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A SIMULATION STUDY OF A REFLECTOR CONTROL SYSTEM FOR A HETEROGENEOUS BOILING REACTOR

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A SIMULATION STUDY OF A REFLECTOR CONTROL SYSTEM FOR A HETEROGENEOUS BOILING REACTOR

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A study was made of the feasibility of using a reflector control system for a heterogeneous boiling reactor through use of analog simulation techniques. The reactor kinetics, reactivity, and steam generation were simulated electronically while the hydraulic portion of the reflector system was represented by a full-scale physical mock-up.

The two portions of the system were coupled together, and an attempt was made to achieve a stable, nonoscillating system. Various configurations of hydraulic coupling between the reflector tank and surge tank were used in an effort to produce the desired representation of the frictional forces in the system. A system of baffle plates in the coupling produced the desired damping.

With the stable system, the effect of steam-load-demand changes for various values of incremental moderator worth was examined.

These studies showed that a reflector control system for this type of reactor is feasible.

INTRODUCTION

One method of control of a heterogeneous boiling reactor uses the steam pressure in the reactor vessel to control the height of the water reflector surrounding the core. As the steam pressure increases, the reflector height and the reactor power level decrease. Thus, as the steam load varies, the pressure varies and forces the reactor power to follow the load changes.

Previously(1) this system was studied by an all-electronic simulation. The equations of motion for the hydraulic reflector system were derived and coupled to the pile kinetic equations. Suitable equations relating the steam-void fraction, reactor power, demand power, and system pressure were also included. The system response following a change in demand power was obtained for various demand-power changes. The results indicated that the control scheme was feasible. However, this simulation required making an assumption concerning the magnitude of frictional forces in the hydraulic system. It also required the assumption that inertial and frictional terms in the equations of motion of the water in the reflector system were determined primarily by the size of the connecting pipe from the surge tank. To avoid the necessity of making these assumptions, a physical simulation of the hydraulic portion of the system was undertaken.

To provide stable operation of this system, a design study was undertaken to specify the amount of damping needed in the connecting pipe. With a stable system the effects of changing the incremental moderator worth could be examined.

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(1) References appear at end.

DESCRIPTION OF REACTOR AND CONTROL SYSTEM

The boiling water reactor is different from most other types of reactors in that since steam is generated directly in the reactor core, an external heat exchanger is not required. A given steam temperature can then be attained with a lower average fuel temperature. Also since excess pressure is not required to prevent boiling, a requirement in other water-moderated power reactors, the pressure vessel can be designed for a lower pressure.

The reactor system as controlled by the height of the water reflector is shown as Figure 1. Boiling in the reactor core produces steam which is collected in the upper portion of the pressure shell and delivered to the load attached to the system. The flow of this steam upward through the core causes water to circulate up through the reactor, out through ports in the annular reflector tank, and down past the core along the inner surface of the main pressure shell.

The annular reflector tank surrounding the reactor core is partially filled with water. This water acts as a reflector for neutrons produced by the core, and as the level of this water decreases, the reactivity decreases. Openings around the top of the reflector tank admit steam to the upper surface of the water in the reflector tank. The water in this annular tank connects, through a pipe, to an external surge tank in which a reference gas pressure is maintained. Any excess steam pressure in the reactor over that required to maintain the water in the reflector system at equilibrium will cause the following sequence:

(1) Flow of water to the surge tank

(2) Decrease in reflector level

(3) Decrease in reactivity

(4) Tendency for a decrease in reactor power

(5) Return of the steam pressure to its equilibrium value.

ALL-ELECTRONIC SIMULATION

To determine the feasibility of using steam pressure to control the height of the water reflector in a heterogeneous boiling reactor, an all-electronic simulation was attempted.

The analysis of the reactivity effects associated with various changes in the reflector arrangement was evaluated using the standard two-group diffusion equations. The two-group constants used were taken from ANL-5452.(2) This procedure was used to calculate the reactivity change when the reflector tank was emptied. The results of these calculations indicated reactivity changes of minus 17.6 per cent.

A self-contained unit, similar to the one described in ORNL-1632(3), was used to simulate the nuclear kinetic equations.

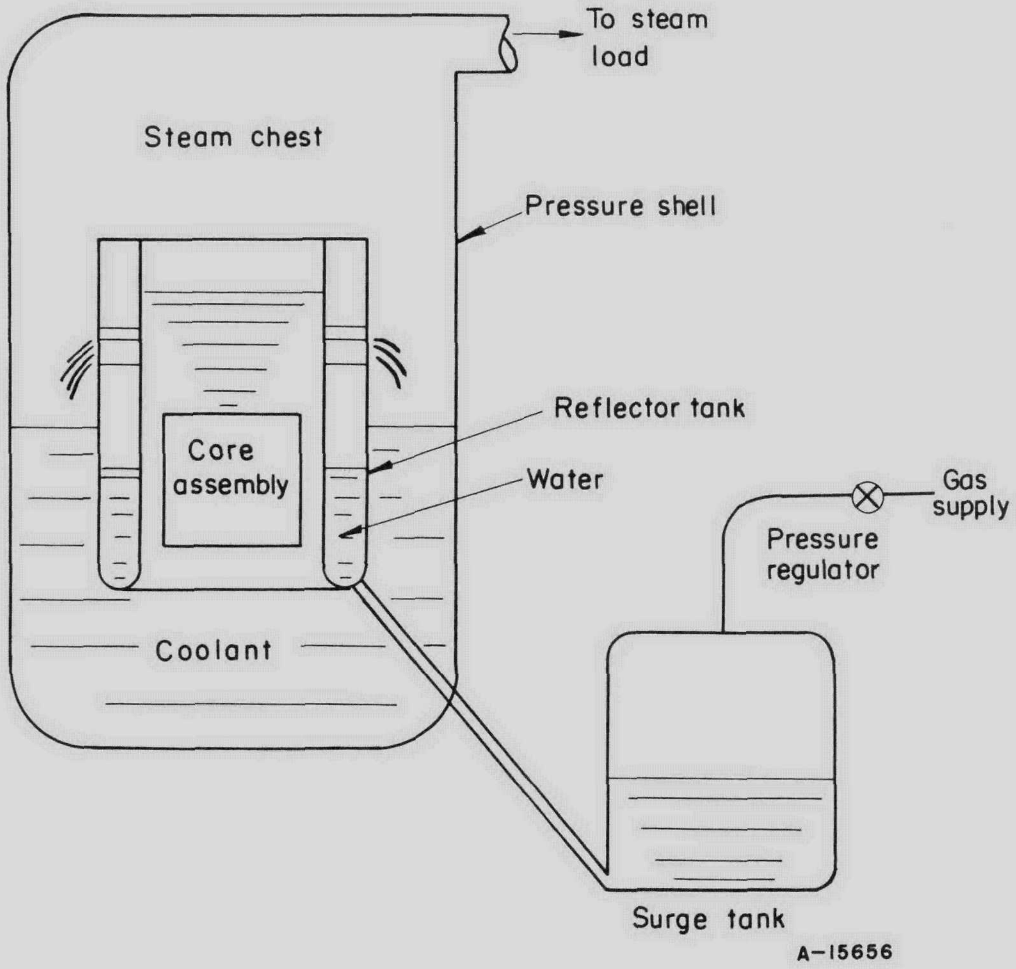

FIGURE 1. DIAGRAMMATIC SKETCH OF HETEROGENEOUS BOILING REACTOR WITH REFLECTOR CONTROL

The temperature coefficient of reactivity was assumed to be minus 10^{-4} δk per deg F and, since it was further assumed that the temperature of the moderator in the core structure was approximately equal to the saturation temperature of water at the operating steam pressure, the pressure coefficient of reactivity became 3×10^{-5} $\delta k/(lb)(ft^2)$.

Information regarding the effect of steam-void fraction to produce a change in the multiplication factor was taken from ANL-5452. The void fraction depends upon the operating power level and upon the steam pressure. An increase in void fraction produces a decrease in the multiplication factor.

It was assumed in this study that the total height variation of the reflector was 2 ft, and that this represented a total reactivity change of 8 per cent.

The annular tank surrounding the reactor core contains the water reflector and is joined to an external surge tank through a connecting pipe. The level of water in the reflector tank changes to offset the change in steam-void fraction as the operating power of the reactor varies and provides a means of reactor control. Equations of motion describing this hydraulic system were derived to represent this portion of the simulation. Such a system tends to oscillate, and with insufficient hydraulic damping, this tendency to oscillate could adversely affect the power system's operation. Also the response time of this control scheme must be sufficiently short to regulate the power level of the reactor without introducing additional oscillating tendencies and to permit the reactor power to follow steam-load variations.

Sufficient damping was introduced into the hydraulic portion of the simulation to eliminate the undesirable oscillations. This optimum system was subjected to disturbances of step changes in steam load. The maximum steam-pressure variation was 4.2 psi and the largest power overshoot, resulting from a change of from 50 to 100 per cent load demand, was about 10 per cent. It was determined from this study that a frictional loss of 6.076 psi/(ft)(sec) would provide optimum damping. It was concluded that control by this method was feasible, but that further investigation would be worth while.

All other equations used in the all-electronic simulation of this system were again used in the present study. These equations are derived in Appendix A.

OBJECTIVES OF THE PHYSICAL SIMULATION

To avoid the uncertainty of the assumption of the all-electronic simulation, a full-scale physical mock-up of the hydraulic portion of the system was constructed as shown in Figure 2. This hydraulic simulator consisted of a reflector tank, a surge tank, the connecting pipe, and two pressure-accumulator tanks coupled with compressors. Figure 3 is a schematic of the hydraulic simulator.

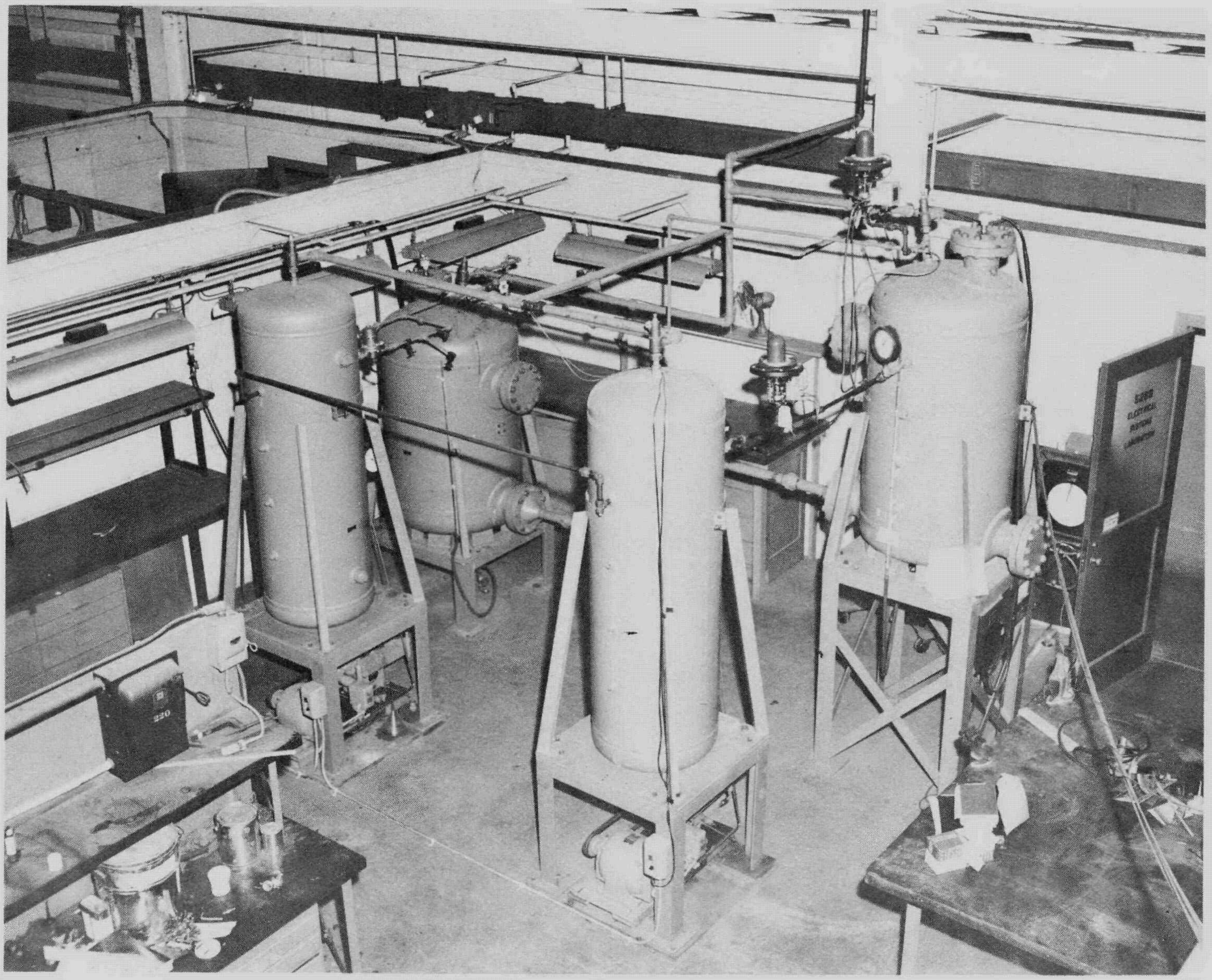

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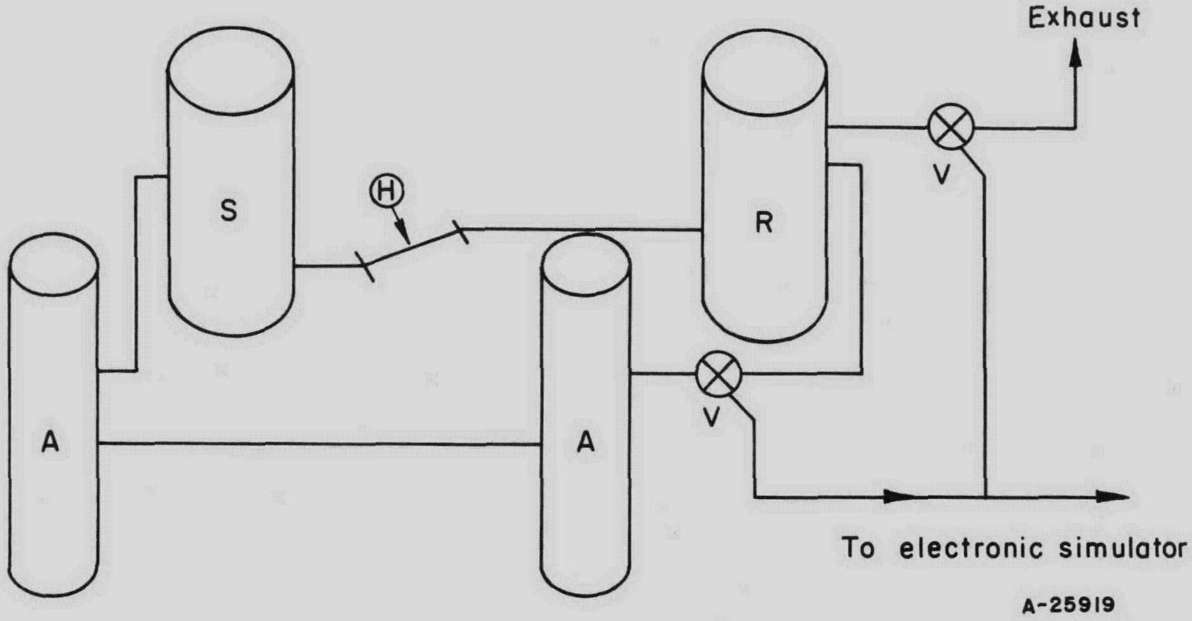
FIGURE 2. FULL-SCALE HYDRAULIC-SYSTEM MOCK-UP



R. Simulated reflector vessel
S. Surge tank
A. Pressure vessels
H. Hydraulic coupling
V. Pressure-control valves

FIGURE 3. SCHEMATIC OF HYDRAULIC SIMULATOR

METHOD OF ANALYSIS

The design parameter of the physical simulation is the hydraulic coupling (H in Figure 3). It was necessary to install damping in this portion of the system to provide stable operation. The purpose of this investigation was to determine an acceptable means of physically damping this system. With a stable system specified, the effects of changing the incremental moderator worth could be examined.

Information regarding the moderator worth was supplied by the Battelle Critical Assembly Facility. This information was used in the determination of the system responses to step changes in reactivity and steam-load demand.

THE ELECTRONIC PORTION OF THE SIMULATION

A description and derivation of the equations used to simulate this reactor system are given in Appendix A of this report.

The nuclear kinetic equations were solved by the use of a self-contained unit built into the analog computer and will not be further examined here.

The equations used are as follows:

$$\delta k = K_h h + 4 \times 10^{-9} P_r{}^2 (1 - 0.00333\ \delta p) \qquad (1)$$

$$- 2.1 \times 10^{-5} P_r (1 - 0.001667\ \delta p) + 2.6 \times 10^{-2}$$

$$K_w \dot{\theta}_w = P_r - P_s \qquad (2)$$

$$P_s = K_s (\theta_w - \theta_{ss} - K_p \delta p) \qquad (3)$$

$$\dot{W} = K_{ws} P_s - K_{ws} P_d \qquad (4)$$

$$W_o \delta p = \frac{A}{K_{vp}} h + \frac{V_o}{K_{vp}} W - W \delta p. \qquad (5)$$

The values of the constants used in this simulation are representative of this type of reactor. They are listed also in Appendix A.

THE PHYSICAL PORTION OF THE SIMULATION

The accumulator tanks (labeled A in Figure 3) are 16 ft^3 ASME-approved 500-psi air-pressure vessels each mounted above, and connected to, a 3-hp 500-psi air compressor. These tanks provide air at 500 psi as needed to the reflector tank and surge tank.

The surge tank (labeled S in Figure 3) is a 36-in.-diameter tank constructed to allow for hydraulic coupling pipes up to 6 in. in diameter, and for various connecting ports for mechanical control valves and relief valves. An inlet air-pressure regulator is used to reduce air at 500 psi from the accumulator tank to 300 to 302 psi in the surge tank. The outlet air-pressure regulator is used to release air from the surge tank when the pressure increases above 298 psi in the surge tank.

The reflector section consists of the simulated reflector vessel (labeled R in Figure 3), two pneumatic control valves with a controller, a capacitance-type water-level indicator, and the necessary safety relief valves. The reflector tank has a cross-sectional area of 5 ft^2, and the water level can be raised 2 ft from the low portion without any interference from inlet air or water connections. One-half-in. pneumatic control valves are used on the inlet and outlet lines to the reflector tank; these are both controlled by the same pneumatic signal from a pressure controller.

Safety relief valves are provided on each tank and are set at 505 psi on the accumulator tanks and 340 psi on the surge and reflector tanks.

COUPLING OF THE HYDRAULIC AND ELECTRONIC SYSTEMS

The electronic and hydraulic portions of the system were then coupled together (as shown in Figure 4) to complete the simulation. A pressure-demand signal from the computer was used to determine the set point of the controller. The actual pressure in the simulated reflector tank was compared with the set-point pressure, and the error determined the pneumatic signal to the control valves. If the pressure in the reflector tank were lower than the demand pressure, the control valve to the accumulator would open to increase the pressure. Conversely, if the pressure in the reflector tank were too high, the control valve to the atmosphere would open to exhaust the pressure. The control valves were adjusted so that at set-point pressure both would be slightly open.

The pressure controller used in this simulation employed proportional-plus-reset-type control. Both the proportional band and reset rate were set at their minimum values. In addition, because of an undesirable time lag between the pressure in the simulated reflector tank and the demand pressure, an anticipation circuit was included. The output of this circuit was added to the pressure-demand signal to produce the controller set-point signal. This was, effectively, rate control. This circuit was adjusted for optimum response of the controller.

In order to complete the loop, a signal proportional to the height of the reflector had to be fed back to the computer. The water height was indicated by a capacitance-type level gage. The output of this instrument was sent to an electronic recorder. The

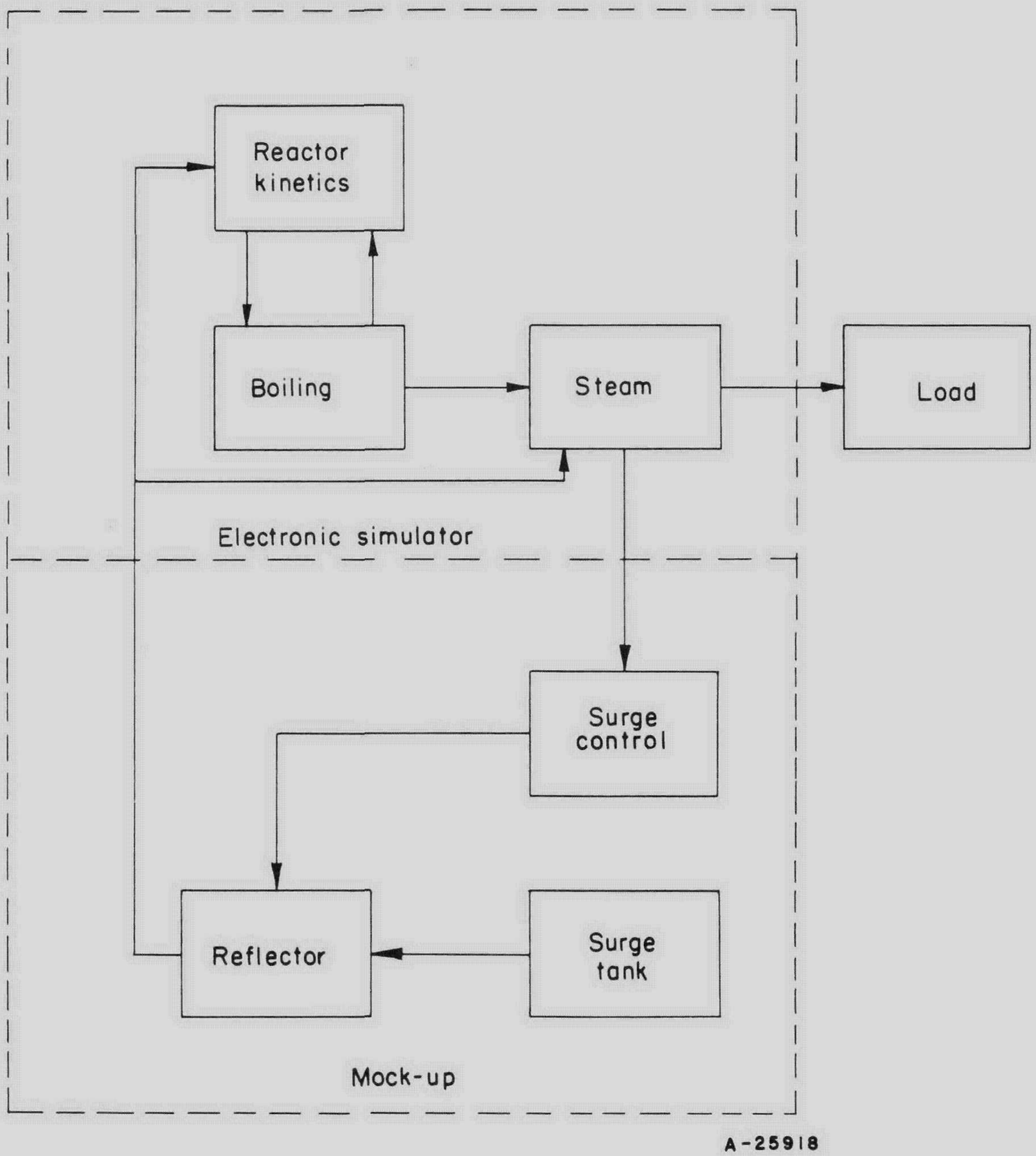


FIGURE 4. BLOCK DIAGRAM OF PHYSICAL SIMULATION

signal from a precision potentiometer geared to the recorder drive mechanism was used as the height indication required in the electronic simulation.

OPERATION OF THE SIMULATOR

To examine this system, the simulated reactor was brought up to power manually by decreasing a shim voltage in the δk simulation. The power-demand signal was adjusted to design-point power. When the demand pressure to the simulated reflector reached the operating level, 300 psi, the system was put on automatic control.

The system, with an open connecting pipe between the reflector and surge tanks, tended to oscillate. To establish the required frictional forces for stable operation, the following configurations in the hydraulic coupling were attempted:

(1) Various concentrations of steel wool

(2) Four 2-in., 90 deg elbows

(3) A 1-in. orifice in a 2-in. pipe

(4) A system of baffle plates.

RESULTS

Curves are presented in Appendix B showing the responses of reflector height, pressure, and reactor power to a step change from 50 to 100 per cent in steam-load demand for the undamped system, the 1-in.-orifice system, and a system of five baffle plates. The steel wool system was unstable and not reproducible because of compacting of the wool. Curves showing the response of this system are not included in this report. As stated before, the undamped system was oscillatory. The orifice system was unstable, but stable operation was achieved with the use of the baffle plates. This coupling of baffles is shown in an expanded view in Figure 5.

The baffle system consists of a section of 3-in.-ID pipe 9 in. long with inserts and spacers to damp the flow of water through the tube. The inserts are made of 14-gage brass and have 16-1/2-in.-diameter holes drilled in each insert. These inserts can be placed in the coupling in various combinations of spacing up to a maximum of 18 baffles. This system was examined using 0, 2, 5, 9, and 18 baffles, respectively. A comparison of the responses of these combinations is shown in Table 1. The steam-load demand for these runs was changed from 100 to 50 per cent and then from 50 to 100 per cent. The incremental moderator worth (K_h) for this series was 0.12 δk per ft.

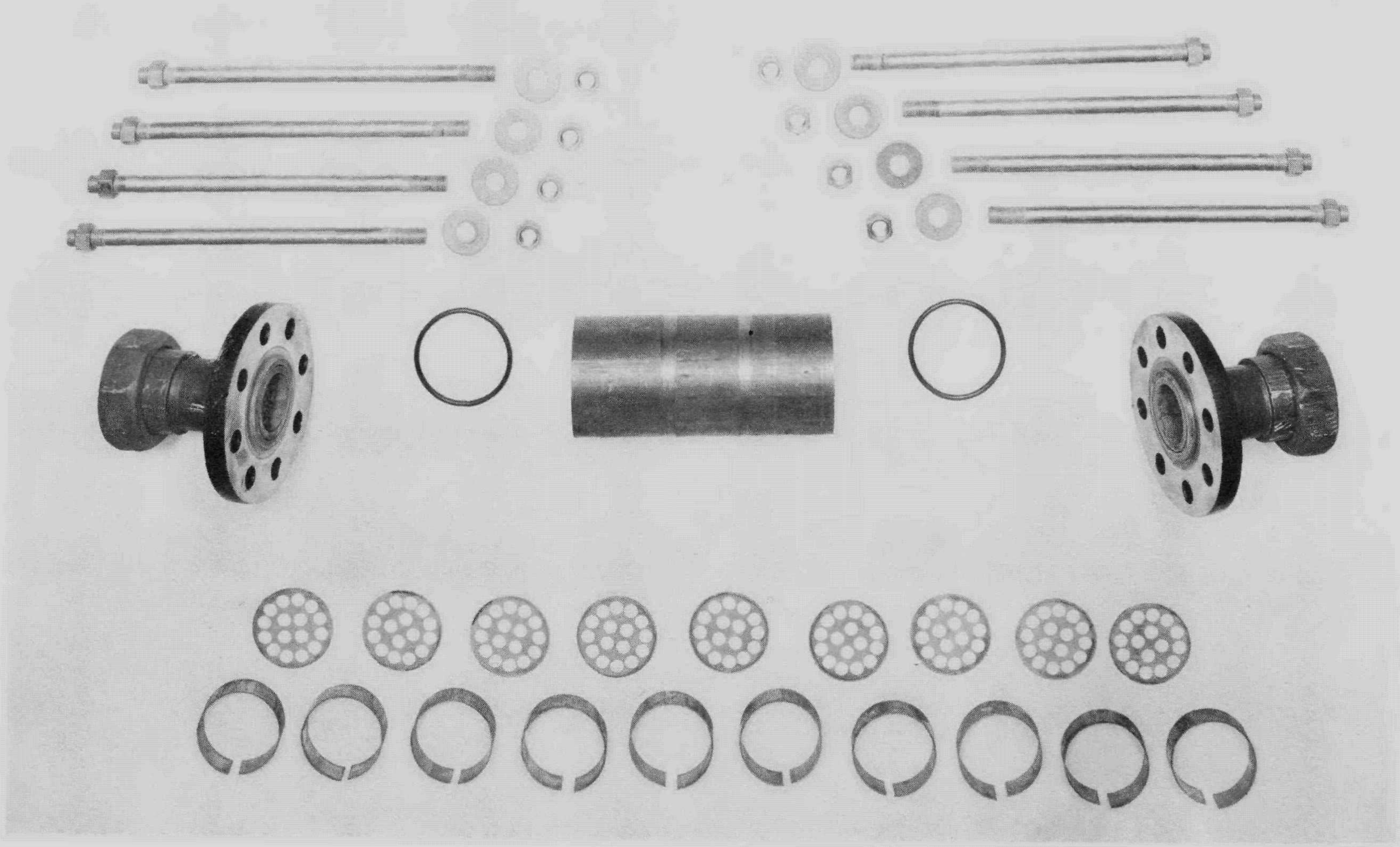


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FIGURE 5. EXPANDED VIEW OF THE HYDRAULIC COUPLING

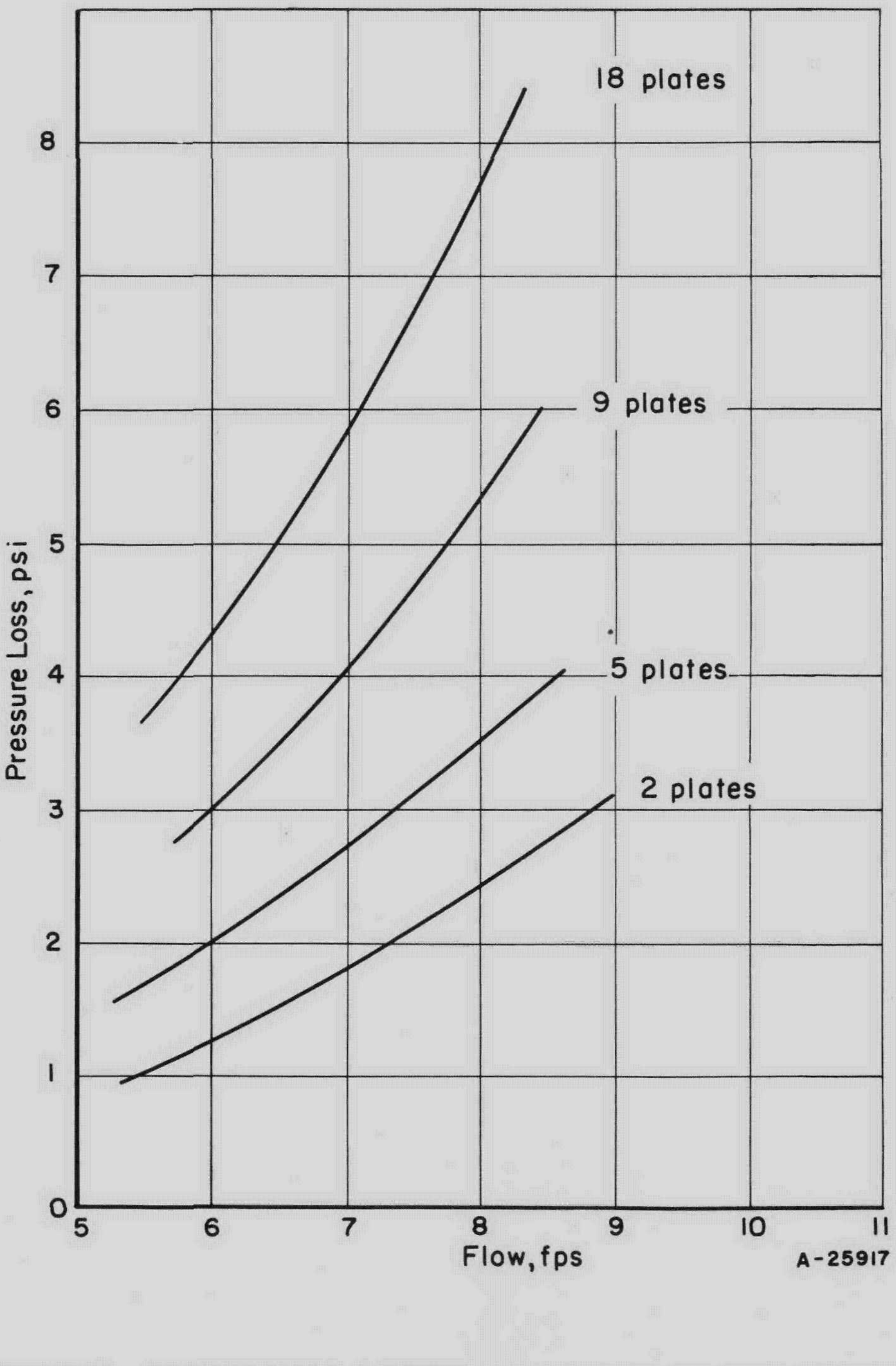

FIGURE 6. FRICTIONAL LOSSES IN BAFFLE-PLATE ASSEMBLY

TABLE 1. COMPARISON OF RESPONSES OF SYSTEMS USING VARIOUS COMBINATIONS OF BAFFLE PLATES TO A STEP CHANGE OF 50 PER CENT IN STEAM-LOAD DEMAND

Number of Plates	Overshoot of Reflector Height, ft	Overshoot of Power, Btu per sec	Change of Pressure, psi	Final Steam-Load Demand, per cent
0	0.092	200	23.6	50
	0.023	200	38.2	100
2	0.137	250	26.4	50
	0.007	220	44.1	100
5	0.097	250	29.2	50
	0.011	280	45.1	100
9	0.103	230	33.3	50
	0.016	300	41.0	100
18	0.115	280	29.4	50
	0.016	320	44.4	100

A separate investigation to determine the frictional losses in the baffle-plate assembly was conducted. The results of this study are shown in Figure 6. The results of this investigation indicated that the frictional losses are proportional to the square of the velocity rather than the first power of the velocity as assumed in the initial all-electronic simulation. The damping coefficient for the five-plate assembly was found to be approximately 0.055 psi/$(ft^2)(sec^2)$.

CONCLUSIONS AND RECOMMENDATIONS

It appears feasible to study the heterogeneous boiling reactor by the use of a physical simulation of the hydraulic system coupled to an analog computer used to simulate the reactor kinetics, reactivity, and steam-generation systems. A simulation of this type can be used to study the effects of changing design parameters such as reflector worth and void coefficient. It is recommended that this working system be further utilized in design studies involving this type of reactor.

REFERENCES

(1) Stone, J. J., and Redmond, R. F., "Evaluation Study of Reflector Control for the Self-Regulation and Shimming of a Heterogeneous Boiling Reactor", BMI-1027 (August, 1955).

(2) Treshow, M., Snider, A. R., and Shaftman, D. H., "Design Study of a Nuclear Power Plant for 100 KW Electric and 400 KW Heat Capacity", ANL-5452 (May, 1955).

(3) Stone, J. J., and Mann, E. R., "Oak Ridge National Laboratory Reactor Control Computer", ORNL-1632 (April, 1954).

(4) Glasstone, S., Principles of Nuclear Reactor Engineering, D. Van Nostrand and Company, Inc., New York (1955).

(5) Keenan, J. H., and Keyes, F. G., Thermodynamic Properties of Steam, John Wiley and Sons, New York (1936).

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APPENDIX A

DERIVATION OF THE SIMULATION EQUATIONS

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DERIVATION OF THE SIMULATION EQUATIONS

Reactor Kinetics

A standard group of nuclear kinetic equations was employed in the study of this reactor.

These are:

$$\frac{dP_r}{dt} = \left[\frac{(1 - \beta)k - 1}{\ell} \right] P_r + \sum_{i=1}^{i=6} \lambda_i C_i + S_o \quad , \tag{A-1}$$

$$\frac{dC_i}{dt} = - \lambda_i C_i + \frac{\beta_i k}{\ell} P_r \quad , \qquad \text{(A-2 - A-7)}$$

where

P_r = reactor power, Btu per sec

$$\beta = \sum_{i=1}^{i=6} \beta_i$$

β_i = fraction of neutrons produced each mean lifetime that are delayed in the ith group

ℓ = mean lifetime, 10^{-4} sec

λ_i = decay constant for ith delay group, sec^{-1}

S_o = term proportional to neutron source

C_i = term proportional to concentration of ith delay group

k = effective multiplication factor .

The values used for the six delay groups are summarized below:

Group	β_i	λ_i, sec^{-1}
1	0.00025	0.0125
2	0.00166	0.0315
3	0.00213	0.154
4	0.00241	0.457
5	0.00085	1.61
6	0.00025	14.28
Total	0.00755	

Multiplication Factor

The effective multiplication factor was assumed to depend primarily upon two factors. It was assumed that k could be obtained by a linear combination of the following: (1) The height of the reflector in the annular tank controls the reactivity of this reactor, as has been previously described. The value of the incremental reflector worth was obtained from critical-assembly data. (2) An increase in steam-void fraction produces a decrease in the multiplication factor. Two effects were considered in treating the void fraction. They were the power level and the steam pressure. The relationship between δk produced by voids and the power level can be expressed as a quadratic equation. This relationship as obtained from ANL-5452 can be expressed as follows:

$$\delta k = 4 \times 10^{-9} P_r^2 - 2.1 \times 10^{-5} P_r + 2.6 \times 10^{-2} . \quad \text{(A-8)}$$

It was further assumed that the ratio of the power level to the void fraction varies as the square root of steam pressure. Therefore P_r as obtained from Equation (A-8) was modified by the square root of the ratio of actual pressure to 300 psi in relating this equation to power.

$$\delta k = 4 \times 10^{-9} \left(\frac{P_r}{\sqrt{\frac{p}{300}}} \right)^2 - 2.1 \times 10^{-5} \left(\frac{P_r}{\sqrt{\frac{p}{300}}} \right) + 2.6 \times 10^{-2} . \quad \text{(A-9)}$$

Since the proportionate change in pressure is small, the following approximation was used.

$$\delta k = 4 \times 10^{-9} P_r^2 (1 - 0.00333 \delta p) - 2.1 \times 10^{-5} P_r (1 - 0.001667 \delta p) + 2.6 \times 10^{-2} . \quad \text{(A-10)}$$

Adding the effect of moderator worth to reactivity gives the final equation used for reactivity changes

$$\delta k = K_h h + 4 \times 10^{-9} P_r^2 (1 - 0.00333 \delta p) - 2.1 \times 10^{-5} P_r (1 - 0.001667 \delta p) + 2.6 \times 10^{-2} , \quad \text{(A-11)}$$

where

δk = change in effective multiplication factor

K_h = incremental moderator worth, δk per ft

h = change in moderator height, ft

δp = change in steam pressure, psi .

Water Temperature

The rate of change of water temperature is proportional to the difference between the power produced by the reactor and the power converted to steam. Any unbalance between the power produced and power used will obviously be stored as heat in the water. This leads to the following equation:

$$K_w \dot{\theta}_w = P_r - P_s \quad , \qquad \text{(A-12)}$$

where

θ_w = temperature of the water, F

K_w = thermal capacity of the water, Btu per F

P_s = power converted to steam, Btu per sec .

Steam-Power Generation

For the purpose of this evaluation, it was assumed that boiling commences at the point where the water temperature reaches the saturation temperature and increases in intensity, linearly, as the water temperature increases beyond this point. This can be expressed in equation form as follows:

$$P_s = K_s (\theta_w - \theta_s) \quad , \qquad \text{(A-13)}$$

where

K_s = effect of temperature on boiling, Btu/(sec)(F)

θ_s = saturation temperature, F .

Since saturation temperature is a function of pressure, this relationship must be included in the equation for boiling. This relationship was linearized from information obtained from the steam tables, and included in the equation for power generation as follows:

$$P_s = K_s (\theta_w - \theta_{s_{300}} - K_p \delta_p) \quad , \qquad \text{(A-14)}$$

where

K_p = effect of pressure on saturation temperature, F per psi

$\theta_{s_{300}}$ = saturation temperature, F, at 300-psi pressure .

Weight of Steam

The rate of change of the weight of steam is proportional to the difference between the rate of steam production and the rate of steam demand.

Therefore,

$$\dot{W} = K_{ws} P_s - K_{ws} P_d \ , \tag{A-15}$$

where

W = change in weight of steam, lb

K_{ws} = weight of steam equivalent of heat, lb per Btu

P_d = power demand, Btu per sec .

Steam Pressure

The steam pressure in the vessel was determined from the weight of the steam in the steam chest and the height of the reflector, in the manner described below.

The steam volume varies with the reflector height:

$$V_s = V_o - Ah \ , \tag{A-16}$$

where

V_s = steam chest volume, ft^3

V_o = steam chest volume with reflector height at center of its travel, ft^3

A = cross sectional area of reflector, ft^2

h = reflector height, ft .

The specific volume of the steam depends upon the temperature and pressure. For small pressure variations, the effect of pressure (at saturation temperature) may be linearized as follows:

$$v_s = v_o - K_{vp} \delta p \ , \tag{A-17}$$

where

v_s = specific volume of steam in the steam chest, ft^3 per lb

v_o = specific volume of steam at 300 psi, ft^3 per lb

K_{vp} = effect of pressure on specific volume, $ft^3/(lb)(psi)$.

Since

$$W_s = \frac{V_s}{v_s} \ , \tag{A-18}$$

where

W_s = weight of steam, lb,

A-5 and A-6

$$W_s = \frac{V_o - Ah}{v_o - K_{vp}\delta_p} \; ; \qquad \text{(A-19)}$$

also,

$$W_s = W_o + W \; , \qquad \text{(A-20)}$$

where

W_o = weight of steam at 300 psi with the reflector height at the center of its travel, lb ,

and

$$W_o = \frac{V_o}{v_o} \; . \qquad \text{(A-21)}$$

Combining Equations (A-19), (A-20), and (A-21) gives

$$W + \frac{V_o}{v_o} = \frac{V_o - Ah}{v_o - K_{vp}\delta_p} \; . \qquad \text{(A-22)}$$

Rearranging this equation to the form most suitable for analog simulation gives

$$W_o \delta_p = \frac{A}{K_{vp}} h + \frac{v_o}{K_{vp}} W - W \delta_p \; . \qquad \text{(A-23)}$$

The electronic portion of the simulation of this system was modeled from Equations (A-1), (A-2 - A-7), (A-11), (A-12), (A-14), (A-15), and (A-23), which completely describe the system.

The values of the constants in the above equations used in the simulation were:

K_h = 0.12 and 0.18 δk per ft

K_w = 328.2 Btu per F

K_s = 1000 Btu per sec F

K_p = 0.306 F per psi

K_{ws} = 8.33×10^{-4} lb/Btu

A = 5 ft^2

W_o = 34.9 lb

K_{vp} = 5.05×10^{-3} ft^3/(lb)(psi)

v_o = 1.5433 ft^3 per lb .

APPENDIX B

SYSTEM RESPONSES TO STEP CHANGES IN STEAM-LOAD DEMAND

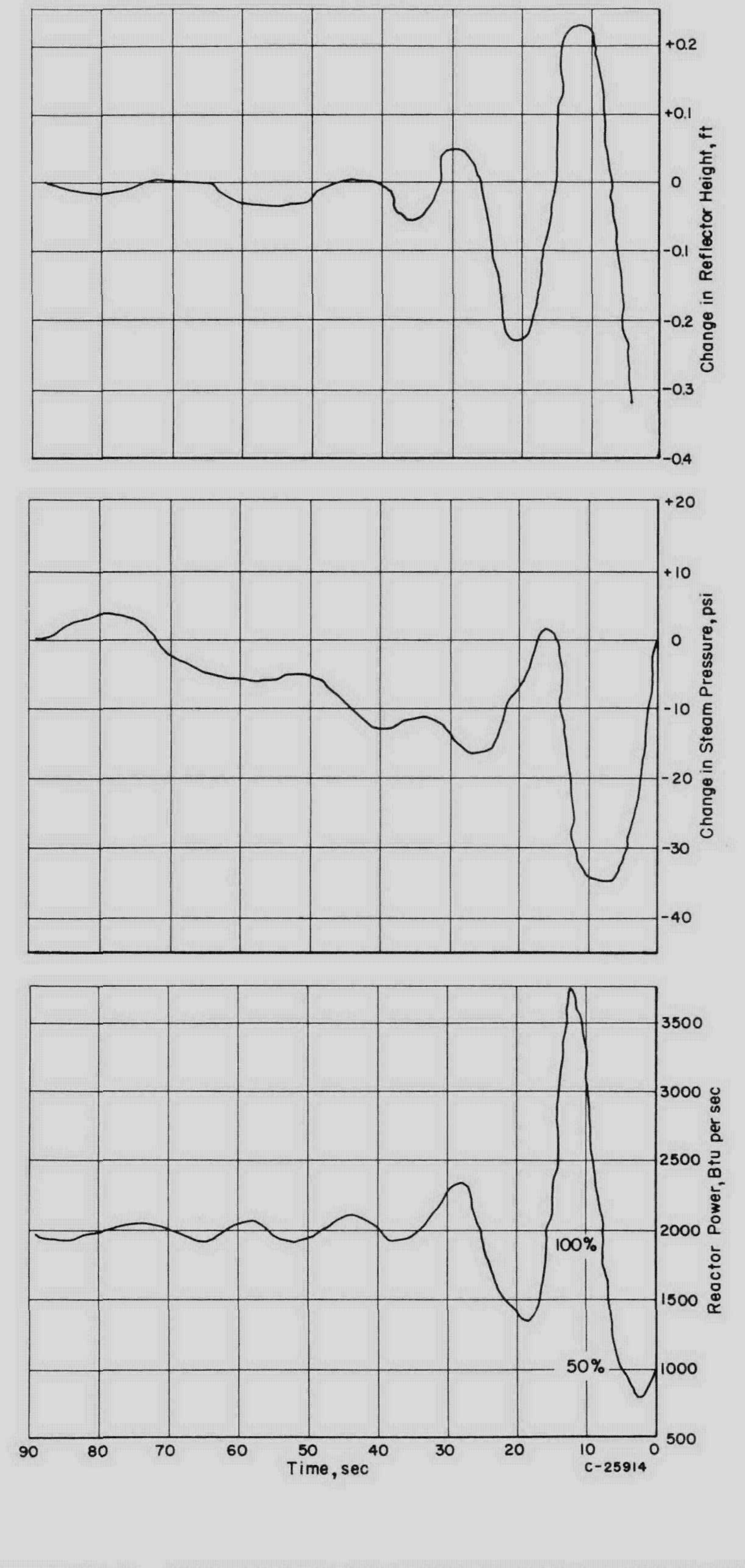

FIGURE B-1. RESPONSE OF UNDAMPED SYSTEM TO A 50 TO 100 PER CENT STEP CHANGE IN STEAM-LOAD DEMAND

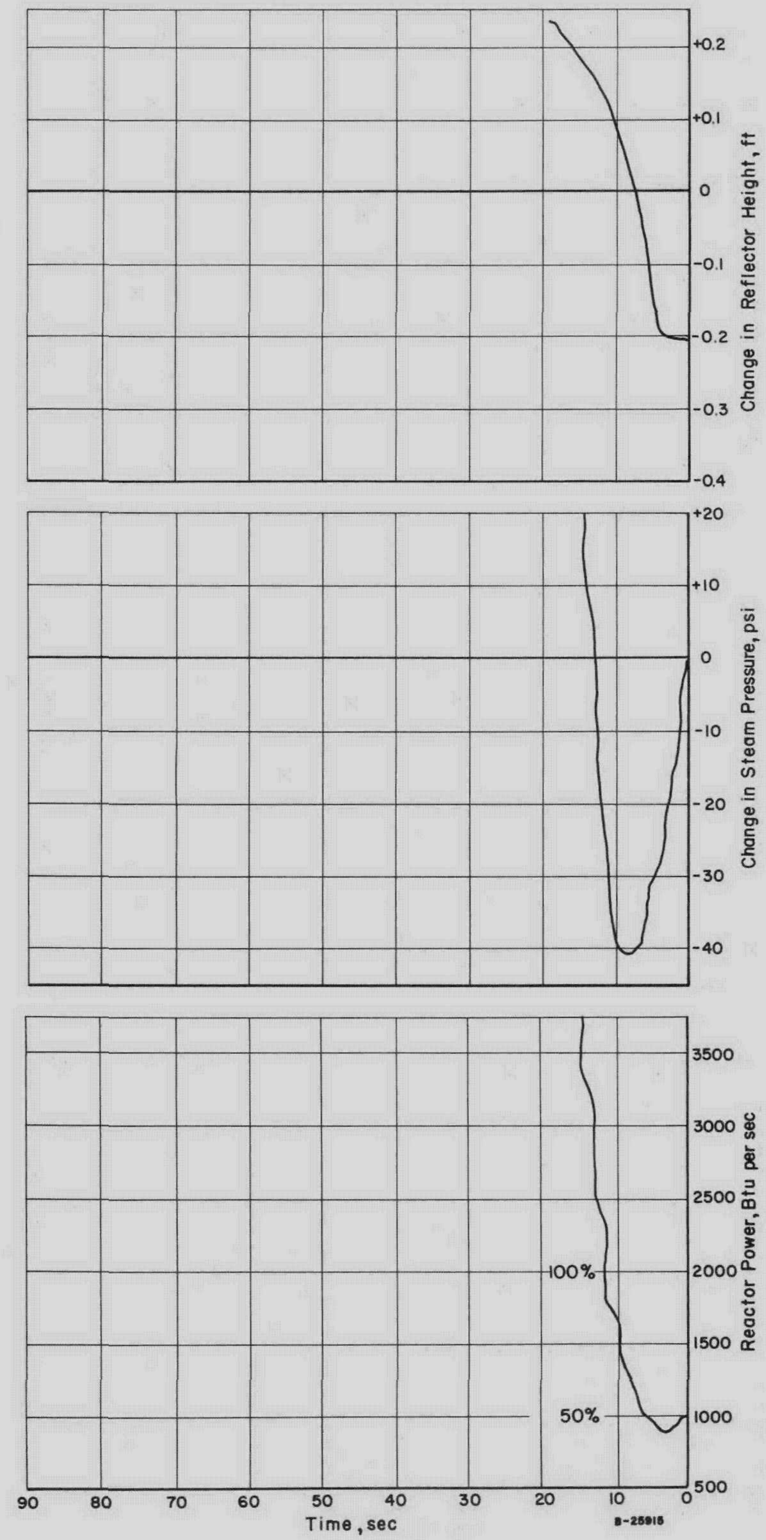

FIGURE B-2. RESPONSE OF 1-IN.-ORIFICE SYSTEM TO A 50 TO 100 PER CENT STEP CHANGE IN STEAM-LOAD DEMAND

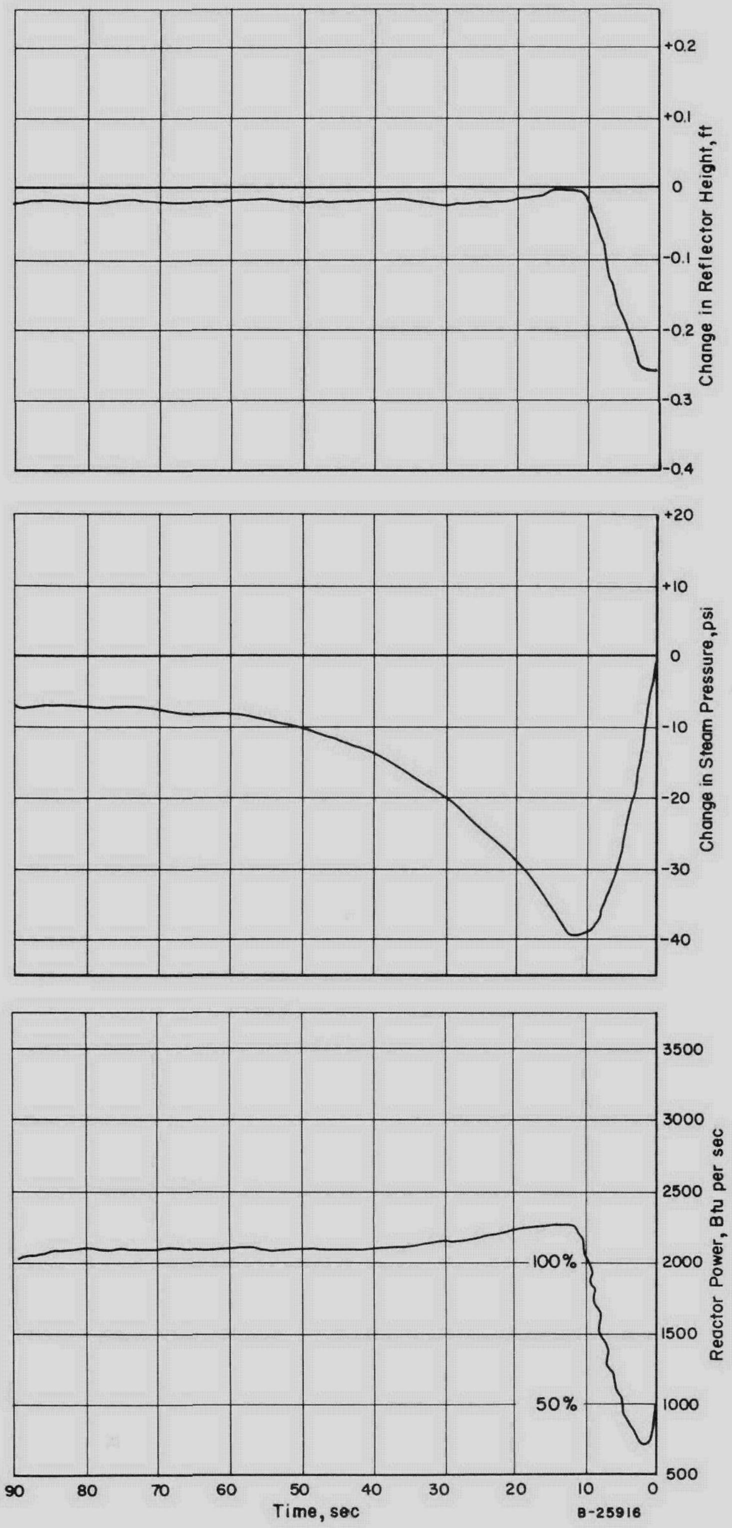

FIGURE B-3. RESPONSE OF FIVE-BAFFLE-PLATE SYSTEM TO A 50 TO 100 PER CENT STEP CHANGE IN STEAM-LOAD DEMAND