**PATHFINDER ATOMIC POWER PLANT
INTERIM PROGRESS REPORT
OF
REACTOR SYSTEM DYNAMIC ANALYSIS
WITH PATHFINDER TRANSIENT SIMULATOR**

Submitted to
**U. S. ATOMIC ENERGY COMMISSION
NORTHERN STATES POWER COMPANY**
and
CENTRAL UTILITIES ATOMIC POWER ASSOCIATES
by

**ALLIS-CHALMERS MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION
Milwaukee 1, Wisconsin**

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By

J. T. Stone, D. Mohr, and R. Schlicht

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ALLIS-CHALMERS MANUFACTURING COMPANY

Under

Agreement dated 2nd Day of May, 1957, as Amended
between

Allis-Chalmers Mfg. Co. & Northern States Power Co.
under

AEC Contract No. AT (11-1) -589

March 15, 1960

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March 15, 1960

INTERIM PROGRESS REPORT
OF
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WITH PATHFINDER TRANSIENT SIMULATOR

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INTRODUCTION

The Pathfinder Atomic Power Plant, which will be located at a site near Sioux Falls, South Dakota, is scheduled for operation in June 1962. Owners and operators of the plant will be the Northern States Power Company of Minneapolis, Minnesota. Allis-Chalmers Manufacturing Company of Milwaukee, Wisconsin, under contract with Northern States Power Company, is performing the research, development, and design; and will construct the plant including the reactor. Conceptual engineering and component research and development is being done at Allis-Chalmers Greendale Laboratories.

The reactor is designated the Controlled Recirculation Boiling Reactor with Nuclear Superheater. Light water is used as coolant and moderator. The core consists of two regions: the annular boiler region in which saturated steam is produced, and the central superheater region in which steam is superheated. Superheated steam passes directly to the turbine.

This report is an explanation and summary of dynamic analyses of Pathfinder performed on the Allis-Chalmers analog computer up to March 31, 1960. The first section describes the Pathfinder Transient Simulator and the assumptions used in its derivations. The second section presents the solutions to problems that have been solved by the simulator.

Among the advanced features that are considered in the dynamic analysis are the forced recirculation system and the integral nuclear superheater. The recirculation system which includes three externally located centrifugal pumps will circulate coolant through the core to increase hydraulic stability and power output over that which could be achieved from the same core with natural

circulation. Reactor power level will be controlled in the operating power range by controlled recirculation flow or by control rod position. Gross power changes will be accomplished by manual control of rods, but smaller power adjustments will be made by varying recirculation rate. Control of recirculation will be via manual control of butterfly valves.

Steam line pressure will be regulated automatically by varying the position of the turbine inlet valves. Thus, no steam will be bypassed for pressure control during normal operation. It should be noted that the terms "control" and "regulation" are used interchangeably in this report when describing the pressure control system.

The reactor core consists of two regions: (1) The annular boiler region in which saturated steam is produced, and (2) the central superheater region where the steam is passed directly to the turbine. The boiler and superheater regions are designed to function together as a single reactor. The effects of nuclear coupling between boiler and superheater, however, are presently being investigated.

DESIGN DATA

CRBR WITH NUCLEAR SUPERHEATER

Plant

Power, boiler region.....164,000 kw
Power, superheater region39,700 kw
Steam flow at rated power.....615,000 lbs/hr
Total core power.....203,700 kw
Gross electrical capability.....66,000 kw
Net electrical output.....62,000 kw
Net efficiency.....30.5 per cent
Steam outlet pressure.....545 psia
Reactor operating pressure.....615 psia
Temperature, boiler region.....489 F
Outlet temperature, superheater region.....825 F
Gross heat rate.....10,370 btu/kw hr
Reactor building size.....50 ft dia x 120 ft

Reactor

Vessel size.....11-1/2 ft x 31-1/2 ft
Total core dimensions.....6 ft x 6 ft
Dimensions of superheater region.....6 ft x 30 in
Fuel, boiler (Al clad).....approx. 1.8 per cent enriched UO₂
Fuel, superheater (S.S. clad).....approx. 93 per cent enriched UO₂
Fuel, loading, boiler (U-235).....117 kg
Fuel, loading, superheater (U-235).....42 kg
Power density (boiler core coolant).....87 kw/liter
Average heat flux, boiler region.....130,000 btu/hr/ft²
Average heat flux, superheater region.....80,000 btu/hr/ft²
Maximum heat flux, boiler region.....462,000 btu/hr/ft²
Maximum heat flux, superheater region.....250,000 btu/hr/ft²
Recirculation rate.....60,000 gpm
Recirculation pump power.....794 kw
Subcooling.....3.6 btu/lb
Superheater fuel hot spot temperature.....1350 F
Coolant recirculation time.....12.0 seconds
Steam quality at boiling core exit, % by weight.....2.6 %
Void reactivity at full power, steady state.....2.8%
Effective delayed neutron fraction.....0.007
Prompt neutron lifetime.....9 x 10⁻⁵ sec
Neutron fluxapprox. 5 x 10¹³ n/cm²sec

SECTION I.

General Description of Pathfinder Transient Simulator

The integro-differential equations describing the transient performance of the Pathfinder reactor and the turbine and associated control system have been programmed on an Electronic Associates Analog Computer (Pace 231-R). The assembly of the overall system is referred to as the Pathfinder Transient Simulator. The system model is valid if the reactor is:

- (1) Light water cooled and moderated.
- (2) Near critical.
- (3) Pressurized between 400 psia and 800 psia.
- (4) The boiling water type.
- (5) Assumed to be a point reactor, i.e. only the time variation of the neutron population is considered, not the distribution of the neutron population.

The simulator has been used to:

- (1) Help design and analyze reactor system controls.
- (2) Compute results of postulated accidents or operating errors.
- (3) Help establish operating and startup-shutdown procedures.
- (4) Predict system stability.
- (5) Show the effects of varying such parameters as power, pressure, void coefficients, and controller constants on transient response.

The equations which describe the Pathfinder dynamics have been constructed to describe deviations of the variables from an operating point. This does not mean the equations have been linearized; indeed, all important non-linear functions

have been retained and simulated by use of function generators and multiplying devices. The "transient" approach was used because the details of the deviations could be studied more easily.

A simplified block diagram of the simulator is shown in Figure 1. The "Reactor Kinetics" block represents the neutron kinetics equations with six delayed neutron groups. As was mentioned in the Introduction, the average neutron population is simulated since a point reactor model is being used. It was also assumed that because of the close nuclear coupling of the Pathfinder core that the superheater section neutron kinetics are identical to the boiling section neutron kinetics. The Pathfinder reactor has been designed for very little boiling of the superheater moderator; subsequently, the void coefficient has been assumed negligible. The temperature reactivity coefficient of the superheater is also negligible. Thus, there is little reactivity feedback from the superheater.

The "Boiler Heat Transfer" section represents the time lag between heat generation in the aluminum clad ceramic cylindrical fuel pins and the heat flow into the steam-water coolant. The thermal resistance includes an appropriate average film heat transfer coefficient for saturated water flowing at 615 psia. The transfer function has been approximated by a lag-lead-lag with time constants of 4.0, 1.37 and 0.4 seconds respectively.

The "Vessel Hydraulics" section is comprised of an energy, mass, and volume balance of the total primary system, including the water and steam in the reactor vessel, recirculation lines and pumps. An unbalance in the summation of energy terms associated with the boiler heat flux, steam leaving the vessel, feedwater

Figure 1

SIMPLIFIED PATHFINDER TRANSIENT SIMULATOR BLOCK DIAGRAM

LEGEND

- ΔK_R - Reactivity in Control Rods
- ΔK_D - Reactivity Due to Doppler Effect
- ΔK_V - Reactivity in Voids
- ΔK_E - Excess (Net) Reactivity
- n - Neutron Population
- $\dot{Q}_B$ - Heat Transfer Rate from Boiler
- W_S - Steam Flow Through Superheater
- W_W - Recirculation Rate Through Core
- Δh - Subcooling of Recirculating Water at Core Inlet
- P_1 - Reactor Dome Pressure
- $\dot{P}_1$ - Rate of Change of Reactor Pressure
- P_2 - Pressure at Superheater exit
- T_2 - Steam Temperature at Superheater Exit
- T_{SP} - Steam Temperature at Superheater Hot Spot
- T_{FP} - Fuel Surface Temperature at Hot Spot
- $\dot{q}_{SP}''$ - Heat Flux at Hot Spot
- S_C - Capacity Coefficient of Turbine
- S_E - Capacity Coefficient of Bypass Valves
- P_G - Power Output of Generator
- θ - Butterfly Valve Angle
- X_E - Steam Quality at Core Exit

entering the vessel and stored water and steam in the primary system causes a rate of pressure change. The transfer function operating on the summation of energy terms is a lead-lag circuit which accounts for the change in stored energy of the recirculating water and vessel steam upon a pressure change. The gain of this transfer function is dependent upon:

- (1) Total mass of water and steam in vessel.
- (2) Total volume of water and steam in the primary system.
- (3) Operating pressure of the reactor.

The lead and lag time constants are proportional to the water recirculation time and have values of 4.0 and 1.92 seconds, respectively. The pressure rate of change is then integrated to yield the pressure change.

The "Steam System" describes the relationship of steam flow rate, pressure at reactor and turbine, (P_1 and P_2), resistance of superheater and steam line, and positions of turbine inlet valves and by-pass valve (S_C and S_B). The compressibility of steam is approximated by means of a simple lag transfer function ($\tau = 0.106$ sec.).

The "Superheater Heat Transfer" block involves the time lag between heat generation in the annular stainless steel clad cermet fuel elements and the heat transferred to the steam coolant. The thermal transfer function is a double lag approximation with time constants of 0.95 and 0.15 seconds, respectively. The heat transfer equations involve the relationship between steam flow rate (W_S), power developed in superheater (assumed to be 21% of total thermal reactor power) and the pressure at inlet and exit of the superheater. The heat transfer coefficient varies with steam flow and film temperature, and the specific heat of steam is simulated to vary with the steam temperature. As was mentioned before,

the reactivity effects of the superheater are assumed negligible and there are no feedbacks to the internal system. The available output information of this block is:

- (1) Superheater hot spot cladding temperature.
- (2) Hot spot steam temperature.
- (3) Bulk average steam temperature at superheater exit.
- (4) Heat flux at hot spot.

The operating temperatures of the steam and fuel at the hot spot of the superheater (as in the boiler) are determined by applying hot spot factors to the power developed and heat transferred. The factors take account of the following effects:

- (1) Axial flux distribution.
- (2) Radial flux distribution.
- (3) Control rod flux perturbation.
- (4) Fuel uncertainty.
- (5) Flux uncertainty.
- (6) Steam flow uncertainty.
- (7) Heat transfer coefficient uncertainty.

The contributions of two separate hot spot factors comprise the total factor at a point. The bulk factors are applied to the heat absorbed by the steam up to a point (integrating effect), while the film factors are applied to the heat flowing from fuel to steam at a point. For the present superheater configuration without an overpower factor, the bulk and film hot spot factors have been evaluated at 1.578 and 2.013, respectively, for the purpose of simulation. In the equations simulating the heat transfer in the hot channel, the average channel

heat integrated to the hot spot is thus multiplied by 1.578. Similarly, the average channel heat flux is multiplied by 2.013 at the hot spot. Thus, the above hot spot factors are incorporated in the hot channel equations and are assumed to remain constant during a transient.

The "Control System" section simulates two separate controllers, each having adjustable proportional, reset and rate action applied to the incoming signals. Provision is made for the following variables to be controlled:

- (1) Reactor dome pressure, (P_1)
- (2) Superheater exit temperature, (T_2)
- (3) Superheater exit pressure, (P_2)
- (4) Power output, proportional to turbine steam flow, (P_T)

Deviations of the above variables can then be made to give any of the following control actions:

- (1) Variation of turbine inlet valve position, (S_C)
- (2) Variation of water recirculation rate by varying valve angle, (θ).
- (3) Insertion or withdrawal of control rods, (ΔK_R).
- (4) Operation of turbine by-pass valve, (S_B).

If the superheater exit pressure is made the controlled variable and change of inlet valve position is made the control action, the "Control System" becomes a simple pressure regulator system. This is the mode of control planned for Pathfinder.

The block labeled "Doppler Effect" relates negative reactivity effects due to a rise in the boiler fuel element temperature. This is a fast acting feedback mechanism.

"Subcooling and Exit Steam Quality" solves for the subcooling at core inlet and the average weight per cent of steam at the core exit (X_E). Exit quality is a function of the following variables:

- (1) Heat appearing at surface of boiler fuel pins ($\dot{Q}_B$): An increase causes an increase in steam void volume and decreased reactivity.
- (2) Recirculation flow rate (W_w): If the coolant is forced at a higher rate through the core, steam volume will initially decrease but eventually settle out at approximately the initial value.
- (3) Subcooling (Δh): The larger the temperature difference between water entering the core and that of saturation, the shorter will be the active core boiling length and the smaller the steam void volume. The transport lag due to water recirculation is included in this model.
(Transport time = 12 seconds at rated flow).
- (4) Reactor pressure (P): Fluctuations in pressure cause flashing (or condensation), and cause changes in subcooling and steam density. An increase in pressure causes a decrease in the steam volume in the core and consequently an increase in reactivity. The faster the pressure changes, the more severe the associated transient.
- (5) Steam flashing (and condensation): Formation of steam is proportional to the negative of pressure rate of change.
- (6) Steam density changes: Since void fraction is the volume per cent of steam in a given volume, it will change with pressure for a constant quality. An equivalent steam quality correction for pressure changes is thus generated as an additional input for the "Void Reactivity" model.

The "Void Reactivity" generates the negative reactivity feedback caused by

the presence of steam voids in the core. It can be described as a "steady state" function of steam quality at the core exit (X_E), and the subcooling (Δh) at the core inlet combined with a simple transfer function. The variables (Δh) and (X_E) inherently describe the void volume in the core, the recirculation rate, and the feedwater temperature. These curves are calculated from the physics and heat transfer characteristics of the core and are simulated on the analog computer by a function generator.

The output signal then feeds into the "transient effects" model involving the transient void distribution. A change in void concentration must be washed up through the core before its steady-state distribution is assumed. This complex transfer function is approximated by a simple lag with a time constant of 0.057 seconds (at rated flow).

The "Hydrodynamics" section generates the recirculation flow (W_w), which depends on the following:

- (1) Pump speed.
- (2) Core exit quality (X_E).
- (3) Butterfly valve positions in the three loops (θ).

A complete derivation of the equations leading to the Pathfinder Transient Simulator Block Diagram is given in a separate report, "The Pathfinder (CRBR) Simulator".

The total analog simulation utilizes approximately 110 potentiometers, 30 integrators, 45 summers, 25 inverters, 12 multipliers, 3 function generators, and 5 relays.

Section II.

Transient Simulator Results

This section of the report contains brief descriptions of various investigations, the analog computer solutions of the equations for various disturbances, and the conclusions drawn about the results.

The investigations can be classified into three general categories:

- (1) The stability of the overall reactor system with external controls.
- (2) System dynamic response to various disturbances.
- (3) External control system investigation.

As was previously mentioned, the Electronic Associates Analog Computer model 231-R was used in the simulation. The computer manufacturer states that the accuracy of the passive components in the amplifiers is $\pm 0.01\%$. The active amplifier accuracy is determined by its open loop gain, which is about 5.0×10^7 . With this high gain the grid current is approximately 10^{-10} amperes. Thus for practical purposes, the amplifier accuracy is determined by its passive elements. For solutions such as were done on the Pathfinder simulator, the servomultipliers have a stated accuracy of $\pm 0.1\%$. Electronic multipliers have even better accuracy specifications. The function generators are as accurate as they can be set, which always results in less than 1.0% error. The overall system accuracy cannot be directly stated without a detailed study since some errors are additive while others are subtractive. The conclusion to be drawn is that the computer handles the data given to it with an accuracy that is better than the accuracy that can be attached to the data itself.

1. Transfer Function Study

The entire reactor, turbine and pressure control system were subjected to a sinusoidal input. The output of $\frac{\delta m}{m_0}$ was recorded and a $\frac{\delta m}{m_0} \delta K$ closed loop transfer function was obtained. The closed loop transfer function was plotted with per cent δK . Both P_1 (steam dome) and P_2 (steam line) control were tried separately. Both curves in Figure 2 show that a low frequency resonance occurs at about 0.2 rad/sec. It has been shown that the superheater pressure drop directly affects this resonance peak. The inclusion of this flow resistance between the pressure sensing point and the turbine reduces the system low frequency damping coefficient. A more judicious choice of controller constants could reduce the magnitude of this resonance somewhat for P_1 control. For frequencies above 1 rad/sec. both P_1 and P_2 responses become identical. The high frequency resonance at 17 rad/sec. is caused chiefly by the fuel thermal time constants.

Generally, it is seen that the reactor system is stable with both types of control. However, the system has a greater margin of stability with P_2 control.

Figure 2

PATHFINDER SIMULATION CLOSED LOOP FREQUENCY RESPONSE
FOR P_1 REGULATION & P_2 REGULATION

2. Control Rod Reactivity Insertion

Conditions:

$\Delta k_{\text{rod}} = 5\text{¢}/\text{sec}$ for 10 seconds (curves 3, 4, and 5). $\Delta k_{\text{rod}} = 5\text{¢}/\text{sec}$ for 20 seconds (curves 6, 7, and 8). These rates of reactivity insertion were used because $5\text{¢}/\text{sec}$ was established as a maximum rate that could be attained by withdrawing the most valuable control rod.

These curves show several variables for both 50¢ and $\$1$ total positive reactivity inserted in a ramp manner. Calculations indicate that the changes are consistent, thus providing a check on the computer setup. This problem is done for both P_1 and P_2 regulation.

Figure 3 shows variations for P_1 control and Figure 4 for P_2 control. Figure 5 is a comparison between the important quantities. T_{FP} is very sensitive to W_s , steam flow rate in the superheater. Since W_s takes much longer to attain its steady state value with P_2 control compared to P_1 control, the superheater temperature peaks are higher with P_2 control. Notice that the steady state power levels are different in the two cases, being lower with P_1 control. This is due to the "tight" regulation of P_1 which in turn directly affects the number of voids in the core.

In curve 3, the dip in T_{FP} starting at about 20 seconds is due to the fact that steam flow was rising while power level was falling. Curves 6-8 are identical to the previous three except that a total of $\$1$ reactivity in rods was added. The variations are significantly larger.

It must be realized that 50¢ and $\$1$ are large amounts of reactivity to add. In all cases Δk_{excess} was less than 10¢ at any time during the transient.

NOTE:

$$\begin{aligned}\text{Cents of Reactivity } (\text{¢}) &= \frac{\Delta k}{\beta} \\ \beta (\text{effective}) &= 0.007 \text{ for Pathfinder} \\ \Delta k &= \text{reactivity } (\%) \end{aligned}$$

Figure 3

CONTROL ROD RUN-OUT

Operation at 100% power, linear reactivity addition
of $5\phi/\text{sec.}$ for 10 sec. Total reactivity added 0.50 .
 P_1 control.

Figure 4

CONTROL ROD RUN-OUT

Operation at 100% power linear reactivity addition
of 5¢/sec. for 10 sec. Total reactivity added 0.50
P₂ control.

COMPARISON OF P_1 AND P_2 CONTROL

Control rod run-out comparison of Figures 6 & 7.

CONTROL ROD RUN-OUT

Operation at 100% power, linear reactivity addition
of 5¢/sec. for 20 sec., Total reactivity added 1.00.
P₁ control.

CONTROL ROD RUN-OUT

Operation at 100% power, linear reactivity addition
of 5¢/sec. for 20 sec., Total reactivity added \$1.00.
P₂ control

CONTROL ROD RUN-OUT

Operation at 100% power, linear reactivity addition
of $5\phi/\text{sec.}$ for 20 sec. Total reactivity added $\$1.00$.
Comparison of P_1 and P_2 control.

3. Variation of Parameters Affecting Dynamic Response

It was expected that the major physical and mechanical reactor parameters have a marked effect on dynamic response during a transient. Parameters considered to be very important in this regard are:

- (1) Void coefficient.
- (2) Doppler coefficient.
- (3) Fuel heat transfer time lag.
- (4) Superheater design pressure drop at steady state.

Expected results were confirmed as shown.

Smaller void coefficient causes less negative reactivity feedback effect of voids; hence any disturbance causes relatively more change in power, pressure, temperature, etc. A smaller Doppler coefficient has the same effect to a lesser degree. Longer fuel element time constants result in higher and longer transients although they do not affect the steady state relationships. Larger superheater pressure drops tend to further isolate the reactor from the turbine, thus requiring a faster acting control system.

The means of simulating important functions also have a noticeable effect on dynamic response. An evidence of this is shown in the results involving re-circulation loop transport lags. ($e^{-\tau s}$). Simple lag representations such as

$$e^{-\tau s} \approx \frac{1}{1 + \tau s}$$

gave slightly optimistic results when compared with the more representative 1st order Padé approximation of:

$$e^{-\tau s} \approx \frac{e^{-\frac{\tau}{2}s}}{e^{\frac{\tau}{2}s}} \approx \frac{1 - \frac{\tau}{2}s}{1 + \frac{\tau}{2}s}$$

The more sophisticated quadratic Padé approximation gives still more pessimistic results.

$$e^{-\tau s} \approx \frac{e^{-\frac{\tau}{2}s}}{e^{\frac{\tau}{2}s}} \approx \frac{1 - \frac{\tau}{2}s + \frac{\tau^2}{11}s^2}{1 + \frac{\tau}{2}s + \frac{\tau^2}{11}s^2}$$

Since there is some degree of mixing and diffusion, it was decided that this last approximation gives a good simulation of the actual case, which may not necessarily be a perfect transport lag ($e^{-\tau s}$).

EFFECT OF SUPERHEATER PRESSURE DROP (ΔP) FOR STEADY STATE VALUES OF 75 psi (SOLID) & 45 psi (DASH) RODS OUT AT 5¢/SEC. FOR 10 SEC. - P_2 REGULATION

EFFECT OF VARIATION OF DOPPLER COEFFICIENT

RODS OUT AT 5 ϕ /SEC. FOR 10 SEC. - P_2 REGULATION

EFFECT OF VARIATION OF VOID-REACTIVITY
COEFFICIENTRODS OUT AT 5¢/SEC. FOR 10 SEC. - P_2 REGULATION

EFFECT OF VARIATION OF BOILER FUEL MAJOR TIME CONSTANT

RODS OUT AT 50¢/SEC. FOR 10 SEC.- P_2 REGULATION

RECIRCULATION LOOP TRANSPORT LAGS, SIMULATION SCHEMES

RODS OUT AT 5¢/SEC. FOR 10 SEC. - P_2 REGULATION

4. Response to Change of Load Demand

Conditions:

- (1) Reactor is operating at full power.
- (2) Load demand is manually changed 0.1%/sec. for 20 sec. for a 2% demand.
- (3) Both P_1 and P_2 control are used.

In this situation, the change of electrical demand is simulated by manual control of the butterfly valves in the recirculation loops. This would amount to the plant operator changing the plant output by further opening the butterfly valves far enough to obtain an increase of electrical output of 2%. The "time constant" of the entire system is seen to be about 30 sec. for P_2 control and 14 sec. for P_1 control. For this disturbance, P_1 control seems to do a better job.

GENERATOR DEMAND CHANGE

Reactor operating at 100% power, demand of electrical load changes 1.75% in 20 seconds, P_1 control.

GENERATOR DEMAND CHANGE

Reactor operating at 100% power, demand of electrical load changes 2% in 20 seconds, P_2 control.

COMPARISON OF P_1 AND P_2 CONTROL

Generator demand change. Comparison of Figures 11 & 12.

43-021

5. Feedwater Valve Opening Rate

Conditions and Results for Feedwater Study

The following initial conditions for the system were assumed:

- (1) Reactor operating at full power.
- (2) No manual or automatic reactor power control.
- (3) Feedwater increased from 0 to 100% of the full power value.
- (4) Initial subcooling enthalpy, Δh , is 1.8 Btu/lb. as compared with rated full power value of 3.6 Btu/lb.
- (5) Feedwater is at rated temperature of 360°F.

The six cases that were run can be divided into two basic groups as follows:

- (1) Increasing the feedwater rate linearly to 100% in 2, 5, and 10 seconds and regulating for constant pressure at the superheater exit, P_2 .
- (2) Increasing the feedwater rate linearly to 100% in 2 seconds and regulating for constant reactor pressure, P_1 , in one case and for constant P_2 in the other.

Comparing the cases for P_2 regulation and various valve opening times; it is seen that rates of change of the variables, e.g. reactor power, $\frac{dn}{dt}$, increase as the feedwater valve opening time decreases. However, the peak values depend very little upon the valve opening time. For P_1 regulation instead, and a 2 second valve opening time, all the peaks are reduced except for steam flow, while the reactor period remained the same.

As a result of this study it was decided to place a maximum opening time on the feedwater valve of 4 seconds (full closed to full open).

FEEDWATER VALVE OPENING

Comparison of feedwater inlet valve opening times.
(5 sec. and 10 sec.) P_2 control, 100% power
 $\Delta h = 1.8$ BTU/lb subcooling.

--- 10 SEC OPENING TIME
— 5 SEC OPENING TIME

REACTOR POWER

STEAM FLOW RATE

SUPERHEATER FUEL SURFACE TEMPERATURE AT HOT SPOT

SECONDS

75 024-038
8/2/57 8 of 9

Figure 48

FEEDWATER VALVE OPENING

Comparison of P_1 and P_2 control for valve opening time of 2 seconds.

-32-

(40)

6. Maximum Allowable Recirculation Flow Rate

In order to determine a maximum allowable recirculating water rate of change, a maximum allowable reactor power was first set at 115% rated power and a minimum allowable reactor period at 10 seconds. These criteria were contingent upon a maximum equivalent external reactivity insertion of 5¢/sec. at any time during a transient.

Computer results have shown that, for an increase in recirculation flow, maximum power is a function of total increase and $\frac{dn}{dt}$ (and minimum period) is a function of rate of recirculation increase, assuming flow always increases linearly.

For steam line pressure (P_2) regulation, the maximum allowable recirculation flow is 108.6% (7230 #/sec.). For a minimum 10 second period the maximum rate of change is 1.35%/sec. (90 #/sec.²). However, the more stringent equivalent reactivity insertion condition reduces this to 0.75%/sec. (50 #/sec.²). This is based on initial 100% power operation at 100% flow (6667 #/sec.).

Total Flow Change (#/sec.-%)	Rate of Change (#/sec. ² -%/sec.)	Max. Power (%)	Min. Period (sec.)
400 - 6	100 - 1.5	112	9.6
800 - 12	100 - 1.5	122	9.6
400 - 6	200 - 3.0	114	7.9
800 - 12	200 - 3.0	125	7.9
575 - 8.6	90 - 1.35	115	10
575 - 8.6	50 - 0.75	115	30

COMPARISON OF RECIRCULATION WATER
FLOW DISTURBANCES OF 6% (400#/SEC.) &
12% (800#/SEC.) AT A RATE OF 1.5%/SEC.
(100#/SEC²) - P₂ REGULATION

COMPARISON OF RECIRCULATION WATER
FLOW DISTURBANCES OF 6% (400#/SEC) &
12% (800#/SEC) AT A RATE OF 3%/SEC.
(200#/SEC²) - P₂ REGULATION

 W_w (%)

 n (%)

 ΔK_{EX} (%)

 P_1 (psia)

 T_{FP} (F°)

MAXIMUM ALLOWABLE RECIRCULATION WATER
FLOW FOR MAX. 115 % POWER & MIN. 10 SEC.
PERIOD: 108.6 % (7230 #/SEC.); 1.35%/SEC.
(90 #/SEC²) - P₂ REGULATION

43-024-104
KRM

7. Reactor Isolation With No Scram or Safety Valve Relief

If the radioactivity of the exhaust air from the reactor building exceeds a desirable level, the isolation valve will close automatically. Figure 22 shows the dynamic response to closing times of 4 seconds and 10 seconds assuming the scram mechanism and safety valve relief system fail. The assumption was made that the valve closes in a manner causing steam flow to decrease linearly with time. Solution of the problem for longer times was prevented due to computer overloading.

Figure 23 shows the pressure rise in the reactor dome following a sudden complete loss of steam flow. The reactor was operating at full power and no scram or pressure relief devices operated. This curve was hand calculated neglecting the change in pressure coefficient of reactivity over the wide range in pressure.

PRESSURE RESPONSE TO A STEP LOSS OF
FLOW ASSUMING NO CHANGE IN PRESSURE
REACTIVITY COEFFICIENT AT HIGH PRESSURE

43-024-176 TRM.

8. Various Control Schemes

Present control philosophy is based on superheater exit pressure (P_2) regulation with manual change of recirculation flow and control rod position for power changes. Simulation studies have included the use of the following signals as error signals for the pressure regulator.

- (1) Reactor Pressure (P_1).
- (2) Superheater exit (steam line) pressure (P_2).
- (3) Both reactor and steam line pressures ($P_1 + P_2$).

An automatic control system using recirculation flow rate or variable speed rod control has proven to be effective for controlling reactor power and steam line pressure.

PRESSURE REGULATION SCHEMES

RODS OUT AT 5¢/SEC. FOR 10 SEC.

AUTOMATIC RECIRCULATION CONTROL
FOR A 2% POWER INCREASE DEMAND (.1%/SEC. FOR 20 SEC.)
WITH β REGULATION

43-024-178 K.R.M.

AUTOMATIC CONTINUOUS CONTROL ROD CONTROL
FOR A 2% POWER INCREASE DEMAND ($1\%/\text{SEC}$ FOR 20 SEC.)
WITH P_2 REGULATION

43-024-179 JRM.

9. Comparison of Pressure Regulator Constants

The following three figures show the values of pressure regulator gains during a transient situation. Note that they have no effect on final steady-state values. The first two figures indicate the relative insensitivity of a P_2 regulator to change in its gain when compared to a P_1 regulator for an internal reactor disturbance (i.e. removal of control rods). The second and third figures indicate the relative insensitivity of a P_2 regulator to change in gain for a reactor disturbance when compared to a P_2 regulator for an external system disturbance (i.e. steam flow constriction). Optimum regulator gains were then derived from this study.

The type of control action used was proportional plus reset control. The output of the controller provides a signal to the turbine inlet valves proportional to the pressure error.

$$\delta S_c \text{ (demanded valve position)} = \delta P \left[K + \int KA \, dt \right]$$

For P_2 regulation it was decided that at this time $K = 0.03727$ and $KA = 0.0405$ gave the best transient response.

COMPARISON OF PRESSURE REGULATOR
CONSTANTS - P₁ REGULATION - RODS OUT
AT 54/SEC. FOR 10 SEC.

δn 10%/DIV.

CHANGE IN REACTOR PRESSURE

δP_2 5 psi/DIV.

CHANGE IN STEAM LINE
PRESSURE

δT_{FP} 20F°/DIV.

CHANGE IN SUPERHEATER FUEL
SURFACE TEMP AT HOT SPOT

0 20 40 60 80 100 120 140

SECONDS

COMPARISON OF PRESSURE REGULATOR
CONSTANTS - P_2 REGULATION RODS OUT
AT 5¢/SEC. FOR 10 SEC.

δn 10%/DIV.

CHANGE IN REACTOR
POWER

δP 2 psi/DIV.

CHANGE IN REACTOR
PRESSURE

δT_{FP} 20 F°/DIV.

CHANGE IN SUPERHEATER FUEL
SURFACE TEMP. AT HOT SPOT

0 20 40 60 80 100 120 140

SECONDS

COMPARISON OF PRESSURE REGULATOR
CONSTANTS - P_2 REGULATION - MOMENTARY
33% STEAM FLOW CONSTRICTION

FORCING FUNCTION ON S_C

δP 40% / DIV.

CHANGE IN REACTOR POWER

δT_{FP} 40 F° / DIV.

CHANGE IN SUPERHEATER FUEL
SURFACE TEMP. AT HOT SPOT

δP_2 5 psi / DIV.

CHANGE IN STEAM LINE
PRESSURE

2 SEC / DIV.

10. Comparison of P_1 & P_2 Regulation for Momentary Steam Flow Constrictions

In the event of a slight flow constriction due to a momentary valve failure or a mismatch of the turbine inlet and by-pass valves, a short transient can be expected. The gravity of the transient is a function of both the magnitude of the constriction and choice of the regulated pressure. The following plots indicate that for such an external disturbance, the maximum magnitude of the transient for reactor pressure (P_1) regulation is about twice the value for steam line pressure (P_2) regulation for both 10% and 20% constrictions.

COMPARISON OF P_1 (SOLID) & P_2 (DASH)
REGULATION MOMENTARY 10% STEAM
FLOW CONSTRICTION

FORCING FUNCTION ON SC

$n(\%)$

REACTOR POWER

$P_1(\text{psia})$

REACTOR PRESSURE

$P_2(\text{psia})$

STEAM LINE PRESSURE

$T_{FP}(F^\circ)$

SUPERHEATER FUEL SURFACE TEMP
AT HOT SPOT

SECONDS

COMPARISON OF P_1 (SOLID) & P_2 (DASH)
REGULATION MOMENTARY 20% STEAM
FLOW CONSTRICTION

FORCING FUNCTION ON S_C

$n(\%)$

REACTOR POWER

P_1 (psia)

REACTOR PRESSURE

P_2 (psia)

STEAM LINE PRESSURE

$T_{FP} (F^\circ)$

SUPERHEATER FUEL SURFACE TEMP
AT HOT SPOT

0 10 20 30 40 50 60 70
SECONDS

SECTION III.

Future Work

In the months ahead the Pathfinder simulator will be used in analyzing the system dynamic response.

The present model will be continuously reviewed and improvements will be made. As more experimental knowledge is obtained about the hydrodynamics and heat transfer of two phase boiling systems, it will be gradually incorporated in the Pathfinder model.

A recent expansion of the computing facility (shown in Figure 32) will allow more detailed studies of the following areas.

All of the system equations will be rescaled so that the large transients expected in some accidents can be simulated. Some expected studies are cold water accidents, isolation valve step closure with and without relief valves, and mismatch between the turbine inlet valves and by-pass valve during a low power turbine trip.

The pressure control system will be simulated in more detail. That is, transfer functions of electrohydraulic valve actuators, valve positions, and controller components will be simulated.

Also, although the effects of superheater reactivity additions are small, these will be studied further and included in the simulation model.

The fuel thermal time constants in the superheater and in the boiling core will be reviewed and necessary changes will be included in the model.

It is expected that the enlarged computer will allow a flux distribution stability study. Tendencies of "flux tilting" which may be caused by xenon feedback and void feedback will be investigated.

Finally, a study of the effects of boiling noise on the reactor dynamics will be initiated.

ALLIS-CHALMERS ANALOG COMPUTING FACILITY

FIGURE 32