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ANALOG SIMULATION OF HANFORD DUAL PURPOSE

REACTOR PLANT

by

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ANALOG SIMULATION OF HANFORD DUAL

PURPOSE REACTOR PLANT

SUMMARY

An analog simulation of the dual purpose Hanford N-reactor was undertaken. Studies were performed to determine the dynamic characteristics of the plant and to determine possible plant, operator, and control system malfunctions. Various operational procedures and proposed design changes were also studied.

The simulation of the reactor plant was made up of a series of subsystems which were coupled together. Each subsystem had been studied in detail previous to being assembled into the total reactor plant simulation.

Analog studies showed that it was possible to predict dynamic characteristics resulting from spurious transients such as reactor scrams and component failures. In addition, study of system control methods revealed certain desirable modifications to the reactor primary coolant and secondary heat dissipation system. Approximate controller settings were determined, by use of the simulation, which increased the stability of both the primary and secondary systems. In this paper, which is a progress report, it is shown that an entire reactor plant, including a heat dissipation system, can be successfully simulated and that simulation results are useful as guidelines in complex plant operation and control.

I. PLANT DESCRIPTION

The N-reactor plant system consists of a group of interconnected subsystems. The complete plant is divided into two flow loops, a primary coolant system, and a secondary heat dissipation system (Fig. 1). The common medium between the two systems is the steam generator where reactor heat is transformed to steam which will operate the electrical generation plant and auxiliary equipment.

The primary coolant system is made up of the reactor, primary side of the steam generator, and the primary coolant pumps. The reactor has a graphite-moderated, water-cooled core with horizontal process tubes. These tubes house both the fuel and coolant water. [The reactor is ^{under} ~~over~~-moderated such that increases in coolant inlet temperature effectively reduce the power level.]

There are five primary pump loops which feed headers supplying coolant to risers that connect to the process tubes. The prime movers used to circulate water through the primary coolant piping are steam-driven turbine-pump combinations.

The secondary heat dissipation system consists of the secondary side of the steam generators, a system of [steam surface condensers] known as dump condensers, a condensate surge tank, and condensate feedwater pumps. The steam generators are shell-and-tube single pass heat exchangers. Each primary pump loop contains two steam generators. Condensate feedwater flow to the steam generator is controlled by feedwater control valves operated from steam generator water level. The dump condensers condense any excess steam not used by the electrical generating plant or auxiliary

HANFORD DUAL-PURPOSE N-REACTOR SCHEMATIC

FIGURE 1

steam loads. The 16 dump condensers have the capacity to dissipate the entire heat capability of the reactor during normal operation. The condensing rate in the dump condensers is controlled by the amount of condensing area available which is a function of the water level. The main steam header pressure setpoint and the condensate suction header-main steam header differential pressure setpoint control the level of water in the dump condensers.

The condensate surge tank serves to maintain secondary water inventory and secondary condensate pressure. Normal fill valves are controlled by the normal surge tank water level. Extremes in surge tank level actuate emergency fill and spill valves. Steam pressure in the main steam header, which is the steam distribution point, is maintained by butterfly control valves supplying the dump condensers. These valves will operate in conjunction with another set of butterfly control valves supplying the electrical generating plant when that plant is in operation.

The basic control of the reactor plant is accomplished by the usual two or three mode controllers. For example, the steam generator water level control employs both proportional and proportional-plus-integral control. Also, the control of the primary coolant pumps employs proportional-plus-rate-plus-integral control.

II. PURPOSE OF THE SIMULATION

The purpose of the N-reactor plant analog simulation was to study the dynamic characteristics of each subsystem as well as the dynamics of the complete integrated system. The simulation was used as a tool to show trends in the physical system dynamics. An approximate value of controller settings was also obtained from the simulation. However, analog results were not expected to match precisely the results of similar transients in the reactor plant due to operator functions and the limited amount of automatic control used at the reactor during testing procedures.

III. MODEL DEVELOPMENT

A. Reactor Kinetics

The N-reactor simulation model was based on the familiar space-independent kinetics equations such as:

$$\frac{d(PL)}{dt} = \frac{\delta K - \beta}{\ell^*} (PL) + \sum_{i=1}^{1 \text{ to } 6} \lambda_i C_i + (PL)_S$$

and

$$\frac{dC_i}{dt} = \frac{\beta_i}{\ell^*} (PL) - \lambda_i C_i$$

Reactor fuel and water temperatures were based on averaged tube temperatures, and flat reactor flux and temperature distributions as shown by

$$\frac{dT_{MR}}{dt} = \frac{a_{L8}b_{12}(PL)}{L_{TR}A_{TR}C_{MR}\rho_{MR}n_{TR}} - \frac{(UA)_{MR}}{A_{TR}C_{MR}\rho_{MR}} (T_{MR} - T_{WR})$$

and

$$\frac{dT_{WR}}{dt} = \frac{(UA)_{MR}(T_{MR} - T_{WR})}{A_{TR}C_{WR}\rho_{WR}} - \frac{\dot{M}_P(T_{OR} - T_{IR})}{L_{TR}A_{TR}\rho_{WR}n_{TR}} + \frac{UA_{GR}(T_{GR} - T_{WR})}{A_{TR}C_{WR}\rho_{WR}}$$

Detailed studies of the reactor kinetics were available by digital computer codes; therefore, for purposes of reactor plant studies, a relatively simple analog simulation was used. This provided a heat source for the heat dissipation system which generated realistic temperature transients for primary and secondary loop transient studies. A block diagram of the reactor kinetics is shown in Figure 2.

B. Primary Coolant System

The primary coolant analog model was simulated in two parts, a hydraulic model and a thermal model. The primary coolant hydraulics consisted of simulating the steam driven turbine-pump combination, the flow rates, and the pressure drops around the loop which included inertial terms. The mathematical model included equations such as:

pump head:

$$\Delta P_{jP} = \rho_{TR}b_{11} \left[H_{1P} \frac{N_{jP}^2}{N_{DP}} - f_{1P} \left(\frac{\dot{M}_{jP}}{n_{jP}} \right)^2 \right] \quad j = 1, 2$$

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pump speed:

$$\dot{N}_{jP} = \frac{a_{17}M_{jTP} - a_{19}}{N_{jP} - a_{18}N_{jP}^2} - \frac{a_{13}n_{jP}N_{jP}\Delta P_{jP}}{\rho_{IR}(a_{14}n_{jP}N_{jP} - a_{15}\dot{M}_{jP})} \quad j = 1, 2$$

flow rate:

$$\dot{M}_{jP} = \frac{n_{jP}\Delta P_{jP}}{\rho_{IR}b_{11}(\ell_{DP} + \ell_{SP})} - \frac{f_{DP} + f_{SP}}{n_{jP}(\ell_{DP} + \ell_{SP})} \dot{M}_{jP}^2 -$$

$$- \frac{n_{jP}(P_{IR} - P_{OR})}{\rho_{IR}b_{11}(\ell_{DP} + \ell_{SP})} \quad j = 1, 2$$

pipe friction factor:

$$f = \frac{2F}{g} \sum \frac{L}{DA^2\rho^2}$$

water inertia:

$$\ell = \frac{1}{g} \sum \frac{L}{A\rho}$$

friction pressure drop:

$$\Delta P = \rho b_{11} f \dot{M}^2$$

inertial pressure drop:

$$\Delta P = \rho b_{11} \ddot{\ell} \dot{M}$$

reactor pressure drop:

$$P_{IR} - P_{OR} = \rho_{IR} b_{11} (\ell_{RP} \ddot{\dot{M}} + f_R \dot{M}^2)$$

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The term j_P was used to allow a multiple pump simulation using the same equations.

The thermal model of the primary coolant included a simulation of the bypass valves which divert warm coolant around the steam generators. The purpose of this diversion was to better control the temperature of the primary coolant as it returns to the reactor. ~~These valves divert one-third of the~~ ^{OK} coolant flow to be mixed again with water from the steam generators. In setting up the equations for the thermal model, the water was assumed to be saturated with no two phase flow. The equations describing the bypass valve calculate the flow around the steam generator, determine the water temperature of that flow, and then average this with the outlet temperature of the steam generator to get the reactor inlet temperature. The water temperature was calculated by using a straight line approximation to a temperature-enthalpy curve of saturated water in the region of interest (see Fig. 3). Examples of the bypass valve equations are as follows:

valve flow:

$$\dot{M}_{BFX} = \frac{\xi_{BFX}}{b_{11} G_{BFX}} f_{PX} \dot{M}_{PX}$$

flow through the steam generator:

$$\dot{M}_{PX} = \frac{\dot{M}_P - n_C \dot{M}_{BFX}}{n_X}$$

coolant enthalpy downstream from steam generators:

$$h_{PP} = \frac{n_X \dot{M}_{PX} h_{OX} + n_C \dot{M}_{BPX} h_{IX}}{\dot{M}_P}$$

coolant temperature downstream from steam generators:

$$T_P - f(h_{PP}) = a_{45} h_{PP} + a_{46}$$

enthalpy approximation:

$$h_{IX} = f(T_{IX}) = a_{43} T_{IX} - a_{44}$$

Due to the physical distance between the reactor and steam generators, a sizeable temperature lag exists between these two points which is dependent on coolant flow rate. These lags were simulated by use of a time variant variable time delay unit² in both the upstream and downstream legs from the reactor. In addition, temperature lags exist in the inlet and outlet headers of the reactor. These were simulated by using the following type of equation:

reactor inlet:

$$T_{IR} = \frac{e^{-\tau_{IR} S}}{\tau_{IR} S + 1}$$

The remainder of the primary coolant thermal model will be discussed later as the primary side of the steam generator.

As a result of temperature changes in the primary coolant, either in the steam generator or in the reactor, or both, as for example, during a scram, there are marked changes in

volume of the coolant mass. These changes in coolant volume are absorbed in the primary coolant pressurizer. For simulation purposes, these volume changes were calculated as mass rate of change, or surge flow, as seen by the pressurizer based on temperature transients in the primary coolant. During a large temperature transient, i.e. a reactor scram, there are large temperature changes in both the reactor and the steam generators. Simulation of these volume changes involved the conversion of temperature to density, assuming saturated conditions, and this converted to a change in mass. The equations describing such conditions are time dependent in that the coolant mass at one instant of time is calculated and compared to the coolant mass calculation at another instant of time. The difference represents the rate of change of coolant mass due to temperature changes. Equations of this model are:

at time = t_1 in the reactor:

$$M_{WR1} = \frac{V_{WR}}{2} \rho_{IR1} + \frac{V_{WR}}{2} \rho_{OR1}$$

at time = t_2 in the reactor:

$$M_{WR2} = \frac{V_{WR}}{2} \rho_{IR2} + \frac{V_{WR}}{2} \rho_{OR2}$$

The difference give

$$M_{WR2} - M_{WR1} = \frac{V_{WR}}{2} (\rho_{IR2} - \rho_{IR1}) + \frac{V_{WR}}{2} (\rho_{OR2} - \rho_{OR1})$$

or

$$\Delta M_{WR} = \frac{V_{WR}}{2} \Delta \rho_{IR} + \frac{V_{WR}}{2} \Delta \rho_{OR}$$

and in the limit as $\Delta t \rightarrow 0$

$$\frac{dM_{WR}}{dt} = \frac{V_{WR}}{2} \frac{d\rho_{IR}}{dt} + \frac{V_{WR}}{2} \frac{d\rho_{OR}}{dt}$$

The same calculations were made for the temperature transients in the steam generator and the sum of the two, reactor and steam generator, gives the mass surge rate seen by the pressurizer. Other parts of the primary loop such as the primary pumps and coolant connecting lines were not considered as sources of temperature transients.

C. Pressurizer-Injection System

The primary coolant pressurizer is used to maintain the coolant pressure and to act as a surge tank for changes in coolant volume caused by temperature transients. The injection system is used to supply makeup water to the primary coolant. The injection inlet valve to the primary coolant is controlled by pressurizer water level and the injection pumps are controlled by the pressure differential across this valve. This differential pressure is a function of the pressurizer pressure. A pressurizer-injection system analog model was not used in conjunction with the overall reactor plant simulation because the dynamics of the pressurizer-injection system do not affect the dynamics of

of the reactor plant to any large degree. For short term transients, this is especially true. The dynamics of the reactor plant, however, do affect the pressurizer injection system dynamics. A separate study of the pressurizer-injection system was made^{3,4}.

D. Steam Generator

The steam generator was simulated by first considering a thermal model of the primary side and then simulating the hydraulics of the secondary side. The primary system model was described by means of finite difference equations of the form:

$$(M_P C_P + M_M C_M) \frac{d\bar{T}_P}{dt} = \dot{M}_P C_P (T_{PI} - T_{PO}) - UA(\bar{T}_P - T_S)$$

which represented each of the three primary nodes. The rate of heat transfer to the secondary is the sum of the heat transferred from each node. The secondary side of the steam generator was considered to be space independent, i.e. uniform steam and water temperature distribution. Heat transferred from the primary to the secondary was calculated on the basis of the difference between each primary section average temperature. Water density was a function^{of} steam pressure and load flow. The steaming rate of the secondary was calculated on the basis of an energy balance of the form:

$$\dot{M}_{WGX} = \frac{1}{h_{GX} - h_{FX}} \left[\dot{Q}_X + \dot{M}_{FWX}(h_{FWX} - h_{FX}) - \dot{M}_{WX} h_{FX} \right]$$

where

$$h_{GX}, h_{FX} = f(P_{GX})$$

Saturated steam and water conditions were assumed in all calculations. The liquid level calculations in the secondary side was based on a volume calculation which was determined by a water mass-density relationship. A shape factor was applied to the volume calculation which considered the curvature of the bottom half of the steam generator.

E. Secondary Coolant System

Steam collected in the main steam header is distributed to various loads. ~~During Phase I,~~ The main steam header acts as a pressure control point for the secondary system. Constant pressure is maintained by adjusting the outflow equal to the inflow. The pressure is assumed to be proportional to steam mass where the mass is the initial steam mass plus the time integral of the difference between steam inflow and outflow from the header, or

$$M_{GH} = \int (n_X \dot{M}_{GOX} - n_D \dot{M}_{GID} - n_P \dot{M}_{TP} - \dot{M}_{2H}) dt + M_{GHZ}$$

The analog models were based on the properties of a single unit and the use of "n" factors (n_D , n_P , etc.) let the model represent the number of units required for a particular study. During Phase I operation, most of the steam will be condensed in the dump condensers which makes the dump condensers of major importance. The condensing rate was calculated as being the product of nonlinear functions of pressure and water level, or

$$\dot{M}_{GWD} = [f(P_{GD})] [f(L_{WD})]$$

A surge tank and four standpipes are used to maintain the secondary coolant liquid inventory. Simulation of the inventory system was based on conservation of mass. Thermal effects were assumed to be constant. This constitutes one of the major limitations of the secondary simulation. Secondary system water was basically controlled by surge tank water level; however, under certain conditions, other types of control were used. Water level in the surge tank was calculated by dividing volume by area, or

$$L_{WS} = \frac{V_{WS}}{A_S}$$

Surge tank pressure is used to control the pressure of the condensate header, or

$$P_{CH} = P_{GS} + \rho_{WS} b_{11} (H_{2S} + L_{WS})$$

Realistic simulation of the inventory control system requires accurate ^{MODELS} models of the fill and spill control valves and associated pumps and piping. Condensate and fill pump characteristics, piping frictional and inertial coefficients, and valve coefficient versus stroke nonlinearities were included where they were significant.

F. Control Systems Simulator

The control systems were considered to be made up of the devices that measure process variables and provide corrective actions that are related to these process variations by preselected

or adjustable control functions. They include process transmitters (pressure, temperature, flow, etc.), controllers, comparators, and final control element actuators.

Continuous controllers are the devices that continuously monitor a selected process variable, compare the measured variable to a desired value, and operate on the instantaneous error (or deviation) signal in such a way that the controller output signal can be used to reduce or eliminate the deviation. The N-reactor heat dissipation system is provided with electronic controllers using a -25 to +25 V signal range to represent 0 to 100% of the desired instrument range. Five basic types of control units are used:

- Proportional (or Summing),
- Proportional-plus-reset,
- Proportional-plus-rate,
- Rate,
- Lag.

Early simulation studies on N-reactor subsystems used actual controllers for real-time simulations. However, it soon became apparent that much time could be saved by operating many of the simulation models on accelerated time scales, especially when doing systematic parametric studies. The limited frequency response of the controllers dictated the use of simulated controllers for this purpose.

With this in mind, it was decided to build a separate control system simulator that could be used with any analog computer

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process simulation⁵. The control system simulator consists of two equipment racks, each of which contains twenty operational amplifiers and associated control circuit plug-in boxes. All mounting receptacles for the plug-in boxes are wired identically to facilitate changing control modes or controller arrangements. Plug-in boxes are available for all of the above basic types of control units except lag.

Four general types of control valve characteristics are in use in the N-reactor Plant:

- Linear,
- Equal-Percentage,
- Butterfly (vane),
- Quick-Opening.

For the linear valve, the simulation is the solution of a linear equation. For the nonlinear characteristics, arbitrary function generators are used to represent the manufacturer's curves. Even so-called linear valve characteristics should be checked, especially if steady-state operation under low-flow (nearly closed) conditions is required. The linearity normally breaks down when the valve is 1 to 10% open.

G. Time Scale

The process dynamics of the N-reactor plant are quite slow, especially in the secondary system during large transients. Also, the time response of these transients can be greatly affected by controller settings. The purpose of

the N-reactor plant study was to determine good operating conditions and best controller settings. Therefore, a large number of studies were required which necessitated an acceleration of the studies being made. For these reasons the simulation was done in ten times real time.

IV. OVERALL PLANT SIMULATION MODEL

The preceding sections discussed the bases for the simulation of major N-reactor system components. Each of the subsystems was simulated separately in various stages of development. Using the subsystem simulations required that certain assumptions be made concerning the behavior of external parts of the plant and that suitable functions be generated to represent all the important connecting variables. As more subsystems were joined, fewer external functions were needed.

Some of the most important considerations in determining the scope of an overall basic plant simulation model were:

- Amount of computing equipment available and arrangement of computer control logic,
- Required degree of detail needed for useful results,
- Relative importance of each subsystem to results obtained from overall system studies.

A. System Design Adequacy

The coupling of each subsystem together into a large overall system presented an excellent opportunity to study adequacy of each component. In a system the size of the

N-reactor plant, it is difficult to piece-meal study each component under all of its dynamic loading. The overall simulation was able to indicate what areas of design could be re-evaluated. For example, reactor scram studies revealed that the enlarging of the surge tank would give better transient operation. Also, a study of the control modes for the pressurizer pointed out the need for rate action in the level control.

B. System Dynamics

The study of large system disturbances such as those due to reactor scrams is difficult analytically for many reasons. Scram action initiates many changes in operating conditions, controller setpoints, etc., in addition to the resultant rapid change in reactor power level. As a result the analytical model must be capable of handling the process nonlinearities that must be considered because of the large changes in process operating conditions. Therefore, the overall basic simulation can be used to study overall system effects due to scrams, and methods of minimizing safety, operational, and equipment hazards. Caution must be used, however, in setting up criteria for optimizing operating procedures on the basis of the basic model, since the effects of unequal operation of paralleled process units should be evaluated.

C. Operating Procedures

The "basic" overall simulation and the control system simulation provide a convenient way of studying the effects of various types of operating practices. For example, a change in the primary coolant temperature controller setpoint might be made by the heat dissipation plant operator. One result will be a change in secondary system steam pressure setpoint and a disturbance to surge tank and steam generator level control systems. Another effect will concern the reactor operator in that the resulting change in primary coolant temperature will tend to change reactor power level, due to the coolant reactivity temperature coefficient. If the reactor operator has been instructed to maintain constant reactor power level, the above change will require compensating action on his part. Thus, interactions between operators as well as plant interactions can be studied safely by using the simulation.

D. Controller Setting

The N-reactor plant uses many automatic controllers to hold system variables within acceptable limits despite the occurrence of various disturbances. Acceptable system performance often depends on relatively accurate adjustment (tuning) of the controller to effectively compensate for process dynamic characteristics (time lags, nonlinearities, etc.). Analytically determining the proper controller settings is difficult and time consuming on complex systems having many interactions and nonlinearities. The overall basic simulation offers a

means of determining "tuning" philosophy and quickly obtaining near-optimum settings for some of the major system controllers, such as total primary coolant flow, primary coolant temperature, steam generator liquid level, secondary system steam pressure and header differential pressure, and surge tank liquid level.

It should be pointed out that the term "optimum controller settings" implies that a performance index has been defined. In general, optimum settings for controllers used in interacting process systems involve some compromises with respect to attainable performance in the control of each specific measured variable in the system. Optimum settings for a specific controller might not provide minimum deviations in the associated measured variable, regardless of its effect on the rest of the system. This is particularly true in the secondary system where it has been found that steam generator level and steam pressure controller gains must be kept relatively low to prevent unacceptable variations in surge tank level during various types of disturbances.

Control systems that have relatively minor interactions with other systems can be adjusted to near-optimum settings quickly using the analog simulation. Examples are the injection system pump speed controller, pressurizer level controller, and primary coolant flow controllers. Performance indexes such as integral of absolute (or squared) error, pressurizer

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level, peak pressurizer pressure, etc. have been used effectively to study control system capabilities. Accelerated time scaling in the simulation (X10 or X100) saves much time when performing controller optimization studies on the slower processes.

Performance indexes are helpful in the study of control system behavior even if a minimum (or maximum) value of the performance index does not yield a true optimum condition. It is often desirable to obtain a measure of the relative sensitivity of the process to changes in controller settings or parameter changes. Using the performance index with the associated process time response curves leads to a better understanding of the overall system behavior.

E. Simulation Limitations

The three basic limitations of the overall simulation are:

- An inability to study effects in one or more of the total number of paralleled process units without assuming the same effects in all similar units,
- The use of constants to represent quantities which may vary significantly in certain types of studies,
- Deletion of various process mechanisms to simplify the model.

The use of only one model to represent primary pumps, steam generators, dump condensers, etc., limits the types of system malfunctions that can be studied to those which affect all parallel units equally. For example, the effect of dropping a primary coolant pump off the line cannot be simulated realistically. Total flow changes might be determined by setting up a special two-pump model simulation of the primary hydraulic system, generating total and loop flow transients, and applying these as functions of time to the steam generator model in the overall simulation, but the effect on the secondary system would still not be the same as if two steam generator models were also used. Similar examples of changes of malfunctions in one or more of the paralleled steam generators or dump condensers would be difficult to simulate.

However, the practice of adding extra process models to the basic simulation improves the approximation and is sometimes justified.

The basic simulation assumes that heat transfer coefficients, primary coolant density, secondary system condensate, etc., are constant during operation near some selected set of operating conditions. As long as deviations from these conditions are relatively small, the approximation is good. However, during scram or similar large transients, the effects of the assumptions must be evaluated. The analog computer multiplier compliment is completely used, thus making it

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necessary to treat some of the variables as constants.

Future computer expansion plans will partially solve this problem by permitting the use of multipliers to replace potentiometers set for constant values of coolant density, heat transfer coefficients, etc.

The third type of limitation is the deletion or simplification of certain process calculations or mechanisms to reduce the amount of required computing equipment. Examples are the lack of process temperature calculations in the secondary system, and the simulation of control valve flow assuming either constant differential pressure or a straight-line approximation to the square root calculation [Equation (13C)] around the normal operating point. These approximations were made to release nonlinear equipment for more critical calculations.

F. Simulation Advantages

The existence of the N-reactor plant analog simulation presented certain advantages which became increasingly more apparent as construction of the physical plant progressed.

Tests were performed on the analog which could not be performed on the actual plant. Simulation of such things as ruptured pipe lines were easily and safely done on the analog simulation. In addition, the physical plant is limited in the number of scrams which it can withstand, the number possible on the analog is unlimited.

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System "bugs" were revealed which beforehand had been unsuspected. It was discovered that signal limiters were necessary on certain control elements because of controller gains and measured variable rate of change. One particular aspect of the simulation, but not yet taken full advantage of, is the possibility of instruction for plant operators to better understand the plant. It would be possible to introduce transients into the system and allow the operator (for example, the power operator) to control reactor power level during the transient.

An accelerated time scale made it possible to study long term transients in a relatively short time.

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