ANALOG COMPUTER SERVES AS BOTH SYSTEMS ANALYSIS TOOL AND OPERATOR TRAINING FACILITY FOR ENRICO FERMI ATOMIC POWER PLANT

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Summary

An analog simulator with specially designed electromechanical equipment was developed to simulate one of three loops of the Enrico Fermi Atomic Power Plant, including all elements except the steam turbine; i.e., the reactor, intermediate heat exchanger, steam generator, mixing and transport delay phenomena, and steam system hydraulics.

A philosophy of plant control was evolved on the basis of plant operating characteristics, as determined by the simulator and supported by a steady-state digital analysis of the plant. Conceptual control hardware designs were then tested on the simulator and an optimum design was selected and tuned. Actual hardware of the automatic control system was simulated, and this simulation circuitry was incorporated in the computer.

Control consoles exactly duplicating the control panel layout in the actual plant were connected to the analog simulator to adapt it for power plant operator training. Trainees thus get the "feel" of plant operating characteristics, learn to meet emergencies, and practice standard operating procedures, using both manual and automatic controls.

The facility has already proved valuable in studying normal and abnormal operating conditions and remains available for any future systems analysis needs; meanwhile it is in continuing service for operator training.

Introduction

The Enrico Fermi Atomic Power Plant on the shore of Lake Erie near Monroe, Michigan, has a sodium-cooled fast breeder reactor as its heat source. Designed by Atomic Power Development Associates, Inc., it is being constructed under the AEC Power Demonstration Reactor Program, but is to be owned and operated by the Power Reactor Development Company, a non-profit organization of 25 industrial and utilities firms.

In the thermal portion of the plant, flowing liquid sodium will carry heat from the reactor to once-through steam generators where superheated steam will be produced. This steam will be delivered to a turbine-generator built and operated by the Detroit Edison Co. Normal power output will be 100 MW (electrical) with steam at 740°F and 600 psia.

Some three years ago a contract was entered into by Power Reactor Development Co. and Holley Carburetor Co. for the study and simulation of an operating power control system for the Fermi plant. Atomic Power Development Associates, Inc. (APDA) was to serve as technical liaison agent for Power Reactor Development Co. (PRDC). Objectives of the program were:

1. To simulate plant performance over a wide power range.

2. To develop a recommended concept for an operating control system.

3. To convert the simulator into a training device for power plant operators.

Because the variables which must be controlled to regulate power production from such a plant are intimately related, with a change at one point causing changes to occur at other points, development of a sensitive and accurate control...
system was necessary to establish safe and stable power plant operation. Uniqueness of certain elements of the plant further complicated control planning, and many of the details of control system evolution recorded herein represented pioneering research efforts.

Early planning in the first phase of the project called for parallel digital and analog computer studies to provide a dual approach to plant simulation and determination of adequate control system requirements. Analog simulation proved workable for the entire problem, but digital studies ran into complications of excessive computing time for certain aspects of plant operation and therefore could not be relied on for a complete transient solution. The digital work, however, was useful in supporting and verifying analog results.

**Power Plant Description**

Figure 1 presents a block diagram of the entire plant. In the power section are the reactor and three parallel heat transmission circuits, delivering reactor thermal energy in the form of superheated steam at 600 psia and 740°F. Each circuit begins with a primary loop of liquid sodium, circulating through the reactor, absorbing and carrying away heat. Since the primary sodium coolant is strongly radioactive, it is not pumped...
directly to the steam producing unit, but instead passes through an intermediate heat exchanger where heat is transferred to a secondary, non-radioactive sodium loop. The heated secondary sodium then flows to a steam generator where feedwater, entering at 600 psia and 340°F, is heated, boiled and emerges as superheated steam. The once-through steam generators of the cross-flow configuration represent a fairly new concept in steam power design.

As shown in Figure 1, the combined output of the three steam generators is delivered to a single turbine driving the electric generator. Use of the three steam generators and three related heat supply circuits from the reactor introduces a substantial margin of plant safety, since simultaneous failures in all three circuits are extremely unlikely. Also included in the steam system are steam and feedwater piping and valving, condenser, deaerator, feedwater pumps, pump drives and emergency water supply.

In the early months of the study the physical details of plant layout had not been determined, nor were details available on the actual intermediate heat exchangers and steam generators. However, conceptual designs and data on required performance of components were available based upon an ultimate reactor thermal power of 430 MW. The control system was to be designed for initial plant operation at 300 MW (referred to as 100 percent power) but was to be adaptable to higher power levels.

**Purpose of the Operating Control System**

This study is specifically concerned with the conceptual design of an operating control system for the power plant. "Operating" is here distinguished from the power limiting or safety system, which has been developed separately to limit large power excursions and to act as a safety-shutdown device in the event of abnormal operation.

The purpose of the operating control system is the maintenance of power plant operating stability, while regulating power in response to external demand. In the reactor this connotes controlled variations in power output to meet changing power demands, and prompt leveling out at each new power level, with any tendency to "hunt" damped out to the greatest extent possible. In the sodium loops temperature rises and drops correspond to power output. Related temperature changes must be controlled to maintain proper phase relationship during power changes to avoid plant instabilities which involve surging of temperature and power output. To the water-steam system, stable plant control calls for regulation of pressure and flow to match power output, while avoiding pressure or flow surges that would cause corresponding fluctuation in steam generator performance and thus reflect back into the sodium system.

Initially a control philosophy had to be derived, determining which of several variables should be selected as controlling, which others they could be made to control, and which could remain passive. Because the Enrico Fermi Power Plant is to a great extent unique, many factors loom large in the control problem that have hitherto been negligible or nonexistent in prior steam and nuclear power development. The complexity of its heat cycle, from the standpoint of system dynamics, its small temperature coefficients, long transport times, and the peculiarities of once-through-type steam generators: these are factors that governed the ultimate choice of control philosophy. Once the philosophy had been established, a control system was to be worked out, and the required operating characteristics of the control components were to be defined.

**Preliminary Planning for Plant Simulation**

Early plans called for simulation of all three circuits of the plant, at all power levels from source to 150 percent of rated power. Since the complexity of the problem would have made this approach prohibitive in terms of computer cost and maintenance time, the objectives were relaxed wherever possible without seriously compromising the results. First, the simulation was restricted to only one of the three heat-transport circuits, saving nearly two-thirds in simulator costs. The technique is valid since all circuits are identical in operation, and a 3-to-1 compensation is easily inserted wherever the three circuits come together, as in the reactor.

Further, because low-power-level simulation involves voltages approaching the error band of the computer, the stability study was limited to higher levels where error effects would be negligible. With the computer used in the early stages of the study, the minimum level for quantitatively accurate simulation was 25 percent of rated plant power.

In addition, because of the advanced state of steam power technology, it was felt that the water-steam system external to the steam generators need not be simulated, as any significant transient behavior could be predicted when necessary on the basis of existing knowledge.
Components Simulated Individually

Within these limitations, it was decided to simulate the plant as thoroughly as possible, representing all significant components and effects individually, avoiding the "lumping" approach of the transfer function technique, where the identity of an individual component or phenomenon is lost. The individual component approach was required because nonlinearities of the heat system limited the transfer function approach to approximately 5 percent of the power range, while simulation was desired over a much wider power range. The characteristics of each major component of the plant thus were established by the functional interrelationship of its simulated parts rather than by mathematical approximation of the whole.

In this way, a clear physical correlation of components in actual plant and simulator could be maintained, for improved operator comprehension, quick location of simulator faults, and ready adaptation to changes made in the course of plant development. Although it might have been designed to operate much faster than the physical plant, the simulator was built to operate in real time, because of its eventual use as an operator training device.

Identification of significant components and effects warranting simulation, and the determination of the manner and extent to which they should be represented, required considerable preliminary study. Extensive digital computer analysis of the dynamic equations describing individual component operation was necessary to devise workable analogs for setting up the simulator. The digital studies also revealed various undesirable steady-state plant operating conditions which the control system must be designed to preclude.

Phase I Simulation

Following the aforementioned preliminary studies, the first plant simulator was assembled by Holley Carburetor Company during the early months of 1958, using a commercially available general-purpose d-c analog computer, together with specially designed and built supplementary electronic equipment which simulated effects impractical to achieve with standard computer circuitry. Continuously variable voltages, adjustable and fixed resistors, and capacitors in the simulator represent and are analogous to the physical variables and parameters of the plant.

The Phase I simulator represented only one circuit of the power-producing section of the plant -- one reactor, one heat exchanger and one steam generator, plus their connecting sodium piping and pumps. Simulations of the individual phenomena and components described in the following paragraphs were interconnected in their proper sequence, following precisely the actual functional relationships of the plant components. Though water-steam dynamics were omitted, a simplified representation of the feedwater pumps permitted a rudimentary simulation of feedwater flow that could be changed either manually or automatically.

Transport Delay

When a system experiences a transient input signal, the system output has some time relationship to the input. This time delay or phase relationship of output to input is an important factor in adapting a control to the system. When the system includes long piping such as is used in the Fermi plant, the piping coolant time (transport delay) between and through components is a significant element in determining the over-all time response of the plant, and simulation of this delay is vital to over-all plant simulation.

Based on the physical analogy of a bucket brigade, an electromechanical system was devised to simulate in a practical and economical fashion the transport time of sodium flow through piping, intermediate heat exchanger, and steam generator. Two delay wheels, one for the primary loop and one for the secondary loop (Figure 2), were constructed using capacitors which represent slugs of sodium flowing through the pipe or element being simulated. Capacitor voltage represents sodium temperature. With the wheel rotating, the time required for a capacitor on the wheel to travel from an inlet to an outlet point is the same as the time required for sodium to travel the length of the physical pipe.

The delay wheel speeds may be varied to simulate different sodium flow rates. Although the basic study was limited to operation at fixed sodium flow rate, the variable flow rate feature permits consideration of cases of abnormal coolant flow, and will allow for higher flow rates if required when simulating plant operation at the higher power levels planned for the Fermi plant after the first few years of operation.

Mixing

Plenums at the inlet and outlet of the reactor, intermediate heat exchanger and steam generator...
Figure 2. Two delay wheels based on physical analogy of bucket brigade were constructed by Holley personnel. Capacitors represent slugs of sodium flowing through pipe or element being simulated.

introduce a mixing phenomenon. If the temperature of sodium flowing into one of these plenums changes, the outlet temperature will also change. However, because incoming sodium mixes with that already in the chamber, the temperature change at the outlet is more gradual than that at the inlet. The relatively sluggish response of mixing tanks to inlet temperature transients results in a phase shift at the outlet, which complicates the control picture, but also has the beneficial effect of tending to smooth out transients.

Reactor

Power level in the reactor is proportional to the neutron population. Any change in power level depends on changing the position of the reactor control rods and/or temperature within the reactor. Reactor simulation provides for all of the interrelationships between neutron population, control rod position, internal temperatures, and heat extraction rate. The neutron kinetics are represented by a classical six-group simulation. The output of this circuit, proportional to heat produced, goes to separate core and blanket simulations. Although their simulation circuits are basically the same, the electrical constants differ to account for their different sodium flow and heat generation rates. Temperature coefficients from the core, blanket and structure simulations combine with rod position to simulate reactivity, which in turn becomes the input to the neutron kinetics simulations.

Intermediate Heat Exchanger

The intermediate heat exchanger (IHX) simulated in the Phase I study is of counterflow design; the primary or radioactive sodium flows through in one direction while the nonradioactive sodium flows in the opposite direction. The two sodium flows are separated by the walls of the stainless steel pipes which carry the secondary sodium. In the steady state a uniform temperature differential exists from inlet to outlet and heat is transferred very efficiently from primary to secondary sodium. When a temperature transient occurs at either primary or secondary inlet, both outlet temperatures change. The close coupling characteristic of the IHX causes the greater response to a primary inlet temperature transient to appear in the secondary outlet while the greater response to a secondary inlet transient occurs at the primary outlet.

The previously described delay wheels were used as a direct electromechanical simulation of the IHX, in an unusual, simplifying application shown in Figure 3. The wheels rotate in opposite directions, thus simulating the counterflow of sodium in the heat exchanger. As the wheels rotate, charge flows from the primary wheel capacitors to the secondary wheel capacitors via
stationary electrical T-networks simulating heat transfer from primary to secondary sodium. This unique simulation is straightforward, accurate and compact, and eliminates a large number of operational amplifiers that otherwise would be required.

**Steam Generator**

The once-through steam generator is the most sensitive element in the power section of the plant. Over the entire power range the sodium outlet temperature follows closely any changes in sodium inlet temperature, feedwater temperature, or changes in sodium or water flow rate. The superheated steam outlet temperature also is sensitive to sodium inlet temperature.

Heat carried into the steam generator by the sodium is transferred through a separating metal wall to the H2O which enters the steam generator as water and leaves as steam. The changing phase of H2O (from water to low-quality, high-quality and superheated steam) introduces complications into the analysis and simulation of the steam generator because density and heat transfer coefficient of the H2O change from phase to phase.

In developing a simulation, the steam generator was divided into 14 sections. Heat flow from sodium to H2O in each section was represented by using a T-network connecting two capacitors (C), simulating heat capacity of sodium and H2O respectively, as shown in Figure 4. A third capacitor between represented heat capacity of the separating wall, and resisters (R) in the circuit represented the heat transfer coefficients. The sodium side of this circuit was readily simulated by capacitors on the secondary delay wheel already described, but the H2O side presented a challenge because of the varying characteristics of the H2O.

Rather than insert a variable resistor and capacitor in the circuit to simulate changing heat transfer characteristics, it was decided to impress a fictitious voltage E (Figure 4) in the circuit, which would allow the same heat flow as variable elements R and C would produce.

E had to be computed for each section in continuous sequence, and so it was necessary to connect the computation circuit with each T-network in rapid succession using a fast stepping-switch which performs several related functions at each station (section), sweeping continuously from steam generator inlet to outlet, in the opposite direction from the rotation of the delay wheel used to simulate the sodium side. With E so developed, it was possible to use fixed elements (a capacitor and resistor) for H2O heat capacity and heat transfer coefficient, and yet obtain the correct simulated heat flow conditions.

The H2O profile obtained by this method of solution is continuously displayed on an oscilloscope and provides an excellent means of examining H2O conditions during performance tests.

**Control System Development—Phase I**

After simulations of the individual components described above had been interconnected in proper sequence, the simulator was ready both for testing plant characteristics and for testing and developing control systems for the plant.

Operating within the limits of basic design conditions, and taking into consideration certain ground rules established by APDA, it was decided that control of the plant on the basis of scheduling reactor upper plenum temperature from the demand power setting offered the best promise of maintaining thermal stability of the system, at the same time avoiding undesirable operating conditions.
Heat Flow Relationships in Steam Generator

With reactor rod control position and feedwater pumping rate as external control mediums, several control systems were studied using the simulator. The system finally adopted embodies rod control in a limited proportional error servo-mechanism with first derivative output control; feedwater control is a scheduling system with integral error bias. Following optimization of this control system, plant characteristics were studied for a variety of operating conditions, with the optimized control system functioning. Figure 5 presents a block diagram of the control system proposed on the basis of Phase I investigation.

**Phase I Results**

In addition to considerable work in analyzing the steady-state and dynamic performance of the several plant components, the end products of this Phase I period were the electronic simulator of the plant, and the conceptual design of the operating control system. The Phase I objective had been to simulate only as much of the plant as necessary to include the basic elements directly related to power control, such as the reactor, the sodium loops, the IHX and the steam generator, omitting the section of the plant beyond the steam generator. However, as the study advanced, it became apparent that the counterflow, once-through steam generator has a much faster response than conventional boilers, and that it is in fact the most important and sensitive single element affecting control of the plant. Therefore its simulation should be as accurate as possible, and all factors affecting its performance should be simulated. Thus the entire water-steam hydraulics would
Figure 5. Schematic Diagram of Proposed Control System, Phase I
have to be introduced because of the effect of \( \text{H}_2\text{O} \) pressure and flow rate on the heat transfer characteristics of the steam generator. Further, it had become increasingly desirable to investigate operation at lower power levels than possible with the simulator available at the termination of Phase I. This was primarily due to a new start-up concept, which involved flooded steam generators. Hence an extension and improvement of the control system study was clearly indicated.

**Phase II Simulation and Control Studies**

Phase II of the control system study was undertaken to expand the simulator's accurate operating range by using an improved basic computer, and also to add an accurate simulation of water-steam dynamics in the power-conversion section of the plant. Other changes in the specially designed supplementary components were introduced to make improvements dictated by the Phase I study. Also the new simulator (Figure 6) was to be developed to serve for training of plant personnel as well as for continuing stability analysis. Since operation is the same in either case with a simulator set up to operate in real time, the training function could be served simply by adding an appropriate training console to the basic simulator.

Further objectives of the Phase II study were simulations of scrams (rapid shutdowns), nuclear start-up, and power start-up with flooded steam generator; a more detailed study of rod control components; and development of feedwater control, represented simply in Phase I, into a complete control subsystem.

**Simulator Scaling Changes and Other Improvements**

Accuracy of the Phase II simulator is greatly improved over Phase I by the use of higher quality components and a broader voltage range which permits finer scaling. A scaling ratio of 5°F per volt makes the Phase II simulator almost 2 1/2 times as precise as the older one. Low-power-level operation can now be carried on down to 10 percent of rated plant power, well below the level where steam generation will begin in actual

![Figure 6. Completed Phase II Simulator with Main Problem Board in Place. Instructor Console at Far End of Room Next to Recording Equipment (right)](From the collection of the Computer History Museum (www.computerhistory.org))
plant operation. The upper limit has also been extended by the scaling ratio revision, to as high as 150 percent power operation.

All of the simulated components in the sodium loop benefit from the refined scaling of the simulator. Minor revisions have been made in scaled values throughout the simulator on the basis of data revised by APDA, and in the reactor simulation a circuit has been added to simulate scrams.

While the Phase I study was in progress, Power Reactor Development Company decided to purchase crossflow, counterflow, once-through steam generators instead of the counterflow type originally planned, but the simulation remained basically the same as in Phase I, with the difference in type being accounted for by introducing an equivalency factor determined from digital studies.

Mechanical improvement in the stepping switch, improved electronic components, revised scaling ratio and a different method of calculating heat transfer coefficients all contribute to greater accuracy of the steam generator simulation. However, the major change in Phase II comes from incorporating in the steam generator simulation the effects of variations in pressure and flow rate, respectively, on the relationship of \( H_2O \) temperature and heat transfer coefficient with enthalpy, which were not considered in the Phase I study. These pressure and flow inputs to the steam generator simulation are received from the steam-water hydraulics simulation.

**Steam System Hydraulics Simulation**

A complex representation of the hydraulics and pressure dynamics for feedwater and steam and their related components was undertaken in Phase II. The interplay of valves in the steam system required consideration of short response times of the order of 2 seconds for the turbine throttle valve and steam bypass (dump) valve.

One steam loop as shown schematically in Figure 7, with associated piping and valving, is simulated on the assumption that all three loops operate identically. Included in the simulation are the feedwater pump, feedwater control valve, steam dump (bypass), turbine throttle valve, and auxiliary line for start-up; plus piping friction losses and flow inertia on both water and steam sides, and steam line storage due to compressibility on the steam side. Also included are the extremely important storage effects in the steam generator, in response to changes in flow and pressure. The turbine, condenser and condensate pump are not included.

Considerable pioneering was necessary in devising the simulation of the foregoing elements. Prior to simulating steam system components, extensive analytical studies were necessary to evaluate all variables involved and determine the best approach to their simulation.

Analysis of the steam system was worked out by electrical analogy (Figure 7), using resistors, capacitors, and inductors to represent frictional pressure losses, steam compressibility and fluid inertia, respectively. These analogous electrical elements were then simulated directly without going through the differential equation step, a relatively new technique explained by Larrowe, that saves much time and effort initially and simplifies the task of making changes.

Water storage effects in the steam generator, which account for a predominant part of the transient response of the entire steam system, were a major aspect of the simulation. These storage phenomena cause steam generator output flow rate to lag input flow rate about 15 seconds, which significantly affects the transient characteristics of the system.

**Control Studies—Phase II**

On the basis of the conceptual design developed by Holley in Phase I of this study, the control system supplier designed automatic control system hardware. These control elements were simulated in a more complete form than in Phase I, and stability of the system was investigated with these controls in operation, this time taking into account the important effects of steam-water hydraulics which had been omitted from the Phase I simulation. Results of these studies engendered further refinements in control elements and helped to determine optimum control settings.

As mentioned earlier, the control system for the Fermi plant comprises two divisions: rod control which regulates reactor output in response to power demand; and feedwater control which regulates water flow rate to match power output and to maintain a scheduled sodium temperature out of the steam generator.

Rod Control. Early in Phase II considerable simulation work was done in finalizing the rod
SCHEMATIC DIAGRAM OF STEAM SYSTEM

ELECTRICAL CIRCUIT ANALOGY FOR STEAM-WATER HYDRAULICS

Figure 7. One Steam Loop Shown Schematically (above) and the Electrical Circuit Analogy Upon Which Simulation Was Based
control system. A large number of computer runs were programmed to illustrate over-all performance of the system in response to loss of signal and disturbances in reactivity, reactor inlet temperature, reactor coolant flow, and power demand set point.

Feedwater Control. The function of the feedwater control is to regulate feedwater flow rate according to the requirements of reactor power and sodium system, while maintaining steam pressure constant. This control function is performed by manipulation of the feedwater control valve for flow control and the turbine throttle valve and dump valve for pressure control.

The three main divisions of the feedwater control subsystem are an automatic control for the feedwater control valve, a pressure controller for dump valve and turbine throttle valve, and a pump speed control.

Conversion to Operator Training Facility

Following the basic systems analysis work, a control console (Figure 8) was built, duplicating the control panels at the Fermi plant, and connected to the completed analog simulator to convert the entire installation to a training facility for power plant operators. An important factor making it feasible to use this simulator for operator training is that all components of the plant were simulated individually, and therefore it is possible to instrument the training console for indications of input and output temperatures of the various components, or flow rate in different locations in the steam system, just as would be done in the operating control room of the actual plant. As already noted, the simulator was built to operate in real time to facilitate conversion to training purposes.

In the training program now in progress, the simulated plant can be operated with either manual or automatic control, starting from a low level of power (30 MW) and carrying on into very high power ranges (450 MW). Both load and unload type operation, normal shut-downs, and abrupt shut-downs can be tried with either automatic or manual control. The console thus gives operators the feel of plant operation and allows them to develop and practice operating procedures.

The training console, built in the exact size and configuration of the plant control console, shows all instruments and controls just as they will appear in the plant control room. Thus, in addition to items required for operation of the single loop simulation, corresponding items for the other two loops have been dummied on the panel. The operator becomes oriented in relation to appearance and location of all instruments, lights, control levers, etc. This familiarity is vital since he will be isolated from normal plant sounds and these indicators are his only avenues to awareness of plant operation.

Nuclear Start-Up Training and Trouble Simulation

Since the fuel cycle of the Enrico Fermi Atomic Power Plant necessitates frequent reactor

![Figure 8. Control Console for the Power Producing Section of the Fermi Plant](From the collection of the Computer History Museum (www.computerhistory.org))
start-up from source level, considerable practice in nuclear start-up and its various ramifications is absolutely necessary for plant operators. Using the simulator as a general purpose computer, a new problem board was set up to simulate the physical behavior of the reactor alone from source level--1 watt power--through six decades up to 1 MW.

The simulation was based on standard equations describing the reactor on a one-point basis. Following the method outlined by Franz and Simcic, 3 the equations were transformed to expressions containing the logarithm of $N$ (neutron population) rather than $N$, because the range of values for $N$ could not be simulated within the usable voltage range of the computer.

A trouble simulation board has also been developed, whereby an instructor can deliberately introduce plant malfunctions into the operating problem without knowledge of the trainees.

### Simulator Capability

The complete one-loop simulation of the plant is now available as a systems analysis tool for any further studies required, and serves at the same time as a training device which familiarizes plant operators with both manual and automatic operation. Both systems analysis console and operator training console are connected at all times, and the type of operation desired may be selected at will.

The simulator is accurate to 1 percent, and with the main power problem board in place operating conditions over a range of 30 to 450 MW power can be simulated. With the nuclear start-up patchboard installed, operation from 1 watt to 1 MW can be simulated.

The entire program has thus been able to meet the three basic requirements set forth at the beginning of the project. The facility in its present form will be transferred to the reactor site on or about May 15, 1960, and will become a vital part of the on-site training facilities.

### References


For complete details of this project write for a copy of Report 59-12 with addenda to:

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