quasi-static solution. In many cases, especially for slow running transients, the dynamic solution of fast response variables is not warranted. Their response may be so fast that they are essentially in static equilibrium at all times. In CHAP an arbitrary minimum solution time step is user specified. Variables which do not converge in a predictor-corrector pass with this given minimum time step are treated quasi-statically. They are implicit variables obtained from Eq. (20) by letting \(\delta_{li} = 0\) and \(\Delta t = \infty\). If the minimum solution interval is specified as zero all equations in the system are solved explicitly. When this parameter is set equal to machine infinity the method becomes a full Newton-Raphson steady state which is fully implicit. A combination of explicit, implicit and quasi-static is achieved when this parameter is specified other than zero or infinity. The user therefore has full control of the solution dynamics.

**THE HTGR NUCLEAR PLANT MODEL**

The HTGR nuclear plant model, based on the 3000 MW(t) HTGR nuclear steam generating plant described in Ref. 5, was developed for NRC to provide an independent method of predicting the dynamic response of many system variables to a wide range of transient scenarios. Schematics of the main components which make up the CHAP-1 code are shown in Fig. 2 and 3.

The model represents an initial release version of the code and currently contains 15 separately coded modules. The total number of state variables for the modules is 114. Eleven modules are used in modeling the primary (helium) side of the system. Six modules model the secondary (water/steam) side of the system. The main steam generator, re heater, and helium circulator modules are common and couple the primary and secondary loops.
Fig. 2. Primary Loop Modules.

Fig. 3. Secondary Loop Modules.
A separate module provides user-specified initial and time-dependent boundary conditions for all component modules. This module dictates the inputs for various transient scenarios via input data option parameters and specified tabular data. Currently there are 13 option parameters which are used for model setup and problem definition.

The model includes a broad spectrum of normal operation and plant protection controllers. They are used to control the main and auxiliary circulator speeds, deaerator level and pressure, steam generator exit pressure and temperature, turbine throttle pressure, reheater exit temperature, feedwater heater level, turbine feedpump speed, control rod position, core orifice valve position, and many valves associated with the turbine bypass systems.

Important safety significant phenomena have also been modeled. For example, the core model predicts both average and maximum fuel temperatures to identify fuel failure rates. Loss of forced cooling can be handled with time dependent decay power models and natural-convection or low-flow heat-transfer and pressure-drop correlations. The Core Auxiliary Cooling System (CACS) is modeled to operate in both the standby and operational mode with three or fewer auxiliary circulators available, and the effects of separate fuel and moderator reactivity perturbations can be studied.

The primary coolant loop models have been verified at power levels from 150% down to 1% of design. The secondary coolant loop models are known to be valid above 25% of design. Below 25% the secondary modules are isolated from the overall model in most shutdown and accident transients because helium flow isolation values are activated in the steam generator loops.

PRIMARY COOLANT LOOP

The main components in the HTGR primary helium coolant loop include the reactor core with top, bottom, and side reflectors; an upper and lower plenum; and cross ducts from the plena to the main steam generator and the core auxiliary heat exchanger (CAHE) cavities; all contained within a pressurized concrete reactor vessel (FCRV). For the 3000 MW(t) reactor there are six steam-generator cavities in parallel each containing a reheater-steam generator unit, a steam-turbine-driven helium circulator, and a helium isolation valve. There are three CACS cavities in parallel each containing a CAHE, a motor-driven helium circulator, and a valve.

The reactor core heat transfer and fluid flow model uses a typical triangular symmetry element (Fig. 4) to derive lumped parameters for a simplified reactor-core state-variable model. Included are the top reflector, core moderator, core fuel, helium gap between moderator and fuel, helium coolant, and bottom reflector. The active core consists of 8 axial segments of moderator and fuel. Heat transfer by conduction is considered axially between core moderator segments. Heat transfer by conduction is also considered radially between the core and the side reflector. Dynamic conservation-of-energy equations determine the average moderator and fuel temperatures in the axial segments. Heat transfer from the moderator to the coolant is treated quasistatically by convection. Heat transfer in the helium gap between moderator and fuel is by radiation and conduction. The model utilizes an exponential description of convective heat transfer along the coolant channel to predict low-flow, or even zero-flow, thermal-hydraulics.
In the setup of the core module, a special finite-element heat-diffusion model is used to compute steady-state thermal conditions for the triangular unit cell. The finite-element model considers the cell geometry, the core-power distribution, prompt and decay-power fractions in all materials, core-flow rate and power level, and inlet helium temperature to compute lumped-parameter shape factors.

The HTGR side reflector surrounds the core and includes both permanent and removable graphite reflector material, a boronated-shield assembly, a structural core-barrel assembly, various concentric bypass coolant annular regions, and a lower seal assembly, within the PQRV cavity. The CHAP-1 reflector module includes the modeling of all of these regions to describe heat transfer from the core to the reflector materials, to the bypass helium coolant, and to the PQRV cavity wall. The model is made up of three axial segments in each material. Material energy equations are treated dynamically. Heat transfer is by conduction in solid materials both radially and axially, convection to the helium coolant, and radiation radially between concentric materials separated by coolant annuli.

Helium flow through the core and the side reflector is from the upper plenum to the lower plenum. The flow paths in these two components and the CACS cavity are in parallel. Flow distributions are computed using the nonlinear parallel-network flow-resistance rebalance routine of CHAP. The upper and lower plenum modules contain models of dynamic heat-transfer conditions from the coolant to the plenum walls and flow obstruction materials within these cavities such as support posts and control rod guide tubes. The helium duct modules in CHAP-1 also model the dynamics of heat transfer from the coolant to the duct walls and compute duct pressure drops.

Fig. 4. HTGR Core Symmetry Element.
The CACS module consists of the CACS top and bottom ducts and plena, the auxiliary helium-to-water heat exchanger for residual core heat removal, a bypass annulus, the CACS valve, and an auxiliary motor-driven helium circulator. Dynamic conservation-of-energy equations are used to predict temperatures in the various plenum, duct, and annulus walls and also in CAHE tube walls and water coolant. Helium temperatures and pressure drops are determined quasistatically.

The CACS model is used for both standby and core heat removal situations. During standby operation helium flows into the top CACS duct, through the CACS valve, down over the CAHE, and exits through the lower duct into the bottom plenum of the reactor cavity. When the auxiliary circulators are turned off (operational mode) the helium flow in the CACS cavity reverses entering from the lower CACS duct, passing upward over the CAHE, through a wide open valve, where momentum is restored by the operating motor circulator, and exits into the upper plenum of the reactor cavity. Flow reversal is accounted for by changing the CACS module boundary conditions.

A special module was developed for CHAP containing a description of point-reactor kinetics and decay-heat dynamics for the HTGR. Two decay-heat dynamic models were developed containing 5 and 10 decay power contributions with different buildup and decay parameters. Options are available within CHAP to employ functional relations of either decay or prompt power versus time, tabular input if desired, and the prompt jump approximation. Feedback reactivity is composed of control rod contributions and separate fuel and moderator temperature effects. An isothermal temperature reactivity model is also available.

Normally helium flows through cross ducts from the reactor bottom plenum to the reheater-steam generator cavities where it first passes upward over the reheater and then over the steam generator tube bundles. Heat is removed by water flowing in the tubes counter current to external helium flow. The helium flow then passes through a single-stage steam-turbine driven compressor where momentum is restored and is returned to the reactor upper plenum cavity through cross ducts. All helium heat transfer to the tube bundles in the HTGR model is treated quasistatically by conduction. Grimison heat-transfer and pressure-drop correlations are used in the model. The main helium circulator turbine-compressor model is based on polynomial fits of actual data obtained by GA in developing the units.

SECONDARY LOOP MODULES

The 3000 MW(t) turbine generator plant produces 1140 MW(e) at full power. All of the components, valves, and controllers of the secondary turbine generator loop are modeled in six separate HTGR modules. Descriptions of the condenser, condensate pump, feedwater heater, deaerator, boiler feedpump and feedpump turbine, and feed system controls are contained in the feedwater module.

The steam generator module consists of a moving boundary model of the water/steam economizer, evaporator, and superheater sections of a once through steam generator. Lead-in and lead-out sections on the steam side
are included. Water momentum, energy, and continuity are treated dynamically. Tube-wall temperature are also computed dynamically. The model is capable of treating start up and flood out.

During normal operation steam leaves the steam generator and enters the high pressure turbine (HPT). The HPT module contains models of the HPT, the turbine throttle valve, an atmospheric relief valve, a bypass valve, desuperheater, flash tank, are auxiliary steam header, and air auxiliary boiler. During startup and turbine trips the HPT is isolated and steam flows through the HPT bypass leg containing a desuperheater and flash tank for extended steam production as required by the helium-circulator turbine. When flash-tank steam is exhausted the auxiliary boiler is used.

The helium-circulator turbine-compressor module contains models of the compressor and turbine with a speed control valve and a pressure-ratio control valve. The circulator speed controller is used to compensate for errors in the steam-generator water exit temperature.

The reheater module contains a model of the helium, steam, and tube-wall heat transfer. Steam momentum, continuity, and energy relationships and tube-wall energy relationships are treated dynamically.

Steam leaves the reheater and enters the intermediate and low pressure turbines (IPT/LPT), then proceeds to the main condenser. The IPT/LPT module contains models of these turbines with appropriate extraction steam flows and the turbine bypass system. The bypass includes an atmospheric relief valve, a bypass valve, and a desuperheater.

PLANT CONTROL

Three major plant control loops are contained in CHAP-1. The input, output, and feed-forward variables for each loop are:

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Feed-Forward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main steam temperature</td>
<td>Helium circulator speed</td>
<td>Feedwater flow</td>
</tr>
<tr>
<td></td>
<td>valve position</td>
<td></td>
</tr>
<tr>
<td>HPT throttle pressure</td>
<td>Feedpump turbine admission</td>
<td>HPT first stage</td>
</tr>
<tr>
<td></td>
<td>valve position</td>
<td>pressure</td>
</tr>
<tr>
<td>Reheat exit steam</td>
<td>Control rod position</td>
<td>HPT first stage</td>
</tr>
<tr>
<td>temperature</td>
<td></td>
<td>pressure</td>
</tr>
</tbody>
</table>

In addition to the 114 state variables contained in the HTGR modules there are 19 state variables associated with valve actuators and controllers.

SAMPLE TRANSIENTS

A CACS transient analysis was performed to study the loss of all main coolant circulation after a turbine and reactor trip from 100% reactor power. Three CACS loops were operating during the decay power transient. The faulted condition represents a total loss of feedwater flow. Secondary loop modules are involved in this transient only in that they help define the initial conditions.
Initially the main circulators are turned off, the main steam generator loops are isolated, the reactor is tripped, and the auxiliary circulators are turned on. Prompt power decreases to zero in 25 seconds leaving decay heat for the remainder of the transient. Three hours of the transient were simulated on a CDC 7600 in 506 seconds of computer time.

At the start of the transient the CAHE inlet water flow rate is increased to its operational setpoint which causes a decrease in the inlet water temperature. Figures 5 and 6 show some of the key variables in the scenario. During the first half hour the auxiliary circulator speed remains at its minimum controlled value until the CAHE outlet water temperature is reduced to its setpoint value. The circulator speed then increases to keep the CAHE water outlet temperature at its setpoint. After approximately 1 hour the speed has increased to a point where the maximum allowable circulator torque is reached. Speed then increases slowly with time for the remainder of the transient. Residual heat removal by the CAHE is very low after three hours.

Reactivity insertion transients have been simulated to predict conditions with and without various system protective actions. CHAP-1 includes the operational protection system (OPS) and plant protection system (PPS) actions which can be impaired through input data options. OPS actions tend to compensate for slow transient behavior and modify the main plant control loops. PPS actions, such as a reactor trip, are required to rapidly terminate fast transients. A summary of the protective actions initiated where the reactor-power rate or the power-to-flow ratio exceed their setpoint is given below.

<table>
<thead>
<tr>
<th>System</th>
<th>Monitored Variable</th>
<th>Setpoint</th>
<th>Protective Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPS</td>
<td>Rate-of-power increase</td>
<td>1 decade/min</td>
<td>Rod withdrawal prohibit</td>
</tr>
<tr>
<td>OPS</td>
<td>Power-to-flow ratio</td>
<td>1.2</td>
<td>Rod withdrawal prohibit</td>
</tr>
<tr>
<td>OPS</td>
<td>Power-to-flow ratio</td>
<td>1.3</td>
<td>Power setback</td>
</tr>
<tr>
<td>PPS</td>
<td>Power-to-flow ratio</td>
<td>1.4</td>
<td>Reactor trip</td>
</tr>
</tbody>
</table>

A rod withdrawal prohibit prevents further withdrawal of any control rod. A power setback initiates an insertion of central control rods until the power-to-flow ratio is reduced to 0.95, where withdrawal prohibit is enforced. A reactor trip causes all control rods to be fully inserted.

Figures 7 and 8 illustrate the response of some core variables to rod-withdrawal transients with and without the OPS action of rod-withdrawal prohibit. Each case was studied using isothermal and separate fuel/moderator reactivity temperature coefficients. The scenario assumes that the central control rod is withdrawn from the core at its design rate. The power-to-flow ratio was the only variable monitored by the protection systems to achieve its setpoint value. For the cases without rod-withdrawal prohibit the negative temperature feedback reactivity stabilizes the power soon after a power-to-flow ratio of 1.2 is attained. The isothermal transients are faster.

One-dollar step insertion transients were also studied with and without the PPS action of reactor trip. All OPS actions were not operational. Figures 9 and 10 show the response of core variables to this simulation.
Fig. 5. CACS Transient for Loss of Feedwater Flow Scenario.
Fig. 7. Power-to-Flow ratios for the Central Control Rod withdrawal Scenario.

Fig. 8. Maximum Fuel Temperatures for the Central Control Rod Withdrawal Scenario.

Fig. 9. Power-to-Flow Ratios for the One-dollar Step-insertion Scenario.

Fig. 10. Maximum Fuel Temperatures for the One-dollar Step-insertion Scenario.
REFERENCES


