A Nuclear Power Plant Simulator

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John Jacob Adams
jjadams@cfl.rr.com

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A NUCLEAR POWER PLANT SIMULATOR

BY

JOHN JACOB ADAMS

A Research Report Presented in Partial Fulfillment of the Requirements for the Degree Master of Science

FLORIDA TECHNOLOGICAL UNIVERSITY

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A NUCLEAR POWER PLANT SIMULATOR

JOHN JACOB ADAMS

ABSTRACT

The United States' energy crisis, which has received so much publicity lately, has focused national attention on how we are to meet our energy demands. Proposed energy sources include conventional nuclear power plants, breeder reactor and fusion reactor plants, coal gasification, liquid hydrogen, solar energy, and geothermal energy. All of these except conventional fission plants are still on the drawing board or in the experimental laboratory, and are described briefly. Government and industry are betting heavily on conventional nuclear power plants. ($40 billion already spent by private utilities for 30 operating plants, 60 under construction, and 75 on order.) A few unpublicized accidents and more and more complex instrumentation in nuclear power plant control rooms has pointed to a desperate need for more effective ways of training individuals to safely operate these plants. Recognizing this need, General Electric Company designed and built a very realistic computer-driven simulator of a plant control room.
The physical enclosures and instrumentation duplicates the Dresden II control room in every way, and response to operator manipulation of controls duplicates that of a real plant. The bulk of this paper describes the simulator and its development. The last section raises questions concerning hazards of continued growth of nuclear power and presents some alternatives.
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CHAPTER I

THE UNITED STATES' ENERGY CRISIS

The winter of 1972-1973 marked the first dramatic personal awareness for many people of the United States' energy crisis. In Denver, Colorado, high schools were on a three day week to conserve dwindling fuel supplies. Throughout the midwest factories were shut down at least temporarily for lack of fuel. Oil companies claimed to be running their refineries at peak capacity, and yet there were shortages in other fuels also. Scheduled non-stop flights from New York to the west coast had to refuel at intermediate points for lack of enough fuel in the east. There are predictions of gasoline shortages for later in 1973, and as of this writing, prices have already risen 10-15 per cent. Clearly, the United States has passed from an era of cheap, plentiful energy that made us the world's leading industrial power, to an era of frantic search for alternate ways of balancing the energy-ecology-economics equation. Most of the research done for this paper was in nuclear energy as a substitute for fossil fuels in electric power plants, and in training operators for these highly com-
plex installations. Some effort went into the ecological and health questions, which are at best controversial, concerning the proliferation of nuclear power plants. Suggestions for other energy sources are also included, along with reports of their possible feasibility. Whatever the solutions to our energy needs, the price will be high.

Americans make up about six per cent of the world's population, yet we consume one third of the world's energy. We must find ways of using our energy more efficiently. Automobiles shoot about 87 per cent of their energy intake out the exhaust pipe to poison our environment. The pilot light on a gas range consumes one third of all the fuel the appliance burns. Over-all, we waste more than 50 per cent of all the energy we burn, but we are improving this somewhat. More efficient air conditioners are now being designed. A news article in the Orlando Sentinel Star in April, 1973, reported that Honda Motors of Japan had designed a new engine head for General Motor's Vega automobile which increased gas mileage by 25 per cent and made the engine capable of meeting 1976 U. S. pollution control standards. Ah so ....

We will inevitably find ourselves with ever higher bills for heating, electricity and gasoline, more blackouts and brownouts, and smaller, more economical
cars. Our priorities may force us to improve relations with the oil-rich Arab states at the expense of our Israeli friends. We are already importing 30 per cent of our oil, and that is not enough. Interior Secretary Rogers Morton feels that it will take a "superhuman effort" for the U. S. energy machine to function as it is now through 1985.\(^1\) After that, nuclear energy will assume much of the burden, taking the pressure off what fossil fuels we have left.

Nuclear energy is expected to produce 13 per cent of all U. S. energy in 1985 vs. about 2 per cent today. Nuclear energy should be supplying more than 26 per cent of our needs by 2000.

CHAPTER II

ENERGY THROUGH NEW TECHNOLOGY

Technology which may revolutionize energy production includes fusion reactors with enough fuel from the oceans for thousands of years of operation, fast breeder reactors, liquid hydrogen and coal gasification, solar energy conversion, and geothermal steam powered turbines.

Present nuclear power plants use fission reactors for heat production. This involves splitting heavy atoms (uranium or plutonium), hence the name fission. When the fission occurs, vast quantities of energy are released along with neutrons, which in turn may split other atoms. This chain reaction is relatively easy to control by introducing a material such as boron or cadmium, which absorbs neutrons, thus inhibiting new fissions.

Fusion Reactors

One of the hopes for future nuclear power plants is the fusion reactor. Our sun and the other hot stars derive their energy through fusion reactions. Fu-
sion reactions form helium ($\text{He}^4$) atoms by the combination (fusion) of lighter nuclei. These light nuclei include heavy hydrogen (deuterium or tritium), and light helium ($\text{He}^3$). This all sounds easy enough, but the problem is that temperatures in excess of 100,000,000 degrees Fahrenheit are required for fusion to occur. No physical container could hold material at these temperatures.

The key to a fusion reactor then, is a "magnetic bottle", or containment of the fusion plasma by a precisely controlled magnetic field.

If a heavy current flows in a continuous track containing a high temperature plasma, such as in a torus, just the current flow will induce a field around itself. This field squeezes the plasma into the center of the track.

*Figure 1* A Simple Fusion Reactor

A simple fusion reactor might take the form of a torus used as the secondary of a transformer. The secondary current flows through the plasma itself, contained within the torus. Since the plasma has a finite resistance, it heats up, hopefully, to a temperature which will support fusion. To provide a net amount of power, plasmas must be contained for a significant period of time. The product of particle density, \( n \), in particles/cm\(^3\) and the average confinement time, \( t \), in seconds, is a measure of the fuel burn-up. An "nt" of \( 10^{14} \) (called the Lawson number) represents a theoretical target level for production of fusion power.\(^2\)

Practically, an even higher nt is necessary to overcome losses. Current machines can produce plasmas as dense as \( 10^{16} \) particles/cm\(^3\), but only for a few microseconds, thus they fall short of the Lawson number by a factor of \( 10^3 \). The feasibility of the fusion reactor should be determined within a decade. If it can be made operational, it will be a large factor in our search for energy sources.

Suppose the fusion reactor does become a practical energy source for the future. What is the fuel supply and how abundant is it? Isotopes of hydrogen and

or lithium would be the fuel. Hydrogen is the tenth most abundant element of the earth's crust. The oceans could supply virtually unlimited amounts of hydrogen.

**Fast Breeder Reactors**

Reactors can be classified in several ways. According to neutron speed (energy), reactors are classified as thermal (slow neutrons) or fast reactors. Thermal reactors are easily controlled, can use natural uranium as fuel and are the type used for current burner reactors. (A burner reactor consumes fissionable material, whereas a converter reactor produces some fissionable material and a breeder reactor produces more fissionable material than it consumes.) Fast breeder reactors use plutonium Pu\(^{239}\) or uranium U\(^{233}\) as fuel and produce more of the fuel than is consumed.

News articles would have us believe we are producing something from nothing in breeding, but that is not the case. What does happen is simple in concept. The new fuel "bred" is actually the changing of a non-fissionable isotope of uranium or thorium into a fissionable isotope of plutonium or uranium respectively. Specifically, uranium-238 is changed to plutonium-239, or thorium-232 is changed to uranium-233.

Through normal nuclear fission, neutrons are released, some of which feed the chain reaction, and some
of which are captured by an isotope which is fissionable only by fast neutrons. For example, consider the following reaction:

\[
_{92}^{238} \text{U} + _{0}^{1}n \rightarrow _{92}^{239} \text{U} + \gamma
\]

In this reaction, \(^{238}\text{U}\), the most abundant isotope of uranium (making up 99.283 per cent of natural uranium), captures a neutron from the fissioning plutonium-239, yielding gamma radiation and uranium-239. The uranium-239 quickly decays, with the emission of a beta particle, to neptunium-239.

\[
_{92}^{239} \text{U} \rightarrow _{-1}^{0}\beta + _{93}^{239} \text{Np}
\]

The neptunium also decays rapidly to produce plutonium-239, the fissionable material which originally was fissioned to produce the neutron captured by the \(^{238}\text{U}\).

\[
_{93}^{239} \text{Np} \rightarrow _{-1}^{0}\beta + _{94}^{239} \text{Pu}
\]

A similar process can be used in fast breeders with uranium-233 and thorium-232, where uranium-233 is the fissionable material producing neutrons and thorium-232 is a naturally occurring non-fissionable isotope.

A serious drawback in the large-scale production of plutonium is the extremely long half-life (24,400 years) which greatly affects the length of guardianship for plutonium wastes compared to uranium wastes; about 800 times as long. This problem will be discussed in more detail in Chapter V.
Coal Gasification

By the next decade, dwindling supplies and high prices will force coal gasification and liquid hydrogen into economic feasibility. The U. S. has one of the world's largest deposits of coal - enough to last us 400 to 500 years, according to the U. S. geological survey. Oil and a gas similar to natural gas can be derived from distillation of coal.

Figure 2*

<table>
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<th>NATURAL GAS</th>
<th>URANIUM</th>
<th>SHALE OIL</th>
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<td>32 billion barrels</td>
<td>$3 \times 10^{15}$ cubic feet</td>
<td>450,000 tons</td>
<td>160-600 billion barrels recoverable only if crude oil prices rise 150%</td>
</tr>
<tr>
<td>10 YEARS</td>
<td>11 YEARS</td>
<td>13 YEARS</td>
<td>35-120 YEARS</td>
</tr>
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**COAL**

1.5 trillion tons - 500 YEARS


Oil can be produced from the shale so abundant in the American West at a cost about double that of present costs. We have about ten times as much shale oil in reserve as we do in conventional oil fields. The higher cost of recovery for shale oil has inhibited exploitation of this resource so far.
Liquid Hydrogen

Anyone who has heard of the dirigible Hindenburg and its disastrous destruction by fire in 1937 knows that hydrogen is combustible. Liquid hydrogen is the fuel for the giant saturn moon rockets. Hydrogen can be produced by the electrolysis of water. In gaseous form, it could replace natural gas, and in liquid form it would be a very clean burning fuel for aircraft and motor vehicles. One drawback for auto use of liquid hydrogen stems from its lower density than gasoline. A car with a 17 gallon gasoline tank would require a 60 gallon tank for the same mileage on liquid hydrogen. The main drawback, however, is that electrolysis of water requires copious amounts of electricity, a commodity of which we are already running short.

Solar Energy Conversion

Solar energy has traditionally been thought of as only practical for heating water or swimming pools. Some of the technology to further exploit this non-polluting source of energy is at hand. A panel of scientists say that one day of sunlight on an area the size of Lake Erie is equal to all the energy consumed by Americans in one year, and that with increased research and development the following timetable is possible:
In five years, many homes and office buildings could be heated by solar energy.

In less than ten years, air conditioners could be operated from solar energy.

In five to ten years, solar heat could be used to convert organic materials into fuel oil and methane gas. This gas could supply a third of our "natural gas" needs within 25 years.

Within 15 years, solar energy (through direct energy conversion) could be producing substantial amounts of electricity.

The last point would be made possible by spreading millions of reasonably efficient solar cells over thousands of square miles of land on "solar farms." A husband and wife scientist team at the University of Arizona, Alen and Marjorie Meinel say that a 1,000 megawatt solar farm using steam-driven turbines would require about seven square miles of land for energy collection in southern parts of the U. S. The barriers to widespread solar energy conversion are presently more economic than technical, but with research providing increased efficiency, the costs should go down.

**Geothermal Energy**

Geothermal energy can be tapped in the form of steam under pressure in certain parts of the world. This steam is produced in areas where faults in the earth's

---

crust allow hot magma to seep up near the surface and heat underground water. The famous geyser Old Faithful derives its energy from this source. In many places in the world, electricity is already being produced by geothermal energy conversion. It is, at best, a regional source of energy following the known earthquake and volcano regions of the world.


In the U.S., the only major geothermal power station in operation is the 290,000 kilowatt plant run by Pacific Gas and Electric Company since the late '50's. Environmentalists say the plant is dirty, noisy, unsightly, malodorous, and possibly dangerous. Other problems include the high mineral content of the hot water which clogs pipes and turbines, and the subsidence of land surrounding a steam field with the escape of water and steam from below.
CHAPTER III

NUCLEAR POWER PLANTS ARE THE WAY FOR THE IMMEDIATE FUTURE

According to Interior Secretary Rogers Morton, "The various fuels are not alternatives to each other. We need them all, including geothermal." From the foregoing descriptions of the "non-alternatives," it seems clear that nuclear power plants will carry the bulk of the responsibility for new energy sources. This will be true at least for the immediate future, and possibly for the next generation.

Nuclear Power's Momentum

Most of the country's utilities have undertaken expansion programs to meet the greater needs for home and business electricity seen for the future. In the Pacific Northwest, for example, industrial loads have been reduced by 900 megawatts this spring because of utilities' inability to supply sufficient electricity. Chemical plants, paper mills and aluminum smelters have curtailed operations in the area. The bulk of the money being spent for new generating capacity is going into nuclear power plants nationwide. At latest count, 30
nuclear power plants are operating in the U. S., 60 are being built, and 75 are on order. To speed up the licensing process, the federal government is encouraging the building of more and more nuclear power plants of standard design. This "standard design", incidentally, has long been a selling point of the General Electric Company's boiling water reactor (BWR) powered nuclear power plant line.

Utilities are paying for full page ads in popular national magazines to promote public support of nuclear power. They emphasize the petroleum shortage, no combustion-caused air pollution, and economy of operation. The last item is a subtle reminder of your current $60.00 per month power bill. They, of course, dismiss environmentalist's objections as a "lack of understanding".

Need for a Nuclear Power Plant Simulator

A "lack of understanding" on the part of nuclear power plant operators has contributed to all of the accidents occurring at plants. There have not been many accidents, but information concerning these accidents is practically nonexistent in published form. Requirements for operators are becoming more stringent, and designers are including more and more "fail safe" automatic devices monitored by computers in nuclear power plant control
systems. The bulk of this paper describes a simulator which was designed to better train power plant operators in the complexities of a modern plant. The need for this simulator has been recognized worldwide. The Japanese government bought the design from General Electric, Germany is considering buying the design or a complete system from G. E., and several large utilities and TVA are negotiating to buy or build simulators of their own.
CHAPTER IV

THE NUCLEAR POWER PLANT SIMULATOR

General Electric Company, a major supplier of nuclear power plants, decided in 1966 that better methods than standard classroom and lab work were needed to train operators. A nuclear power plant simulator was conceived as the major training aid for a super training center to be located in Morris, Illinois, near Consolidated Edison's Dresden site, 50 miles south of Chicago. The author was a contributor to the design and development of the software which makes up the "brain" of the simulator. He also helped install and effect final debug of the system on site in May and June of 1968.

Inasmuch as man is a real time creature and cannot be conveniently time scaled, any simulator or trainer designed for training humans must, of necessity, be programmed to operate in real time. The concept of this simulator was based on the real time programming of the complete functional model of the nuclear power plant. A General Electric process computer in conjunction with a high-speed, solid-state, input-output system provides a real time software simulation of the power plant, pre-
senting the operator with real time dynamic response. The simulator control panels and bench boards, which duplicate the configuration of the actual plant control room and the real plant instrumentation, provide the operator with a realistic environment.\textsuperscript{4}

An Instructor’s Console allows the instructor to initialize the simulator to any of a number of preset modes and to introduce system malfunctions to extend the realism of an operating power plant. A diagram showing computer room equipment interfaces is shown in Figure 4. The simulator room equipment interfaces are shown in Figure 5.

\textbf{Program Development Cycle}

The programming team was established under one project leader; eight programmers in three teams: Spatial Model, Dynamic Model, and System. The latter team had the responsibility for the test and diagnostics and for picking up all the loose ends and service tasks that did not seem to belong to either of the other teams.

\textsuperscript{4} Much of the following descriptive material was compiled originally by many unknown General Electric employees. Most of it has been previously published in various forms by G. E.-employed authors listed in the bibliography. I would especially like to thank Mr. J. L. Katz for his permission to use portions of a previously unpublished report he did on the nuclear power plant simulator.
Figure 4  Computer Room Equipment Interfaces
Figure 5 Simulator Room Equipment Interfaces

Simulator Room

Operator Panels

Operator Back-Panels

11 12 13

Discrete Analog and Digital Data

3 2 1

Hardlines for Malfunctions Bypass Signals, etc.

14 15 16 17
Upon completion of the analysis and the issuance of the system schematics, design specifications for the computer programs were begun. The design specification blocked out the logic and the data tables necessary for each program. The start was made on the COMMON map.

From the schematics and following the outline in the design specification, each programmer started on the detail flow charts for the programs. A review cycle was set up in which the team leader and the analyst jointly reviewed the flow chart with an experienced power plant engineer. Completion of this review started the coding cycle. All coding was done in the first level symbolic language of the GE/PAC 4020, Process Automation Language (PAL). To avoid the possibility of machine time conflicts between assembly and debug efforts, all assemblies were performed on a GE-415 computer using the 415 PAL assembly program. Each programmer proceeded to debug his unit programs to the best of his intuitive ability. Unit programs were then combined into subsystems tying together a group of programs to form an integral plant subsystem. These were debugged under the direction of one of the analysts who had prepared input data, test procedures, and predicted output. The contributions of the analysts at this point were significant in terms of time. While it may be assumed that the programmers would have eventually learned to diagnose the problems, it was quite evident
that the analysts' experience with the model was a better guide to sources of difficulty. System test was a formal period, with programmers and analysts in the background. A group known as Test Engineering had prepared formal test procedures - which really amounted to an operating manual for the Dresden Plant. These procedures involved the cold start of the plant and its operation throughout its total range. All of the control conditions were exercised at points at which they were estimated to be the most visible. The most delicate part of this operation was the choice of the calibration, or tuning constants to bury in the programs for the best overall simulation.

Experienced Power Plant Engineers operated the simulator for weeks, pointing out discrepancies in simulator and actual plant responses to maneuvering. When final tuning was complete (by decree rather than scientific determination) the engineers agreed that one could forget that he was not in the control room of a real plant while operating the simulator.

**Plant Description**

The simulator design is based on the Dresden II Nuclear Power Plant located near Morris, Illinois. The plant employs a single cycle, forced circulation, boiling water reactor with a thermal rating of 2260 megawatts and a gross electrical power output of 850 megawatts. Plant
operating steam pressure is 1000 psig with a steam flow of $8.6 \times 10^6$ pounds per hour. The turbine is a 810,000 kw, 1800 rpm, tandem-compound, six flow, non-reheat steam turbine with 38-inch last stage buckets designed for steam pressure of 950 psig. The generator is a direct-driven, 60-cycle, 18,000-volt, 1800-rpm, conductor-cooled, synchronous generator rated at 920 megawatts at a 0.9 power factor. The feedwater and condensate pumping develop the necessary pressure head to return the feedwater to the reactor vessel. The feedwater is heated to improve cycle efficiency. The recirculation system with ten jet pumps and a centrifugal pump in each of its two loops controls the feedwater flow into the reactor vessel and provides a means of power level control.

Reactor auxiliary systems include head and shutdown cooling, head vent, reactor water cleanup, and control rod hydraulics. Reactor safeguard systems provide emergency support to suppress hazardous conditions. These systems are the isolation condenser, core spray, low pressure coolant injection, high pressure coolant injection, isolation valves, relief valves, and standby liquid control.

Turbine and generator auxiliary systems provide support functions to the turbine and the generator such as cooling, oil pressure, and shaft sealing. The auxiliary power system is a local power distribution source and
supplies plant power requirements from either the generator or the grid. The diesel generator produces emergency power to non-interruptable systems.

The reactor is fueled by UO₂ pallets in clad rods which are assembled into 724 fuel bundles. Reactor power is controlled by 177, bottom entry, axial translated, boron carbide control rods. These rods are interlaced with the fuel bundles as shown in the cutaway diagram in Figure 6. A reactor core arrangement diagram is shown in Figure 7 which illustrates the control rod arrangement. The location of the detectors of the three neutron monitoring systems is also shown in this diagram. The three systems are constituted by a 4-detector source range system (SRM), an 8-detector intermediate range system (IRM), and a 164-detector (arranged in 41 strings) local power range system (LPRM). A 6-channel average power range system (APRM) provides power limiting. A rod worth minimizer (RWM) programs the control rod pattern at low flux levels. A neutron protective system monitors the reactor systems and initiates rod blocks, alarms, and scrams according to the condition of the reactor and plant.

Plant Model

The simulator control panels and bench boards and the operators console are basically duplicates of the
Figure 6 Dresden II Reactor Pressure Vessel
Figure 7  Dresden II Reactor Core Arrangement

Typical Core Arrangement
Actual Number
Control Rods = 177
Number Fuel Assemblies = 724

Fuel Assembly
49 Elements

Monitor
Dresden II control room. The plant functions are represented by a mathematical model programmed on a GE-PAC 4020 digital computer. The digital computer interfaces with the switches, meters, recorders, and lights on the panels and bench boards by way of an input/output which includes over 3000 discrete channels and 300 analog channels. The plant model is divided from both a functional and an organizational standpoint. The spatial model which, except for the reactor kinetics, covers the reactor functions was developed by Walt Morgan of the Atomic Power Equipment Department (APED), San Jose, California. The dynamic model includes those plant functions which require dynamic representation for operator realism. The dynamic model was developed by Dave Ahner and Richard Mills of the Electric Utility Engineering Operation, Schenectady. The logic model encompasses those plant functions which can be represented adequately by logical operations, and the logic which couples the discrete signals from the hardware input and output devices to the spatial and dynamic models. A graphical illustration of the model breakdown is shown in Figure 8.

**Spatial Model**

The spatial model has three functionally distinct parts: the control rod system, the rod worth minimizer, and the spatially characterized neutronics. The
Figure 8  NPPS Mathematical Model

Plant Dynamic Model  
- Doppler
- Xenon
- Neutron Kinetics

Reactor Spatial Model  
- Control Rod System
- Rod Worth Minimizer
- Spatial Neutronics

Thermodynamics
(Pressures, Flows, Temperatures, Level, voids, Boiling Boundary)

Feedwater Flow and Heating

Turbine-Generator
EHC Condenser
Steam Seal
Oil Pump
Gen Cooling

Control and Protective Logic

Recirc. Flow System

Control Room
Controls and Indications
Instructor's Console

Engineered Safeguards
Isolation Condenser
Core Spray
LPCI Containment
Spray Liquid Poison
Isolation Valves
Relief Valves
Diesel Generator

Auxiliary Systems
Clean Up
Head Cooling
Head Vent
Shutdown Cooling
Control Rod
Hydraulics
control rod system model consists of the logical selection and positioning of each of the 177 control rods. The selection of each rod is accomplished with a bank of pushbuttons arranged in radial similarity to the control rod configuration. Upon selection, a rod may be axially positioned in any of the 25 mode levels a notch at a time or continuously in an override mode of operation. Rod status lights and rod position displays provide rod location information to the operator. The rod worth minimizer enforces an axially prescribed withdrawal or insertion sequence at low power levels to preclude reactor hot spots and to maintain operational safety and integrity. The spatial model characterized the reactivity established by the rod patterns and the flux distribution as seen by the various neutron detectors. The rod reactivity model considers basically three elements to calculate an effective single point reactivity change: the axial travel of the rod being positioned, the axial density of the proximal rods, and the intrinsic rod worth of the subject rod.

**Dynamic Model**

The dynamic model deals with four basic areas: thermodynamics, fluid dynamics, rotating devices, and neutron kinetics. The thermodynamics model is the most complex and defines the transient response of the temper-
atures, pressures, enthalpies, voids, boiling boundary, etc., in response to the nucleonic heating in the reactor core and steam heating. The model employs conventional thermodynamic principles with simplifications where appropriate. Some thermodynamic modeling is included in the turbine, condenser, and feedwater representations where heating and cooling is integral to the simulation.

The turbine model is a simplified representation derived from standard relationships of rotating inertias with the assumption that power is a function of steam flow. The generator model is derived from simplified electrical representation for a synchronous generator and assuming it is looking into an infinite bus.

Much of the dynamic model involves fluid dynamics. In most cases, simplified representations of fluid dynamic relationships were considered sufficient to provide adequate transient response without compromising the required degree of realism.

The neutron kinetics model is based on the single-point neutron kinetic equation derived from the diffusion equation for homogeneous, thermal reactors. Reactivity feedback factors include the doppler effect, voids, and moderator temperature. Iodine poisoning and xenon poisoning are also included.
Logic Model

The coupling logic consists primarily of memory logic for the many spring return switches and addressing logic to lights to register the proper mode of operation, or state of the system. Controllers required coupling logic to the controls inasmuch as the controller functions were simulated. Sequential and permissive logic also constituted a significant part of the required coupling logic.

The simplified representation of systems requiring primarily logical operations to drive output display devices included the turbine auxiliary systems, the circulating water system, off-gas system, and the radiation monitoring system.

The auxiliary power system model was represented primarily by logic operations such as the circuit breaker logic for the generator and auxiliary busses, the synchroscope logic, voltage and power calculations, and other logical operations.

The logic model contained those operations not included in the spatial or dynamic model. It served also as a vehicle to integrate the total model. A sample of the system schematic which graphically described the operations of the total model is shown in Figure 9.
Figure 9 NPPS Sample System Schematic
Computer and Associated Hardware

The computer complex chosen for the NPPS consisted of a General Electric Process Automation Computer (GE/PAC) 4020, a 24-bit word, fixed-point, binary machine. Core size is 32K with a 1.6μs cycle time. The add time is 3.2 μs and there are seven index registers. The most powerful features of the GE/PAC 4020 are the table input, table output, and bit manipulation commands which made the logical gyrations involved in the simulation feasible. A 164K drum provided the bulk storage for all the programs and data. The drum-to-core transfer is done in parallel with computation; the effective rate is approximately 13,000 words per second. A standard peripheral buffer connected the 4020 to an input/output typewriter (typer) for programmer control, a paper tape reader and punch for programs and data, and two output-only typers that simulated the power plant computer typers. A channel expander was used to interface the GE-4020 with the input/output unit which served as the buffer between the physical switches and meters on the control room panels and the computer. To the programs, the input/output unit looked like a block of contiguous data that could be read in to sense switches and filled to drive the displays. The input/output unit performed all sample-and-hold functions, analog-to-digital, and digital-to-analog
conversions. Figure 10 shows the functional hardware.

**Software**

The software for this real time simulation consisted of an operating system, a set of functional programs, and a test and diagnostic program—totaling somewhat over 40,000 lines of code.

The operating system (OS) was derived from the computer manufacturer's Real Time Monitor Operating System (RTMOS). It had the routines to handle simulator initialization, the rolling in and initiating of functional programs, the input from and output to the simulated controls and instruments, and the library of mathematical functions. The model was broken down into about 40 programs to achieve modularity and distribute the work load of coding. In use, the 40 programs were grouped into six core resident blocks, six pages transferred into core from the drum on each simulator cycle, and a "fast loop" of three programs executed 10 times per simulator cycle. The Test and Diagnostic Program was designed to aid in localizing hardware or suspected hardware malfunctions to either the computer, in which case the computer diagnostics were to be used, the input/output unit, or the simulated instruments.

**Software Organization**

The software organization concept adopted was
Figure 10  NPPS Functional Hardware

Simulation Control

Instructor's Console

Simulated BWR Control Room

Panels and Benchboards

"Plant"
Operator's Console

Computer System

Drum 164K 24 Bit

Drum Electronics

32K, 24 Bit 1.6 μs cycle

GE/PAC 4020

Peripheral Buffer

Console Typer

Paper Tape Reader

Paper Tape Punch
designed by J. L. Katz of General Electric and was that of a ring of functional programs surrounding a common area for communication. The ring is, in turn, surrounded by the operating system which provides services and all external communications. This is illustrated in Figure 11, Software Concept. The program ring defined the basic simulator operating cycle; once around the ring is one cycle.

The simulator cycle starts when the operating system reads into core memory the entire contents of the input/output buffer and fills the output buffer from core memory. The program blocks and pages are then executed, one after the other in the fixed and predetermined order. The "fast loop" operates as a special interrupt, 10 times per cycle without disturbing the other programs except as the result of a "fast" computation might affect succeeding computations in the normal cycle. The normal cycle is defined as a second; when the last program in the cycle has been executed, the system stalls until the tenth "fast" interrupt has been completed. This restarts the cycle at the beginning. It may be seen from this that the system's average response to an operator action is, of necessity, one-half second after the action. For training purposes, it turns out that this delay is quite adequate, even realistic, for a nuclear power plant. It may also be seen that, as the cycle is fixed, all compu-
Figure 11 NPPS Software Concept
tations take effect on programs that are downstream from the computation. No computed changes are retro-active. Considerable thought was given to the order of the programs in the cycle with the result that, in the majority of cases, the required most immediate effects do indeed follow their cause. In the initial design, the use of execute interrupts were considered for operator actions that would be defined as requiring rapid response, and a flexible sequence of program execution was considered rather than the predetermined cycle. As the implementation progressed, it became obvious that no action would require a response in less than the average one-half second, and that the complexity of a flexible sequence far outweighed any advantages to the simulation. Further, it appeared that under certain plant conditions, a simulated reactor "scram" for one, all of the plant model programs would have to be available and operating with realism. Thus, the design objective was modified to encompass a one second cycle with all programs loaded and executing. This design goal was met, as was the goal of realism in the simulation. The sequence of events in a simulator cycle is shown in Figure 12.

Once the programs had been assigned to blocks or pages, it was a simple matter to complete the core and drum space allocations as shown in Figure 13 and Figure 14 respectively.
Figure 12  NPPS Program Sequence

Time
START

Run Block 6
Run Page A
Run Block 1
Run Page B
Run Block 2
Run Page C
Run Block 3
Run Page D
Run Block 4
Run Page E
Run Block 5
Run Page F

Roll in Page A
Roll in Page B
Roll in Page C
Roll in Page D
Roll in Page E
Roll in Page F
Simulator Operation

The operation of the NPPS begins by powering up the consoles and external I/O system and initializing the computer (bulk load of the system from the drum), and the instructor selects the mode in which the power plant is to operate. The OS brings in the correct set of initial conditions to establish that mode, checks the consoles to see that all switches are set to correspond with the memorized conditions, illuminates the appropriate lights for the mode, loads the core resident program blocks and the first of the rolling pages, and then, upon release, starts the internal clock.

The instructor has the switches, on the Instructor's Console, to enter further "control conditions" into the simulation, at initialization or at any time during the exercise. These "control condi-

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**Figure 13 Core Map**

<table>
<thead>
<tr>
<th>OS</th>
<th>Common</th>
<th>Fast Loop</th>
<th>Output Buffer</th>
<th>Page Buffers</th>
<th>Blk 1</th>
<th>Blk 2</th>
<th>Blk 3</th>
<th>Blk 4</th>
<th>Blk 5</th>
<th>Blk 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>32K</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td>D</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Figure 14 Drum Map**

<table>
<thead>
<tr>
<th>OS</th>
<th>Cold Start</th>
<th>Common</th>
<th>Fast Loop</th>
<th>Output</th>
<th>Three Sets</th>
<th>Spare</th>
<th>Functional PCMS</th>
<th>Test and Diag.</th>
<th>15 Sets Initial Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>164K</td>
</tr>
</tbody>
</table>
tions" enter the models the same way that any other input does. The programs have been written to recognize these control conditions as, in general, simulated plant malfunctions. These can range from a stuck, disconnected, or drifting rod to a failed pump or valve to a persistent alarm annunciator. In this manner, realistic training situations can be set up that would be impossible or dangerous to duplicate in a real plant.

Test and Diagnostic Programs

Maintenance of the simulator is handled by one technician on the site. In his work he uses the test and diagnostic programs provided by the computer manufacturer, a set of test and diagnostic programs written to exercise the computer/panel interface, and a maintenance panel on the input/output (I/O) unit.

The computer diagnostics are essentially the standard set, arithmetic, input/output, core read/write, and drum transfer.

The computer/panel interface diagnostics permit the selection of signals to turn all lights on or off, to drive the analog displays to one-quarter, one-half, or three-quarter scale, and to drive the binary-coded-decimal displays to all ones or all eights. To test the input side, the program scans the panels and reports any and all switches that change position be-
The maintenance panel permits the selection, on input or output, of any specific signal to monitor it or set it to a specific value.

**Summary and Conclusions**

The Boiling Water Reactor Training Center has been in active use since its commissioning in June, 1968. The computer-driven simulator has proven to be the useful tool planned. The programs have revealed no latent bugs, though detail improvements have been made. The following points can be made as a result of careful evaluation of trainees and compilation of questionnaires returned by trainees.

1. Training is more complete at the simulator for both normal conditions and abnormal conditions. Training in situations that would be impossible or dangerous on the real plant gives valuable experience that cannot be gained elsewhere.

2. The trainee is removed from the pressures associated with operating a power plant, so that he can concentrate completely on the training activity.

3. Training time is optimized by the ability to initialize to a given condition. It is estimated that 40 hours on the simulator is equivalent to over 200 hours on an operating plant in terms of exposure to desired condi-
tions and manipulation of controls.

The experience in the use of the simulator points to the fact that operators can be more effectively trained and evaluated through its use. The application of it and a corresponding training program can do a great deal to ensure the continued staffing of our nation's nuclear power plants with high quality operators.
CHAPTER V

SKULL AND CROSSBONES

This chapter will raise some questions as to the safety of nuclear power plants and their operation. First, some background on radiation hazards. According to Dr. Gofman's research, there is a direct, proportional relationship between radiation dose, and incidence of cancer. Any radiation at all will cause some cancers.

The natural, ambient radiation in the United States is probably responsible each year for about 20,000 cancers.

The insidious aspect of man-made radiation is that radiation now will not have any effects in terms of leukemia or cancer for five to ten years. Radiation is also cumulative, a fact that proponents of yearly X-rays

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Much of the information in this section was gleaned from an article by Jack Shepherd appearing in the March, 1973 issue of Intellectual Digest in which he interviewed Dr. John W. Gofman, who holds M. D. and Ph.D. degrees. Dr. Gofman has done special work in heart disease, and cause and effect relationships between radiation and cancer. He was one of the original scientists on the Manhattan Project. In 1970, Dr. Gofman charged the Atomic Energy Commission with risking "genocide" by approving dangerous levels of radioactivity for peaceful nuclear uses. He and a colleague argued that if Americans received the permissible "safe" dose of radiation endorsed by the AEC, there might be 32,000 additional cancer deaths a year.
have only grudgingly begun to admit.

In the case of the uranium miners, it has been a 15 year lag between radiation dose and disease. The miners were not warned in the 1940's and '50's about lung cancer. The first safety standard was not enforced until 1967. It is hard to get some people excited about a danger that does not appear for 15 years. They think, "Look, it doesn't hurt - no rash - I feel fine".

By the late 1960's, it was recognized that there was an epidemic of lung cancer in the uranium miners. More than 125 are dead, and another 500 to 600 will die in spite of our best efforts to save them. The same abysmal story may be true of the nuclear power plant operators, but it will be written in the 1980's. Scientists at the University of Pittsburgh are compiling statistics on operators and dose.

**Nuclear Power Is Perfectly Safe If Radioactivity Is Contained Perfectly**

The word "if" is the most significant word in the title of this section. We are told by the AEC, power companies, and engineering firms who build nuclear plants that containment is "perfect" enough to exhibit less radiation than nature herself. Under normal
circumstances I believe engineering and construction are adequate to ensure this "perfect" containment. Our engineering cannot, however, cope with sabotage, human misjudgments, psychotics, or natural events such as earthquakes or tornadoes.

Containment within a plant is only part of the question. The unpublicized containment problem is for that of fission products (or nuclear wastes).

Every year a 1000-megawatt nuclear power plant will generate the cesium 137 and strontium 90 equivalent of 1000 Hiroshima bombs - 22-megatons of atomic fission bomb equivalent. These two isotopes have half-lives of about 30 years, and it takes roughly ten half-lives to get the radioactivity down by a factor of 1,000. If a thousandth of it is not considered harmful, then it must be contained for at least 300 years.

Plutonium, which will be produced in ton lots by breeder reactors in a more mature nuclear power industry, has a half-life of 24,400 years. This means that waste plutonium guardianship will be for at least 240,000 years, longer than the recorded history of man. Considering this quarter-million years, every bit of plutonium that escapes into the biosphere will be a problem forever on a human time scale. Can we handle tons of this stuff every year shipping it over highways or railways and not lose some of it?
Nuclear Waste Disposal

The AEC has asked congress for $1.9 million to dig up 200 to 400 pounds of plutonium buried at its Hanford, Washington facility since World War II. They had assumed that the soil would hold the plutonium by ion-exchange methods, but now fear that water flooding might cause the whole trench to explode and blast plutonium into the atmosphere.

It was thought that the salt mines in Lyons, Kansas would be an ideal nuclear dumping ground until the American Salt Company lost 175,000 gallons of water during an attempt to flush salt up from the other end of the mine. There are few alternatives. Above-ground tanks have leaked, burial at sea is unthinkable, yet has been done, and burial in bedrock at the Savannah River Laboratory in South Carolina continues in spite of the National Academy of Sciences reporting that the practice was not reasonable. It may not be reasonable, but it is cheaper than any other method. Consideration has even been given to blasting the stuff into outer space via saturn "moon" rockets, but that is not without risks. If that is done, I personally hope it is launched from Vandenburg AFB in California rather than Cape Canaveral. The optimistic assumption now is that a "perfect" method of disposal will be developed within
15 years and we should be content to contain the stuff temporarily for now. What an incredible gamble!

According to Dr. Gofman, if one per cent of the waste located at Barnwell, South Carolina were to be released into the atmosphere, we could expect 33,000 square miles of the U. S. to become uninhabitable. Southern New York, all of New Jersey, Eastern Pennsylvania, Washington, D. C., Maryland, Delaware, Virginia, West Virginia, and the Carolinas would have to be evacuated. One small, well placed bomb by an unfriendly button pusher could make a lot of folks homeless.
Conclusion

Why is a situation such as this allowed to exist? One answer is $$\text{\$40 billion in private money invested in the nuclear fission approach to producing electricity now, with untold billions of federal dollars involved. Many very learned and ambitious men have staked their reputations on developing nuclear fission as the ideal power source. However, as has been discussed, a number of grave problems persist.}

If solar power generation or nuclear fusion, can in fact, be made feasible, the problem will then be replacing a working, but dangerous source of power with an experimental, but environmentally sound source of power. A number of engineers think that given money, publicity, and a redirection of governmental priorities, we could shift our economy over to solar energy conversion in 20 years. This question of priorities should become the most debated public issue of all for the next several years.
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