Physical Simulation of Nuclear Reactor Power Plant Systems*

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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.

Fig. 1 illustrates, diagrammatically, the reactor system as controlled by the height of the water reflector. The upper portion of the pressure shell collects the steam produced by the boiling within the reactor-core assembly and delivers this steam to the load attached to the system.

Water coolant in the lower portion of the pressure shell covers the reactor-core assembly. Boiling of this water within the core produces steam, and the flow of steam upward through the core results in a circulation of water up through the reactor, and then, after passing through ports in the annular reflector tank, the water flows 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, via a pipe, with 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, and
5) Return of the steam pressure to its equilibrium value.

Initially the system was studied by an all-electronic simulation. This simulation required making assumptions concerning the magnitude of frictional forces in the hydraulic system. It was assumed also 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. To determine the validity of these assumptions, a physical simulation of the hydraulic portion of the system was undertaken.

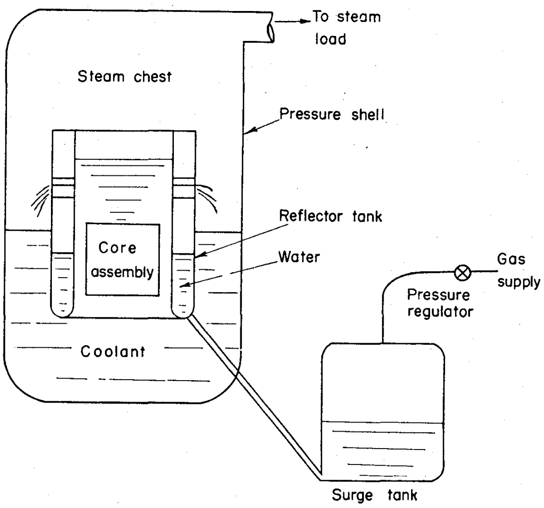

Fig. 1—Diagrammatic sketch of heterogeneous boiling reactor with reflector control.

A full-scale physical mock-up was constructed as shown in Fig. 2. This hydraulic simulator consists of a reflector tank, a surge tank, and a connecting pipe, together with pressure accumulator tanks coupled with compressors. Fig. 3 is a schematic of the hydraulic simulator.

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

The surge tank (labeled S in Fig. 3) is a 36-inch diameter tank so constructed to allow for hydraulic coupling pipes up to 6 inches in diameter, and to have various connecting ports for mechanical control valves and relief valves. An inlet air pressure regulator is used to reduce 500-psi air from the accumulator tank to 300-302 psi in the surge tank. The outlet air pressure regulator is used to release air from the surge tank when the pressure increases above 295 psi in the surge tank.

The reflector section consists of the simulated reflector vessel (labeled R in Fig. 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 five feet^2, and the water level can be raised two feet from the low portion without any interference from inlet air or water connections. One-half inch pneumatic control valves are used on the inlet and

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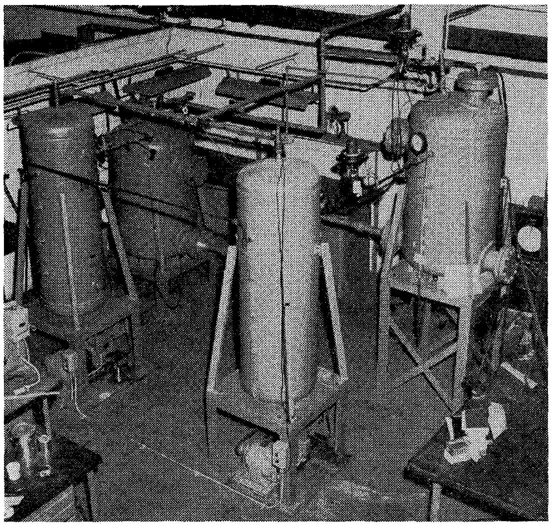


Fig. 2—Full-scale hydraulic-system mock-up.

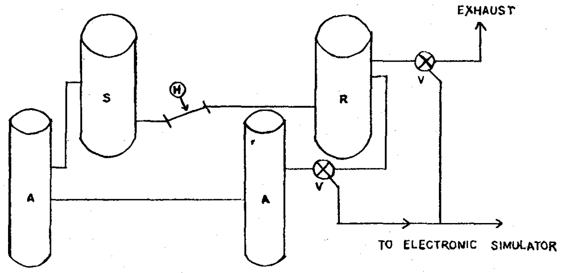


Fig. 3—Schematic of hydraulic simulator. R = simulated reflector vessel, S = surge tank, A = pressure vessels, H = hydraulic coupling, V = pressure control valves.

outlet lines to the reflector tank, and 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.

The design parameter of the physical simulation is the hydraulic coupling (H in Fig. 3). It is necessary to install some sort of damping in this portion of the system to provide stable operation. The purpose of this investigation is to determine an acceptable means of damping this system.

An analog computer was used in the analysis and evaluation of this reactor. The computer was used to solve the equations describing the reactor kinetics, reflector reactivity, and steam pressure under various load conditions.

A standard group of nuclear kinetic equations were employed in the study of this reactor. These are

$$\frac{dP}{dt} = \left[\frac{(1-\beta)k-1}{l}\right]P + \sum_{i=1}^{i=6}\lambda_i c_i + S_0$$

$$\frac{dc_i}{dt} = -\lambda_i c_i + \frac{\beta_i k}{l}P$$

where

P = reactor power, btu/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_0 = term proportional to neutron source,

c_i = term proportional to concentration of ith delay group,

k = effective multiplication factor.

The Battelle analog facility has a self-contained "nuclear kinetic feedback unit" to solve these equations. The use of this unit requires only two operational amplifiers, and saves considerable setup time.

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, linearly, in intensity as the water temperature increases beyond this point. The rate of change of water temperature was computed as the difference between power produced by the reactor and power used to convert water to steam. From these relationships the rate of steam production was determined.

The rate of change of the weight of steam in the steam chest is proportional to the difference between the rate of steam production and the rate of steam used to satisfy the power demand. The pressure in the steam chest was determined from the weight of steam and the volume of the steam chest. This volume varies inversely as the height of the reflector, since an increase in the volume of water in the reflector leaves less volume to be occupied by the steam. A voltage proportional to this computed pressure was fed to the hydraulic mock-up as the pressure demand signal.

Two main factors affect δk in this system. These are reflector worth, which is a function of reflector height, and steam-void fraction, which is a function of power level and pressure. The functions used were obtained from experimental data.

The electronic and hydraulic portions of the system were then coupled together (as shown in Fig. 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.

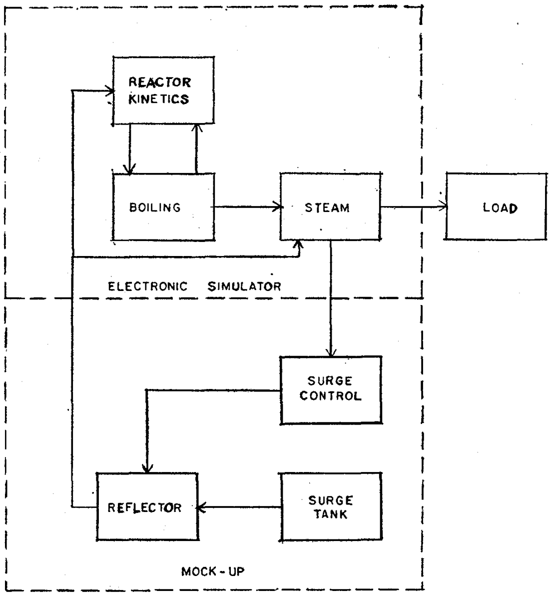
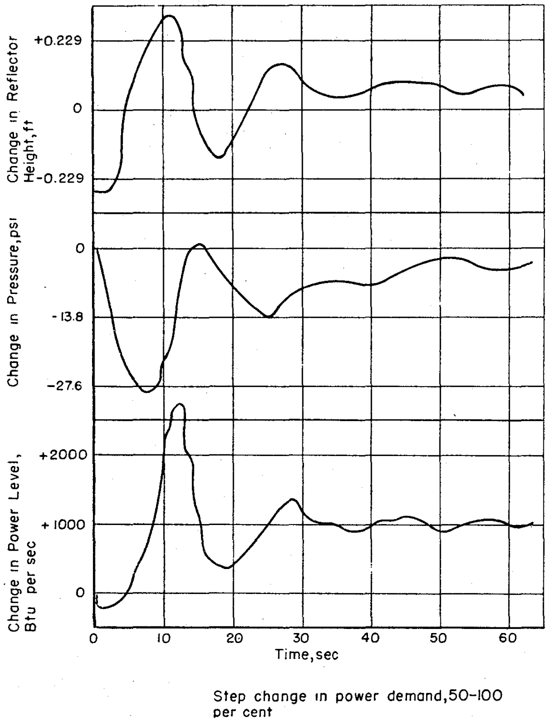


Fig. 4—Block diagram of physical simulation.



Step change in power demand, 50-100 per cent

Fig. 5—Responses of undamped system.

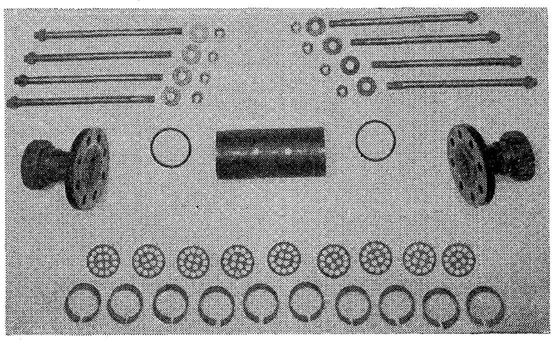
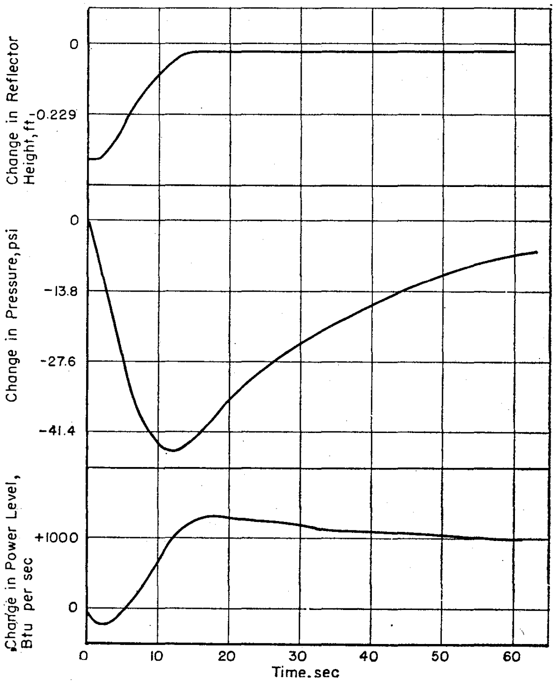


Fig. 6—Expanded view of the hydraulic coupling.



Use of five baffle plates.
Step change in power demand, 50-100 per cent.

Fig. 7—Responses of damped system.

The pressure controller used in this simulation employed proportional-plus-reset (integral) 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 level was indicated by a capacitance-type height gauge. The output of this instrument was sent to an electronic recorder. The signal from a precision poteniometer geared to the recorder drive mechanism was used as the height indication required in the electronic simulation.

To examine this system, the simulated reactor is brought up to power manually. The power demand signal is adjusted to design point power. When the demand pressure to the simulated reflector reaches the operating level, the system is put on automatic control. The system thus far described tends to oscillate. Fig. 5 shows the responses of power, pressure, and reflector height for the undamped system.

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-inch 90-degree elbows,
3) A 1-inch orifice in a 2-inch pipe,
4) A system of baffle plates.

Stable operation was achieved with the use of the baffle plates. This coupling is shown in an expanded view in Fig. 6. It consists of a section of 3-inch-ID tubing 9 inches long with inserts and spacers to damp the flow of water through the tube. The inserts are made of 14-gauge brass and have 16½-inch diameter holes drilled in each insert. These inserts can be placed in the coupling in various combinations of spacing up to 18 inserts.

The optimum responses occurred with the use of five inserts. These results are shown in Fig. 7.

With this stable system, the effects of changing the void coefficient and the incremental moderator worth of the reactor were examined.

Discussion

N. Irvine (Convair): Since you bring the system up to rated output manually, I take this to imply that control is most applicable over a limited range. What are the difficulties of control from start?

Mr. Boyd: Our study involved control over the operating ranges of 100 per cent of power to 10 per cent of power. However, when a nuclear reactor is brought up from zero power it becomes very important that this so-called start-up is very carefully handled.

We presented an illustration showing the nuclear kinetic equations which indicated that the rate of change of power was proportional to power. This was solved using a special unit involving only two operational amplifiers. Most engineers are familiar with the fact that two amplifiers in a loop will tend to be unstable, and consequently it's very easy for the output of this system to go exponential. This is true of reactors if there is too much disturbance or error in the initial start-up; where the power is very low, the reactor power could be exponential. This is considered in reactor technology as the period. It turns out that the period is nothing more than the amount of time it takes the reactor power to increase by a factor *e*. At very low power, a very short period could cause a reactor to go supercritical in a very short time.

Consider a period of half a second or even less, in which case an operator having to react to the situation might not be able to react fast enough to control the reactor. Consequently, at reactor start-up, which is specifically mentioned here, control is done manually. For our simulation, which is direct analog, the feedback unit will not operate at extremely low power levels because of this tendency for the power exponential.

O. Updike (University of Virginia, Charlottesville, Va.): When the reflector liquid leaves the reactor vessel, discharging to the surge tank, it is saturated and any lowering of temperature should cause some steam to "flash off." Could you go into more detail as to how this flashing was handled in the simulation?

Mr. Stone: In direct answer to the question, this condition was not considered in the simulation, so no detail could be gone into there. However, the liquid from the reactor does move out of the reactor toward the surge tank when the pressure in the reactor is above the equilibrium value, or when it has just risen from the condition at which it was being maintained to some higher pressure. This would imply first that the saturation temperature has gone up; then, that the water going from the reflector tank towards the surge tank is at a saturation temperature for the pressure. The drop in pressure, primarily in the pipeline, would perhaps be the result of 1) the change from a higher to a lower elevation and 2) velocity heads for the flow velocities. The resulting pressure changes in either case were not of a major amount in the pipe itself; consequently we did not feel that they constituted a problem.

The simulator was conducted with the amount in the pipe itself; consequently, we didn't have to consider flashing in the experiment itself.

H. T. DeFrancesco (Westinghouse Electric Corp., Baltimore, Md.): What amount of time was required in the study and programming phases of the simulation?

Mr. Gordon: Approximately three man months went into the study and programing phase of the simulation but by far the larger portion of that was in the study. The actual programming phase required about one man week.

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