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EVALUATION OF HYBRID COMPUTER PERFORMANCE ON A CROSS SECTION OF SCIENTIFIC PROBLEMS

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EVALUATION OF HYBRID COMPUTER PERFORMANCE ON A CROSS SECTION OF SCIENTIFIC PROBLENS

Edited and Assembled
by
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EVALUATION OF HYBRID COMPUTER PERFORMANCE ON A CROSS SECTION OF SCIENTIFIC PROBLEMS

R. D. Benham

ABSTRACT

Hybrid and small digital computers were evaluated on several types of technical problems, using a recently developed software system called SIMPL (Simulation Implementing Machine Programming Language). Comparisons with batch processing on a large digital computer were made for 12 scientific studies. Accuracy, time and cost (man and machine), convenience and flexibility, and computer requirements were evaluated by a cross section of scientists and engineers.

PNL Hybrid-1 Computer System

CONTENTS

FIGURES

EVALUATION OF HYBRID COMPUTER PERFORMANCE ON A CROSS SECTION OF SCIENTIFIC PROBLEMS

INTRODUCTION

A way of using hybrid and small digital computers that has been developed at the Pacific Northwest Laboratories uses scaled analog/digital simulation techniques. The hybrid computer software system that employs this technique is called SIMPL-1 (Simulation Implementing Machine Programming Language - Version 1) and is imnlemented on a PDP-7 digital computer and an EASE 2133 analog computer designated PNL-1.[(1),(2)]

The purpose of this report is to describe the capabilities of this hybrid system on the following scientific and engineering problems:

1) U.S. nuclear rower economy
2) reactor vessel dynamics
3) nuclear plant dynamics
4) river water quality dynamics
5) metal annealing
6) reactor core design
7) steam particle deposition
8) fuel sintering
9) ultra-centrifuge data analysis
10) smoke polution dynamics
11) ground water systems analysis
12) two-group diffusion equation.

The points considered by a cross section of scientists and engineers who evaluated the above studies were: (1) accuracy, (2) time and cost (both men and machine), (3) operational convenience and flexihility, and (4) the amount of computer equipment required as compared to batch processing on a large digital computer.

SUMMARY

ACCURACY

Hybrid (analog/digital) computers have sufficient accuracy and capacity to solve a wide variety of scientific and engineering problems at less cost with greater convenience than on large (batch processing) digital computers. Small digital computers (8K to 16K of core) also have sufficient accuracy and capacity to conveniently solve a wide variety of problems when scaled analog/digital techniques are used.

TIME AND COST

Twelve comparative studies have been conducted at Battelle-Northwest in the past year. These studies confirmed that a relatively small computer can do many scientific simulation problems more quickly and at less cost than batch processing on large digital computers. Time and cost savings were greatest on parametric surveys or optimization runs.

CONVENIENCE AND FLEXIBILITY

It is estimated that small hybrids can do an adequate job on at least 50% of the scientific and engineering problems now being solved on very large digitals. No scientific problems were found that required more capacity than 200 analog amplifiers and 16K of digital memory. The studies also indicate that many problems now being worked on large digitals can be readily done on relatively small digital machines.

LEARNING EFFORT

A person already familiar with Fortran or similar languages requires some familiarization with SIMPL-1 or related machine codes. With this factor included, the hybrid or small digital computer, in the majority of cases, demonstrated a cost savings while meeting accuracy and capacity requirements.

EXAMPLES

1) In view of the time and resource allotment for this study, the complexity of the Nuclear Power Economy Model was reduced from 900 equations to 300 equations and solved entirely on the PDP-7 digital computer. A qualified 3.2-to-1 speed advantage was demonstrated by the hybrid method and it was determined that a 25,000 word drum memory would allow the extra capacity for solving expanded problem on the small computer. The large digital solution produced more optimum results by about $1 billion with a different reactor mix. The dollar difference represents only a small percentage (0.4%) of the total cost but accounts for 10% of the savings between all fossil and the combination of fossil and nuclear plants.

2-3) The reactor vessel study demonstrated cost savings of 75-to-1 when compared to DYNASAR programming on a UNIVAC 1108 computer. An estimated cost savings of 100-to-1 was indicated in qualitative comparisons of DYNASAR to the hybrid computer for the Fast Flux Test Facility (FFTF) dynamic simulation. Comparisons from both simulations demonstrated no significant loss in accuracy. The time required for developing the reactor vessel simulation was from 2 to 3 times greater than that for the DYNASAR simulation.

4) A 3.6-to-1 minimum machine speed advantage and an overall cost advantage of 36-to-1 was indicated for parameter surveys on the river water quality study. The cost of one or two parameter studies is about equal for the large digital and hybrid because of hybrid computer setup and checkout. For model optimization studies, the increased effectiveness of engineering personnel is multiplied by a 36-to-1 machine advantage to produce a net economic advantage.

5) The metal annealing simulation demonstrated a cost advantage of 35-to-1, a speed advantage of 3.5-to-1, and a core memory savings of 30%.

6-7) The steam cooled fast reactor core and the steam particle deposition studies indicated a cost savings of 2-to-1 and time savings of 3-to-1.

8-10) Cost saving factors of 10-to-1 to 50-to-1 were demonstrated on the fuel sintering, ultra-centrifuge, and smoke pollution problems. The savings were primarily derived from increased efficiency of technical personnel and accelerated work performance.

11) The ground water simulation was performed at about the same speed using SIMPL techniques on PDP-7 computer as when FORTRAN IV was employed on the UNIVAC 1108. However, the hybrid demonstrated a 24-to-1 advantage in manpower in preparing input to the computer and a factor of 1440-to-1 advantage in time required to analyze the computer results when compared to batch processing on a UNIVAC 1108.

12) The two-group diffusion and steam particle deposition problems were sensitive to equipment resolution, configuration, and scaling. Acceptable solutions were obtained with third generation analog computer equipment on the steam particle deposition problem. Acceptable results for such functions as few-group flux and power profile studies were obtained with the PDP-7 digital computer and a fourth generation analog computer. There is some question about the applicability for reactor physics perturbation studies. It appears that the only way to resolve the question is for the hybrid or small digital computer to solve the complete problem of determining reactivity coefficients for accuracy comparison with large digital methods.

CONCLUSIONS

The optimal way to use hybrid and large computer simulation programs is to use each method in a complementing rather than a competing manner. For large expensive computer simulations, situations often occur where independent computer check solutions are extremely valuable. When one or two computer runs are needed, batch processing on large digital computers excels. Small problems generated by a large-user clientele may be more economically solved on large computers; however, when parametric surveys or optimization runs are needed, the SIMPL concept is more economical.

CRITERIA FOP COMPUTER COMPARISON

This study was designed to evaluate the cost savings potential of using hybrid and small digital computers. The following sections explain how the comparative problems and performance guidelines were selected.

PROBLEM SELECTION

The object of this study is to evaluate small computer techniques on problems formulated and programmed for large digital computers prior to the development of hybrid computer technology. The only restrictions were:

1) Availability of comparison information
2) Future potential for cost and time savings.

The resons for selecting the problems for this study are presented in the following paragraphs.

U.S. Nuclear Power Economy. The Nuclear Power Economy problem was selected because of its cost savings potential. The problem[3] also uses linear programming which most text books consider the domain of the large digital computer.

In view of limited time and funds, the complexity of the problem was reduced from 900 equations to about 300 equations to see if this problem could be reformulated for hybrid computer application and to see how much hybrid equipment was required to solve the problem.

Reactor Vessel and Nuciear Plant Dynamics. These studies were selected because:

1) Comparative information was available.
2) The problems provided an opportunity to test and evaluate the modular component concept previously developed for the dynamic simulation.

River Water Quality Dynamics. Proper use of natural resources is a subject often discussed by Government, industry, and professional societies. The problem considered in this area was the Columbia River water quality model.[4] It presented a special challenge to hybrid methods because the digital model was based on discrete digital concepts rather than differential equations. Since the digital model is capable of simulating river flows and temperatures from Lake Roosevelt to the ocean, there was doubt about the hybrid computer's ability to accurately simulate the model with 8192 words of memory and 160 analog amplifers, compared to the 30,000 words of UNIVAC 1108 memory required to solve the problem digitally.

This problem was selected because:

1) There is a growing need to simulate natural resource systems.
2) The hybrid method could benefit the work effort while relieving the economic penalties associated with sole use of a large digital computer.
3) It provided an opportunity to evaluate such factors as problem reformulation requirements, equipment requirements, and computer accuracy.

Metal Annealing. The computer simulation of radiation damage phenomena uses the ANNEAL code.[5] The model performs a Monte Carlo walk through lattice points to simulate the random motion and interaction of lattice defects. A large quantity of UNIVAC 1108 digital computer time is required to obtain statistical significance.

The reasons this code was selected are:

1) It provided an opportunity to evaluate problem reformulation and equipment requirements in a problem area unfamiliar to simulation engineers.

2) The hybrid method could benefit the work effort while relieving the economic penalties associated with the sole use of a large digital computer.
3) Irradiation effects simulation is a growing field.

Reactor Core Design and Other Miscellaneous Problems. The reactor core,[6,7] fuel sintering, smoke pollution, steam particle deposition,[8] ultra centrifuge,[9] and ground water deposition,[10] problems were brought to the hybrid computer facility as regular jobs during the time that the evaluation studies were being made. These are included since they provide useful additional information.

Two-Group Diffusion Equation. A one-dimensional, two-energy-group reactor diffusion model was selected to evaluate accuracy considerations on the most accuracy-sensitive equations known at the time of this study.

GUIDELINES FOR COMPARISION

Primary consideration in performance guidelines are accuracy, time and cost benefits, operational convenience and flexibility, and computer requirements.

Accuracy. Scientists and engineers who use large digital computers are familiar with double precision techniques necessary to preserve accuracy. Several applications (such as recursive equations, subtraction of large numbers, division by small numbers, etc.) will produce inherent errors independent of word length and computer precision. One manufacturer produces a machine with a 60 bit word length to overcome double precision problems. Some computer users are now using scaling methods to improve library subroutine precision for the 60 bit word length computer. With this background many scientists, engineers, and mathematicians tend to compare analog and hybrid computer accuracy. The one part in ten-thousand precision of an analog computer or one part in 2^{17} for small digital computers appear inadequate when compared to precisions of one part in 10^{37} available with large digital computers.

With analog or small digital computers, precision for solving technical problems is more a function of what is done with available hardware. Inaccuracies resulting from numerical approximations are overcome by applying different modeling techniques, amplitude scaling, and time scaling.

Most of the accuracy comparisons made in this report were made by visual comparison of plotted results. Some comparisons show (1) the percent deviation between two methods, (2) the percent deviation from the maximum value, (3) the integral of the squared deviation, (4) bounded areas between curves and axis.

Time and Cost Benefits. Some of the factors that determine computer chargeout rates are:

1) Rental (depreciation) of the computer
2) Computer operator costs
3) Maintenance
4) Systems software development
5) General adminstrative functions
6) Building utilities and maintenance
7) Rent (depreciation) of building,

Since the hybrid computer used in this study is owned by the U.S. Atomic Energy Commission, depreciation of the computer and buildings are not included in the normal $18/hr charge rate. The normal charge rate includes maintenance and some systems software development. Simulation engineers who program and develop math models also operate the hybrid computer. These costs are not included in the computer rate. Since most large computers rates include equipment depreciation, and extra $20/hr is added to the normal hybrid charge rate to arrive at the $38/hr value used in this study. Hybrid computer equipment amortization was established by depreciating $400,000 over 10 years.

Chargeout rates for large hatch processing digital computers vary widely ($100/hr to $1,200/hr) across the country. Rates are usually established to liquidate total cost which includes all major items listed above. This study uses a nominal value of $400/hr for a UNIVAC 1108 computer. This is sufficient to amortize the computer, provide computer operators and maintenance, and liquidate administrative overhead for a modest computer operation. Costs for developing and programming mathematical models are not included in the computer rate.

Manpower cost comparisons must be on a equitable basis. For an ideal comparison, identical problems would be given to two (or more) competent scientists or engineers to carry from problem definition through problem formulation, programming, debugging, and analysis stages. Since ideal conditions are difficult to achieve, care must be exercised to insure that inequalities are identified and properly weighted. For example, it is inappropriate to include model development costs in a comparison if one method was used in developing the model and the other method merely invoved programming and running a developed model. However, the reprogramming, computer running cost, the total elapsed time, and percentage of effort required to get the job done can be identified.

Every effort was made to insure a comparison of machines and techniques and not people because different people have different degrees of expertise. It is not prudent to compare a programmer with two years of college experience with an experienced scientist, engineer, or mathematician.

To factor out people comparisons, six different hybrid-oriented simulation staff members participated in the study. Three were electrical engineers with Bachelor of Science degrees, two were physicists with Bachelor of Science degrees, and one completed two years of college (however he received help from a physicist and engineer). The steam particle deposition problem (both hybrid and digital) was conducted by a PhD Chemical Engineer on an open-shop basis with help from an experienced electrical engineer. The education and experience of people solving the problem on the digital computer include a PhD Electrical Engineer, four B.S. Mechanical Engineers, one M.S. Mechanical Engineer, and a M.S. Sanitary Engineer. The noticeable differences in people would appear to be in their disciplines.

The other factors such as programming and analysis, computer debug time, computer running time, analysis time to present results, and total costs are dependent on the circumstances surrounding each problem and are discussed in more detail in the PROBLEM DESCRIPTION AND ANALYSIS section.

Operational Convenience and Flexibility. Most scientists and engineers share familiar experiences with large batch processing digital computers and know that for an additional 10% in programming effort they can get a factor of 3 increase in line printer or plotter output.

For an additional 10% of hybrid computer programming effort a factor of 10 increase in machine output is easily obtained. Analog and hybrid data are almost always graphically displayed for immediate analysis. Readout devices include x-y records, strip chart recorders, oscilloscopes, black and white CRT memory displays, color displays, teletype, and line printers. The quality of display output is adequate for on-line analysis but for permanent record storage or report documentation, some improvements are in order. Specific examples of display output are given with the technical discussion of each problem.

Computer Requirements. It is difficult to make comprehensive equipment comnarison among analog, hybrid, and digital computers because of operational differences. The purpose of the computer equipment comparisons in this report is to identify the type and quantity of equipment required to solve the cross section of problems. The unique circumstances affecting the quantity of equipment required are discussed in the PROBLEM DESCRIPTION AND ANALYSIS section. This information should be useful in sizing other problems for hybrid and small computer solution and for designing more efficient software for large time-shared computers.

PROBLEM DESCPIPTIPN AND ANALYSIS

This section of the evaluation study contains a general description of each problem along with a detailed evaluation by customer engineers.

U.S. NUCLEAR POWEP ECONOMY - (L. H. Gerhardstein, W. F. Black, R. L. Engel)

A large programming system was developed to evaluate the U.S. electrical power economy between the years 1970 and 2020. For this evaluation study, one subsystem of the overall power economy model was selected for a comparative optimization study. The model is in the form of linear programming[13] and is solved with the Bonner & Moore LP System[11] as modified for the UNIVAC 1108. The model incorporates the detailed characteristics of individual nuclear reactor types. Solution of the model provides the mixture of specific nuclear reactor types and fossil plants that result in the minimum discounted cost while satisfying the power requirement projected over an extended time interval. The model simulates the interaction of fossil and nuclear plants in ten geographic regions, with each region consisting of the area where fossil fuel costs are nearly equal. Additional features of the LP model include: (1) fissile Pu, ^{233}U, and enriched tails stockpiles, (2) uranium price increasing as a function of uranium used (step function), and (3) introduction constraints on new reactor concepts. The full-scale model results in about 900 equations for a time interval of 35, two-year periods.

It was obvious from the inception that the problem could not be formulated in terms of a linear programming scheme on the PNL-1 hybrid computer. Hybrid computers are not generally designed to employ linear programming (or matrix manipulation) techniques. However, it appeared that another optimization technique could be developed after a complete rewrite of the mathematical model.[12] To minimize the reformulation effort, the size of the model was reduced to about 25% of the complete model. The principal questions considered in the evaluation were:

1) Can large optimization problems such as the one under consideration be run on a hybrid computer or on a small dedicated digital computer?
2) Can the smaller computer systems offer economic benefit?
3) Does the hybrid or small digital computer increase decrease the power of a total computing method?
4) If the problem is so large that a large amount of core memory or a mass storage device is needed, what portion of the larger problem can be run on a small computer with limited core memory?
5) What is the accuracy of the smaller machine and specialized method compared with that of the larger machine?

Accuracy

Similar systems were modeled on the hybrid computer and on the UNIVAC 1108. Comparison curves for fossil plants are plotted in Figure 1. They show a good comparison for total fossil plant construction. However, nuclear plant construction does not agree nearly as well (see Table 1). Figure 2 shows the comparison for the plutonium stockpile. The linear programming optimization model produced a slightly smaller plutonium stockpile (9.96×10^8 kg compared to 10^9 kg for the hybrid model over the 70-year period).

The deviations in the hybrid output from that of the UNIVAC 1108 might be attributed to fixed point scaling throughout the hybrid simulation. Since the optimization

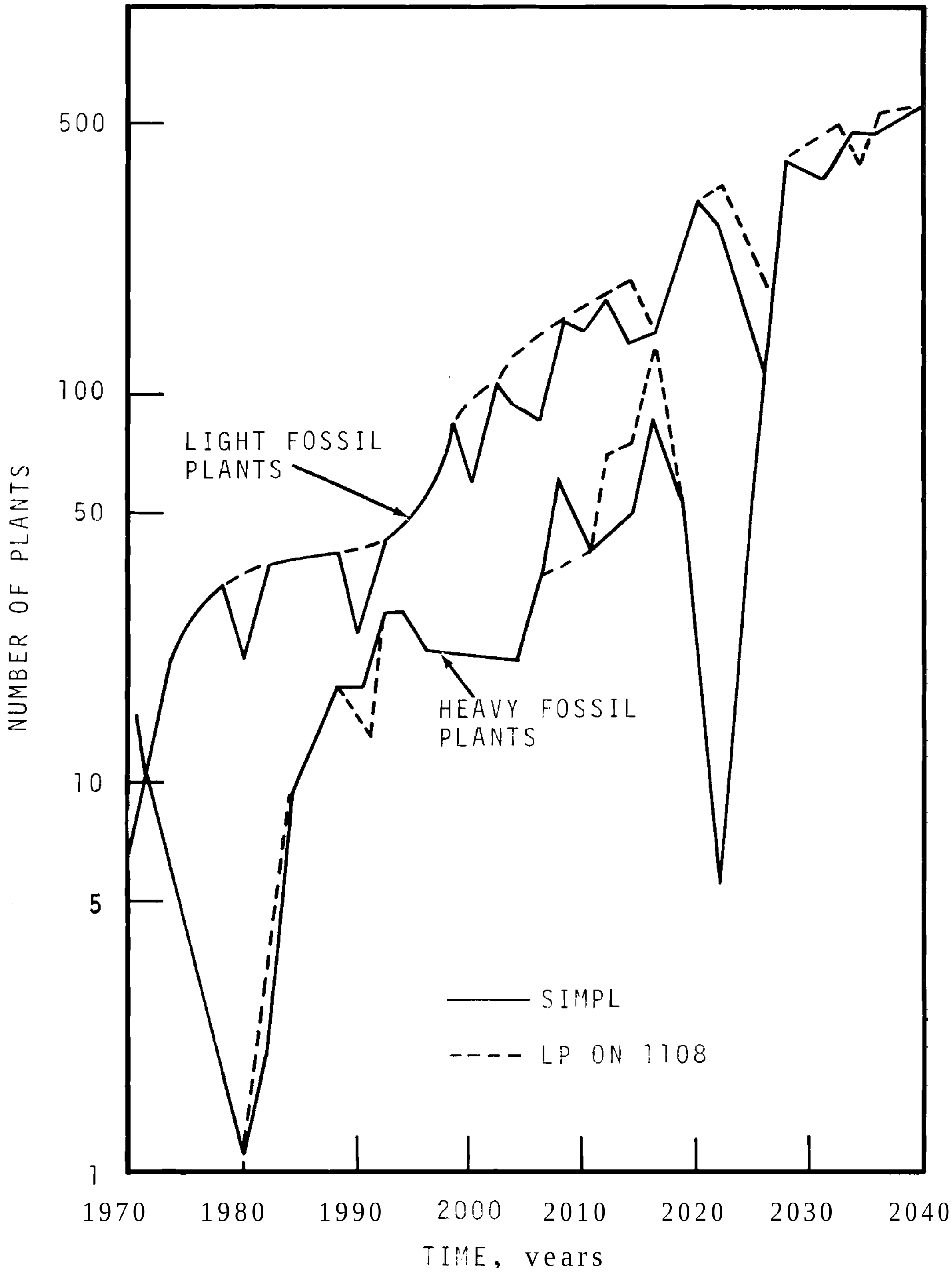


FIGURE 1. Fossil Plant Comparison of Linear Programming (LP) Results to Those Generated by SIMPL Techniaues

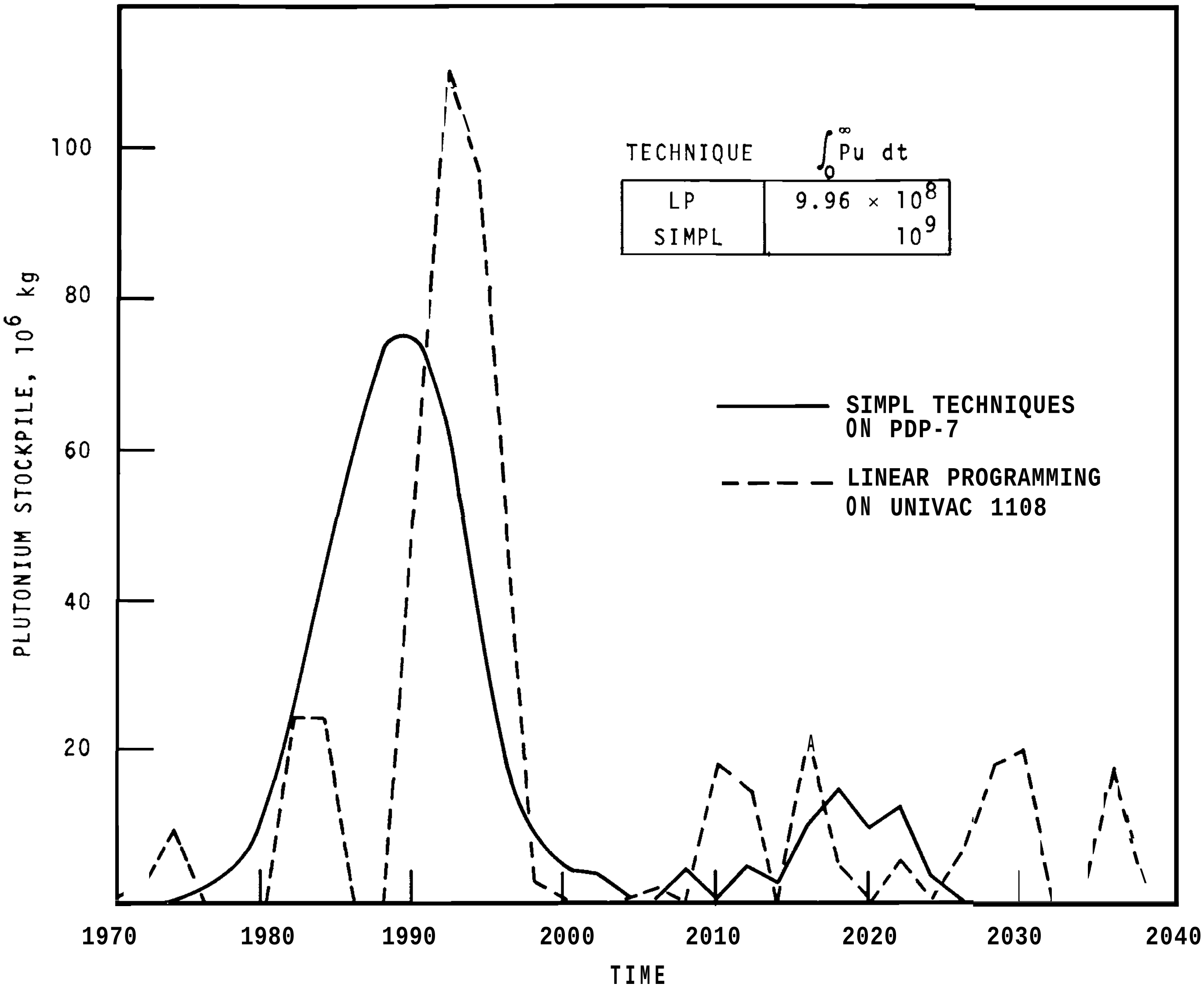


FIGURE 2. Comparison of Plutonium Stockpile for Linear Programming and SIMPL Techniques

TABLE 1. Comparison of Nuclear Plant Built as Function of Time

		Reactor Types											
	TIME PERIOD	WU3H etc. (LP)	WU3H etc. (Hybrid)	WU3L etc. (LP)	WU3L etc. (Hybrid)	WPOH etc. (LP)	WPOH etc. (Hybrid)	WPOL etc. (LP)	WPOL etc. (Hybrid)	YP2H etc. (LP)	YP2H etc. (Hybrid)	YP2L etc. (LP)	YP2L etc. (Hybrid)
	1970	8.74	8.73	4.03	4.03	0.0	0.0	0.0	0.0				
	72	5.19	4.16	6.73	7.79	0.0	1.02	1.06	0.0				
W	74			13.88	12.11			1.03	2.77				
	76			17.54	14.26			0.0	3.39				
	78	0.37	0.0	3.04	16.09	0.0	0.37	16.96	4.96				
	80	1.93	1.93	22.35	38.17	0.0	0.0	0.0	0.0				
	82	1.89	3.22	15.99	23.23	0.0	0.0	7.24	0.0				
X	84	5.68	5.68	7.58	24.46	0.0	0.0	16.88	0.0				
	86	2.46	7.46	0.0	23.52	5.00	0.0	23.52	0.0				
	88	0.0	10.97	0.0	24.20	10.97	0.0	24.20	0.0				
	90	23.05	16.96	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.77	25.94	43.57
	92	17.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.03	25.77	25.77
Y	94	17.47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.47	30.03	30.03
	96	13.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.75	38.20	38.20
	98			5.03	47.11			0.0	0.0			51.70	9.62
	2000			62.73	103.58			0.0	0.0			0.0	
	02			66.92	66.92			0.0	0.0			0.0	
	04	8.03	0.0	12.99	8.81	0.0	0.0	7.61	0.0	5.03	13.06	29.82	50.48
	06	4.99	23.16	0.0	56.68	0.0	0.0	0.0	0.0	18.17	0.0	0.0	
	08	2.62	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.46	0.0	0.0	
	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.72	0.0	23.66
	12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.91	28.71	0.0	
	14	0.0	0.0	0.0	65.25	0.0	0.0	0.0	0.0	0.0	31.91	0.0	0.06
	16	0.0	25.12	0.0	0.0	0.0	0.0	0.0	0.0	9.36	32.56	0.0	
Z	18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.05	36.05	0.0	
	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	5.76
	22	0.0	0.0	0.0	43.70	0.0	0.0	0.0	0.0	3.47	3.47	0.0	34.83
	24	0.0	0.0	0.0	109.34	0.0	0.0	0.0	0.0	43.36	43.36	0.0	
	26	0.0	86.49	0.0	76.39	0.0	0.0	0.0	0.0	20.88	0.0	0.0	
	28	0.0	0.0			0.0	0.0	0.0		0.0	36.39		
	30	0.0	0.0			0.0	0.0	0.0		0.0	113.80		
	32	0.0	0.0			0.0	0.0	0.0		0.0	24.28		
	34	0.0	0.0			0.0	0.0	0.0		0.0	54.91		
	36	0.0	0.0			0.0	0.0	0.0		0.0	53.00		
	38	0.0	0.0			0.0	4.95			6.59	0.0		

program must compare very small numbers to determine least costly choices, the optimization program could make an incorrect choice.

When the final cost (objective function value) for the two methods, were compared the LP solution total cost was slightly less than the hybrid solution total cost.

LP cost	$259.59 billion
Hybrid cost	$260.57 billion

The difference figure of $0.98 billion is approximately 10% of the total cost change in reaching optimum when an all fossil condition is used initially.

Time and Cost

Time and cost information is useful in documenting manpower requirements in reprogramming using SIMPL. A total of 528 manhours and 200 hr of computer time were required to complete the study. Of this, 80 hr were required to reformulate the model, 48 hr were required to develop the interactive display techniques, 170 hr were required to program the model, and 230 hr were required to debug and document the study.

The PDP-7 computation time was 4.5 min while the UNIVAC 1108 computation time was 14 min and 26 sec. However, these computation times should be qualified because:

1) The LP model arrived at a more optimum solution,
2) The LP model includes two additional stockpiles which complicate the optimization.
3) The simplex method (the algorithm used in solving linear programs) is a generalized mathematical technique and does not take advantage of physical characteristics modeled. The optimization used for the hybrid, on the other hand, considered the physical properties being modeled and this resulted in a more optimum program.

The results of this comparison are rather inconclusive to evaluate hybrid versus large digital computers. However, there is a definite computing time advantage indicated.

Operational Convenience and Flexibility

The major advantage of the hybrid method for modeling of the economics problem is that the operator can manually and visually communicate with the optimization problem in realtime. Figure 3 shows a typical oscilloscope display of plutonium stockpile at an intermediate step in the optimization. The operating system used with the economics model allows the operator to make changes in the input functions (through the oscilloscope display) and immediately see the effect by examining the various output functions of the problem.

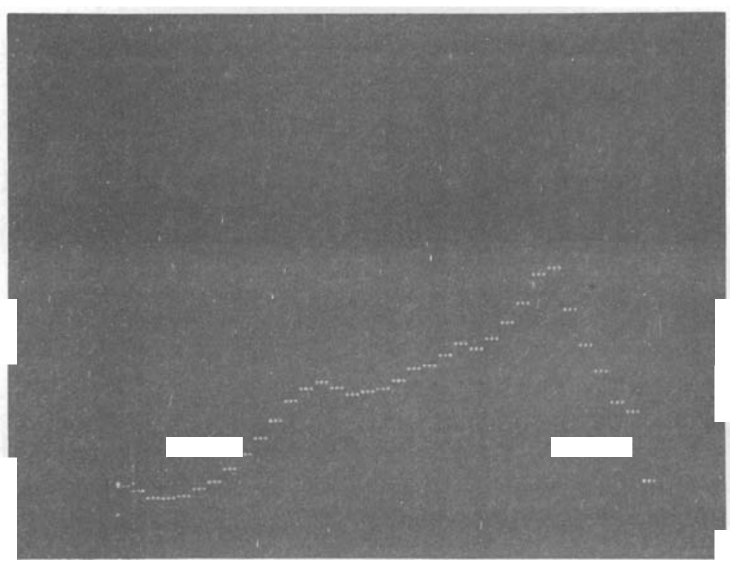


FIGURE 3. Typical Display Showing the Plutonium Stockpile at an Intermediate Step in the Optimization

Computer Requirements

The problem modeled and run with the nonlinear hybrid method represents approximately 25% of the ten region problem that was run with the linear program method. The "25% problem" requires approximately 6K words of the PDP-7 8K memory.

To solve the expanded problem on the hybrid computer would require the 25,000 word drum interfaced to the PDP-7 computer. This would also provide the extra memory for evaluating only two convolution integrals for each partial derivative evaluation in the optimization procedure. With 8192 words of core available it was necessary to evaluate at least 20 convolution integrals for evaluating each partial derivative. Since very little time is sacrificed in drum reading and writing, the computation time would be reduced a factor of 5 to 10 with this programming change.

The Power Economy Model reauires 39,565 words of UNIVAC 1108 memory to solve the fully expanded problem.

REACTOR VESSEL **DYNAMICS** - (C. D. Flowers and G. A. Worth)

The reactor model is based on the FFTF vertical core reactor concept V-A. The model divides the reactor into 44 separate nodes where reactor temperatures are calculated. The nodal breakdown is shown in Figure 4. Inlet and outlet mixing plena are simulated with four flow paths through the reactor: (1) average driver fuel tube coolant, (2) average leakage coolant outside of driver fuel tubes, (3) average radial reflector coolant, and (4) vessel wall coolant.

Several solid material regions have been simulated using from one to nine separate nodes for each area. The nodal temperatures represent average conditions within the reactor

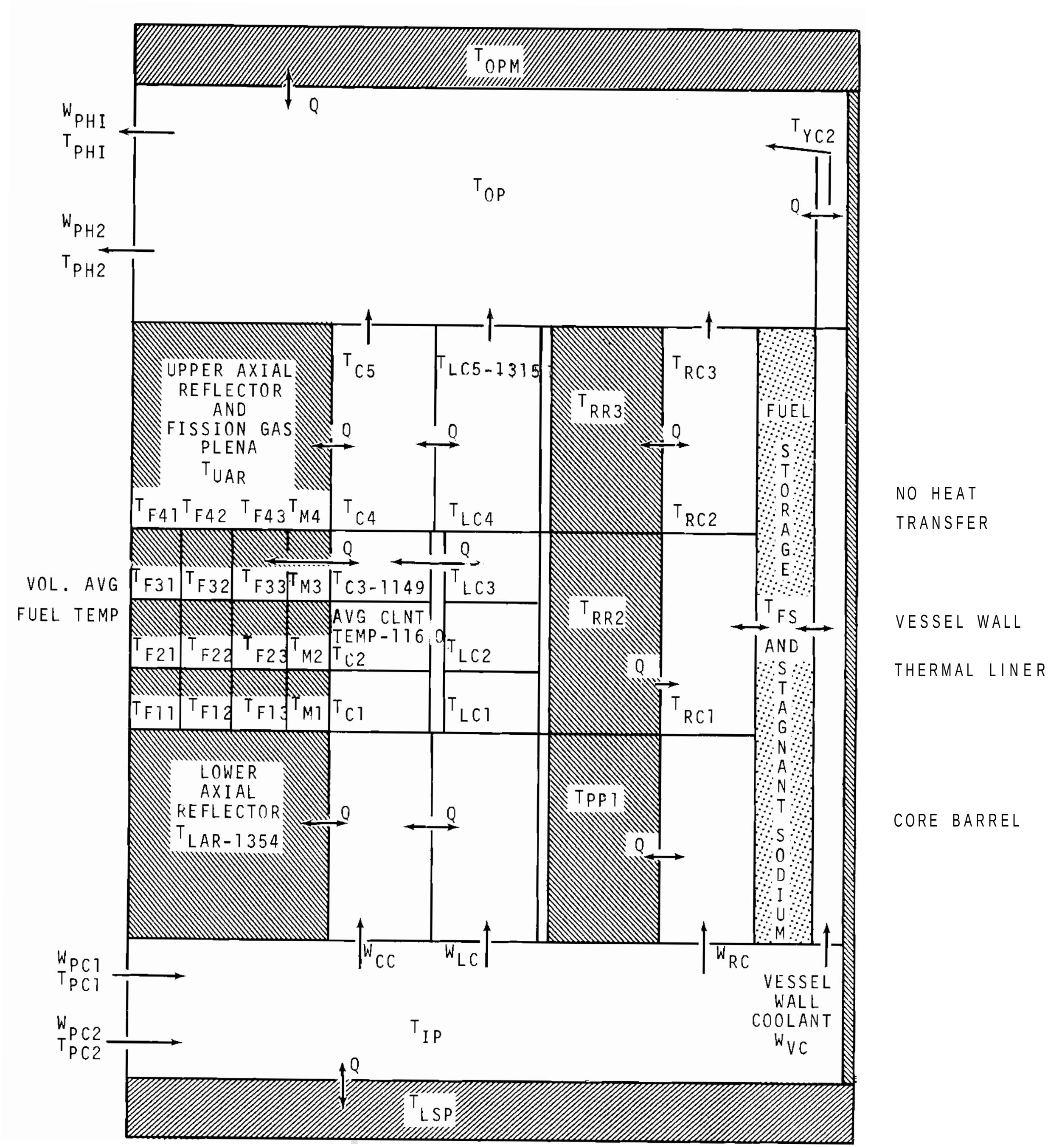


FIGURE 4. **Schematic of Reactor Core Showing Temperatures and Box Numbers for DYNASAR Simulation of Reactor Vessel**

vessel. The solid material regions are fuel, fuel cladding, lower and upper axial reflectors, driver fuel duct wall (in core zone), inlet plenum metal, outlet plenum metal, radial reflectors (includes radial reflectors, shields, control rods, etc.) and a region that represents the fuel storage region outside of the reactor core barrel (simulated as stagnant sodium). Heat transfer between all adjacent regions is included (indicated by double point arrows in Figure 4).

Heat generation is included in the following regions: fuel, axial reflectors, and radial reflectors. The total reactor power includes power generated by fast (prompt) neutrons and power generation by beta and gamma decay of fission products. The neutron power is calculated by the simple point kinetics equations with the assumption that the neutron lifetime is small enough (neutron lifetime is about 10^{-7} for fast reactors) to make the neutron power calculation algebraic (i.e., neglect ℓ^* dP/dt term - restricts reactivity step insertions to less than +1$). Three reduced neutron decay groups are assumed for input to the neutron power calculation with, the following reactivity feedback terms: Doppler, sodium temperature, and structural effects. Three groups are also assumed to represent the fission product decay heat generation. A reactor power controller is also simulated.

Other miscellaneous temperatures that are calculated include average fuel, average driver fuel channel coolant, hot channel core outlet, and hot channel maximum clad.

The total reactor simulation contains 52 differential equations of which 44 calculate reactor temperatures, six calculate total reactor power, and two calculate power controller response. The remainder of the simulation consists of algebraic calculations and function generators.

All sodium, fuel, cladding, and driver tube wall material properties are computed as a function of temperature at each node point. Reflector and plenum metal properties have been assumed constant.

The hybrid model was developed entirely on the digital portion of the hybrid computer (on the PDP-7). The comparison which was made was not one of hybrid versus digital computers but rather one of structured assembly language (SIMPL-1 on the PDP-7 computer) versus a large general purpose dynamic digital code (DYNASAR[13] on the UNIVAC 1108). The hybrid method uses a fairly simple rectangular integration scheme as compared to the more sophisticated fourth-order predictor-corrector scheme used by DYNASAR.

Accuracy

Steady-state reactor temperatures and power were found to be identical in both simulations. Four transients were studied to make a comparison of the dynamic response of each simulation. They were:

1) Full flow reactor scram
2) Simulaneous reactor scram and primary flow coastdown
3) Flow transient for double-ended break at reactor vessel inlet, with scram 2 sec after break, and pump coastdown 1 sec after scram. Input flow data were taken from previous DYNASAR pipe rupture studies with 1 ft^3/ft inlet downcomer standpipe.
4) Flow transient for one square foot hole type break at reactor vessel inlet with scram 2 sec after break and pump coastdown 1 sec after scram. Input flow data were taken from previous DYNASAR pipe rupture studies with 1 ft^3/ft inlet downcomer standpipe.

The results from Runs 1 and 3 are shown in Figures 5 and 6. The results show that there is almost perfect agreement in the dynamic response of the two models. For Run 3 (see Figure 6) the core outlet temperatures and the average fuel temperatures disagreed by approximately 5 °F during the first 2 sec. From that point on there was perfect agreement throughout the two models. These differences are felt to be insignificant and it has been concluded that both models perform in essentially the same manner.

Time and Cost

There were 323 hr spent in developing the hybrid simulation. Of this about 48 hr, including 24 hr of computer time, were spent in developing a general program to handle all aspects of the simulation aside from actual problem simulation (time synchronization, input/output, man-machine interaction, integration programs, etc.). This general program can be used for any simulation, and time used in its development will not be required in future simulations. The remainder of the time (275 hr including 99 hr of computer time) was spent in programming, debugging, and in making the comparison transients.

The time spent in developing the DYNASAR simulation can only be estimated since the reactor model is a portion of an overall system which has gone through several stages of development. A rough estimate of the amount of time that would have been expended in the DYNASAR simulation of only the reactor portion of the system would be a minimum of 2.5 to 3 weeks or roughly 100 to 120 hr. This is approximately 30 to 45% of the time required for the SIMPL-1 simulation.

For a simulation which will be used over an extended period of time, the primary concern from an economical standpoint often switches from development cost to computer cost

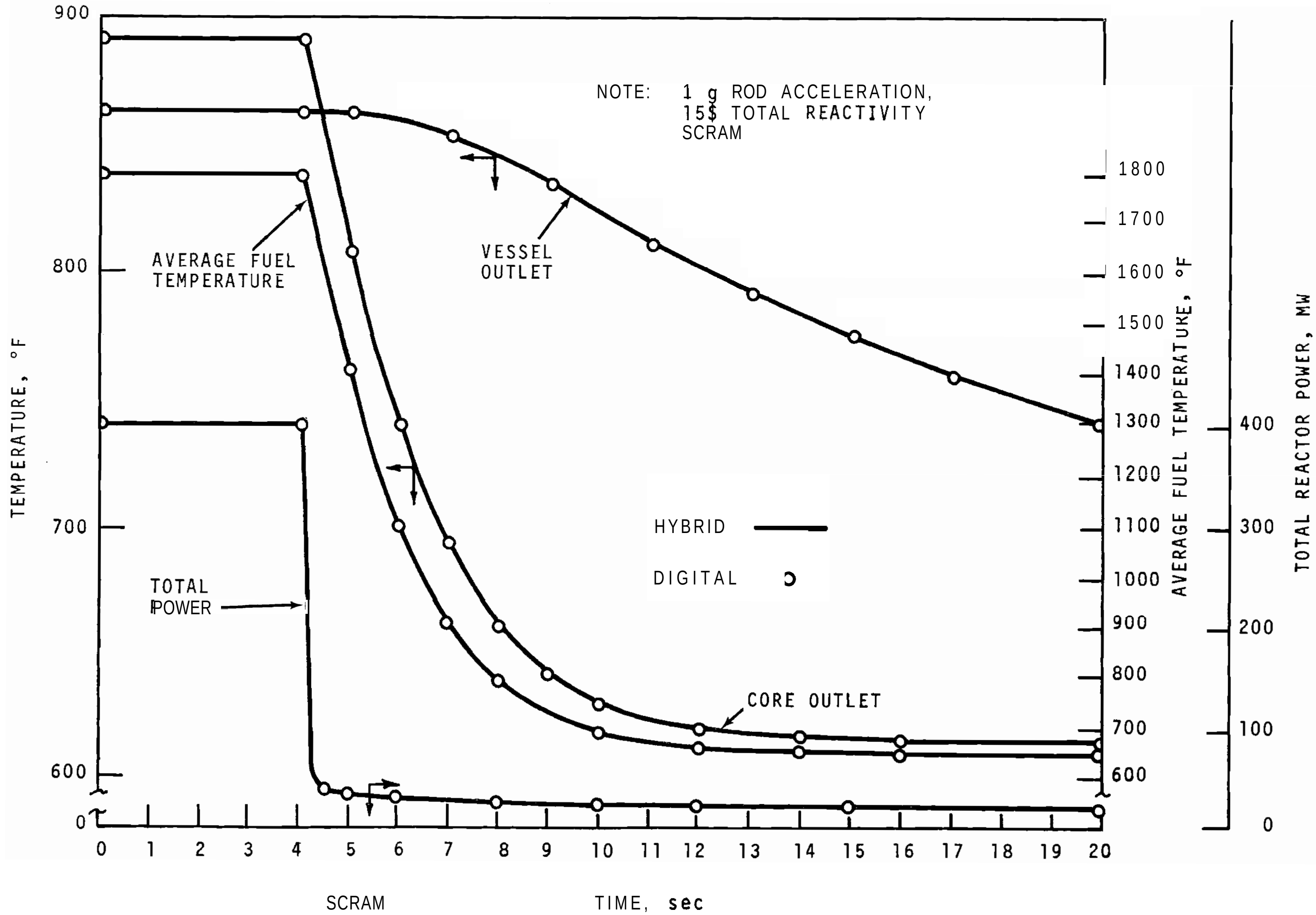


FIGURE 5. Comparison of Results From Hybrid and Digital Models for Full Flow Reactor Scram

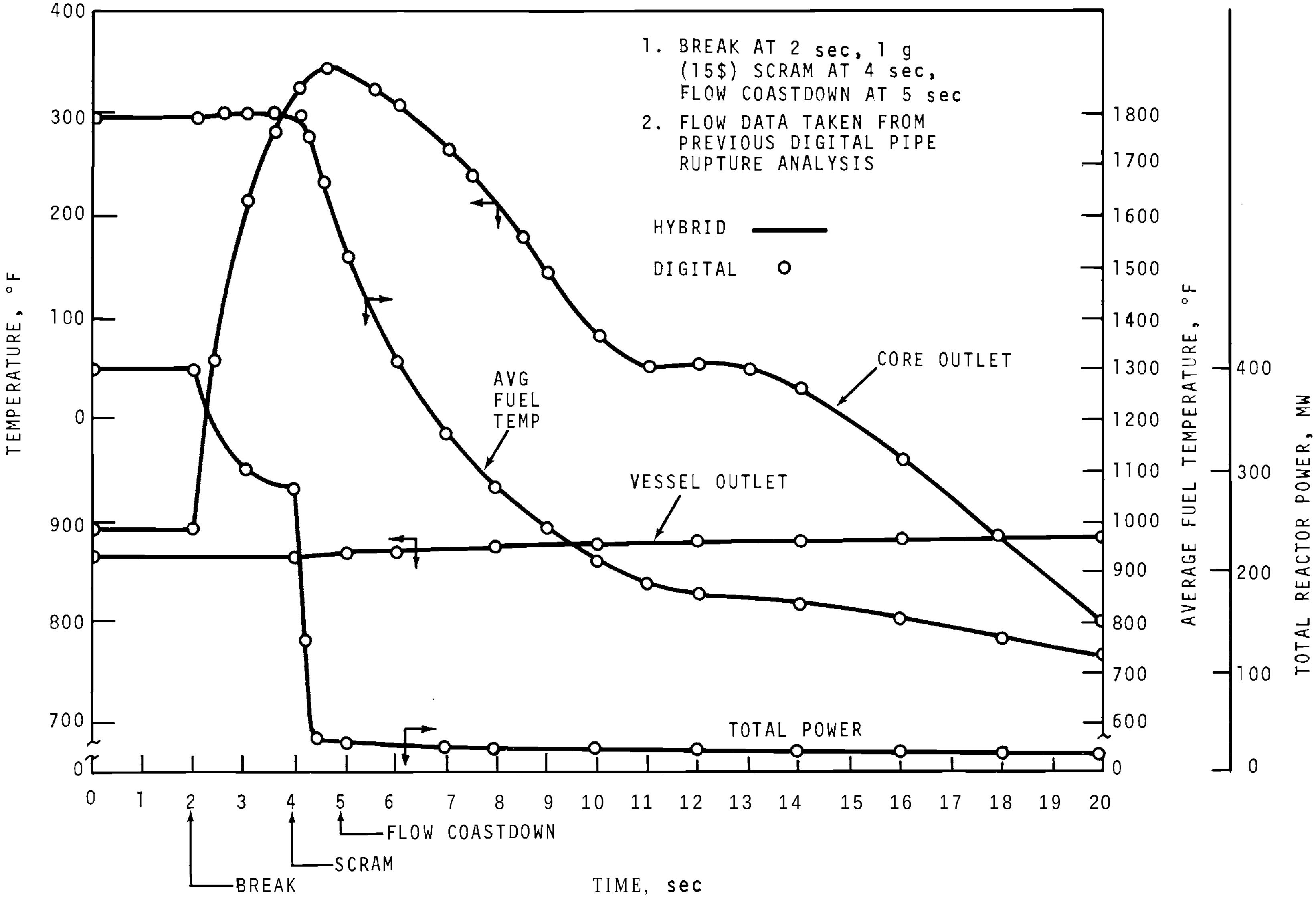


FIGURE 6. **Comparison of Results From Hybrid and Digital Models for Flow Transient Due to Double-Ended Break at Reactor Vessel Inlet Nozzle**

for making transient studies. Table 2 shows the amount of computer time required per second of transient in the solution of the four transients described previously. As can be seen, the DYNASAR program requires from 16 to 88 times as long in the problem solution as the SIMPL-1 program. One point of interest is that Runs 3 and 4 more closely approach the type of transient for which the model is needed (pipe rupture studies) thus, for this particular need, the ratio of problem solution time is between 15 and 2C-to-1.

TABLE 2. Comparison of Computer Time Reauired Per Second of Real Process Time

Run	SIMPL-1, sec	DYNASAR, sec	Ratio
1	1	88	88
2	1	32	32
3	2	32	16
4	2	36	18

Cost and speed ratios are somewhat misleading because time is required on the PDP-7 to setup for a transient. A fair comparison might be made in the following manner. If 1 hr were required for a DYNASAR solution to simulate a 1 or 2 min transient, the same solution could be obtained at the same cost ($400) with SIMPL-1 even if 10 hr were required. In general, with SIMPL-1, about 10 min are required for problem setup and about 2 to 3 min are required for the setup of a particular transient. Since the 1 to 2 min transient would require 2 to 4 min, a single transient would require a maximum of 15 to 20 min, much less than the allotted 10 hr. When several transients are run, the 10 min necessary for problem setup is averaged between all of the transients, and the time required for a single transient becomes less than 8 min. Seventy-five transients could be run for the same $400. It is difficult to make absolute statements in a cost comparison of this type, but it is certain that SIMPL-1 has a definite cost advantage over DYNASAR.

Operational Convenience

Use of the UNIVAC 1108 requires a full day for transient turnaround. The hybrid computer must be scheduled in advance (usually a few days). Both of these are disadvantages. However, the hybrid system offers the advantage of having almost instant turnaround between transients once the program is operating

Hybrid output is immediate and can be either plotted or presented in tabular form, or both. For the comparison studies, the maximum number of variables that could be output in tabular form was six. This, however, has been modified and now all necessary variables can be output. Tabular output now occurs on a line printer simulaneously with the problem solution or it can be transferred directly to magnetic tape for permanent storage and listing at some later date.

The hybrid system also provides more flexible man-machine interaction. The user can make changes in the program on-line and see the immediate results and significance of the changes made.

Computer Requirements

The UNIVAC 1108 computer has 65,000 core memory locations of which 52,000 are needed by the DYNASAR program even though it may not use them all. It has an effective machine cycle time of 0.750 μsec. The SIMPL-1 simulation uses a PDP-7 digital computer which has 8192 core memory locations and has a machine cycle time of 1.75 psec.

Even though the PDP-7 computer is smaller, its full capabilities were not reached. Besides the fact that the analog computer was not used, the digital program used only 6100 of the available 8192 core locations. Figure 7 shows a memory map of the simulation program. As shown in the figure, the actual reactor simulation used 2700 locations plus general subrountines. The simulation could be expanded by about 75% if the 2062 free locations were used.

The PDP-7 has an 18 bit word length as compared to the 36 bit word length of the UNIVAC 1108. Accuracy was maintained on the PDP-7 by scaling ail variables in the system.

NUCLEAR PLANT DYNAMICS - (G. A. Worth)

The development and use of Fast Flux Test Facility (FFTF) simulation models started during conceptual design in 1965 and will procede through construction and operation of the plant.[14,15] The modeling and simulation effort has nrogressed through several phases in response to conceptual design needs and subject to availability of hybrid software and hardware. A parallel all-digital effort employing the DYNASAR simulation code has been used for detaiied calculations and for checking the adequacy of the hybrid models. However, direct time and accuracy comparisons have been made.

The major elements of the FFTF plant simulation are illustrated in Figure 8. The figure also illustrates the split in computational work between the hybrids analog and digital computers.

Neutron kinetics in the reactor vessel are simulated with three delayed groups, as in the method of Albrecht and Metelmann[16]. An algebric expression for neutron dynamics is used to eliminate the need for extremely high-grain analog integration. Heat generation due to fission product decays

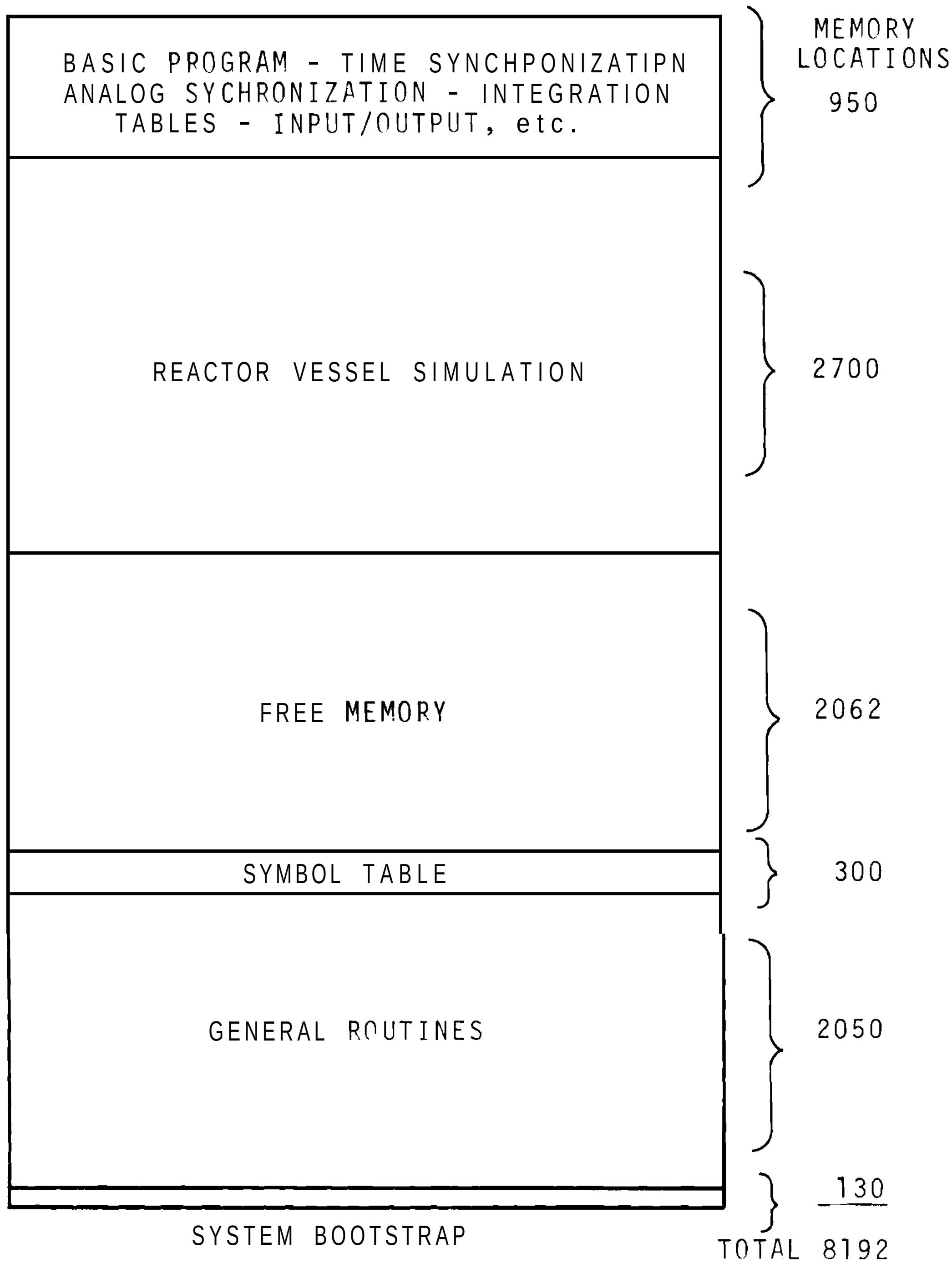


FIGURE 7. **Memory Map for Reactor Vessel Simulation on PDP-7 Digital Computer**

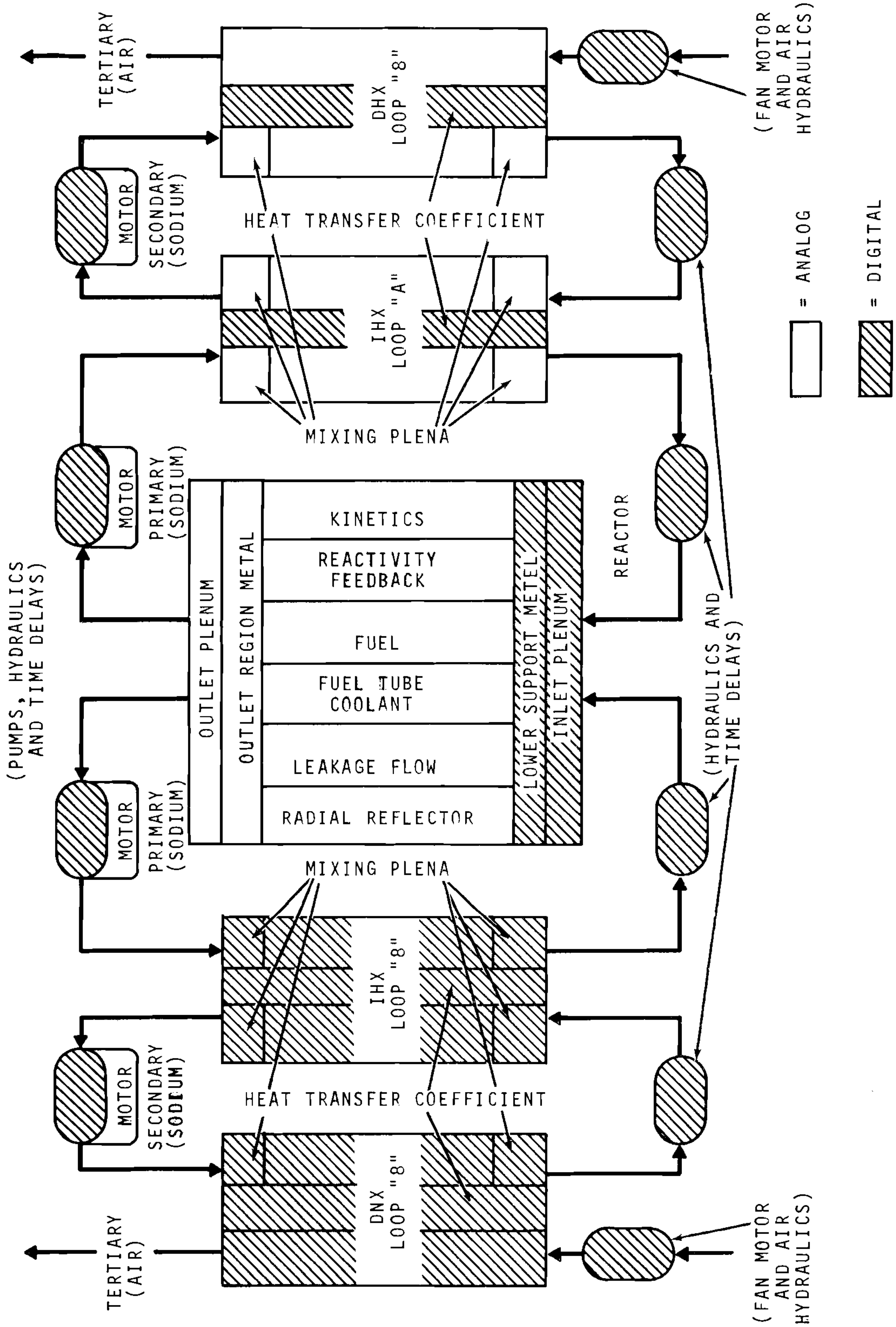


FIGURE 8. FFTF System Hybrid Simulation

is separated from the total power generation and is also represented by three decay terms. Reactivity feedbacks include linear terms for sodium and core expansion (based on average sodium temperature), and for core bowing (based on core ΔT), as well as a logarithmic term for Doppler (based on average fuel temperature). Inlet and outlet plenum models assume perfect mixing throughout the plenum volume, with heat transfer to steel structures in the region being represented by a single node for each plenum.

Heat transfer within the core is divided in three parts by three coolant streams: fuel coolant, leakage, and radial reflector coolant. The radial reflector region is modeled by a single node as though heat were generated directly in the coolant. Simulation parameters account for the stored heat in the reflector and to approximate the time constant of coolant temperature response to power changes. Leakage coolant acquires heat from the fuel coolant through the reactor tubes, and is also simulated by a single axial node. The core itself is simulated by two lumped nodes representing fuel and coolant. The fuel is divided into three radial nodes of equal volume.

Sodium hydraulics are simulated by the standard equation of motion for incompressible fluid. Flow versus head loss is expressed by a single exponential term, with an exponent of 1.8. Pump and motor dynamics are simulated with speed control by an eddy-current clutch. Pure temperature delays are used as a conservative approach, since stored heat in the piping dampens thermal transients moving down the pipe. Each coolant circuit is capable of simulating one, two, or three of the actual circuits.

The intermediate heat exchangers (IHX) are simulated as counterflow exchangers with each exchanger divided into 4 nodal segments with flow-dependent mixing plena at inlets and outlets. Finite difference approximations for the partial differential equations are used, employing central difference and three-point backward expressions (backward with respect to flow direction). The heat transfer coefficients are flow- and temperature-dependent. Stored heat in the tube metal is equally divided between tube and shell sodium.

In spite of their crossflow design, the dump heat exchangers (DHX) are simulated as three node counterflow devices with flow-dependent sodium mixing plena at the inlet and outlet. Heat storage in the finned tubing is lumped with that for the sodium. This assumes the metal temperature behaves substantially like the sodium temperature. Finite difference approximations for the standard partial differential equations are employed, with central difference and three-point backward expressions. The heat transfer coefficients are simulated as a function of both coolant flows and temperature.

Analog simulators of proportional-plus-reset controllers are used separate from the analog console of the hybrid. Switching arrangements allow a wide variety of process control loops to be formed. Reactor control simulation is based on a reactivity-neutron flux loop which moves a simulated control rod when the flux signal moves outside a preset deadband. A plant protection system is simulated on the digital portion of the hybrid with the capability of looking at any computer variable, comparing it to a setpoint, and initiating control or protective action in any desired sequence (e.g., power setback, controlled shutdown, and reactor scram),

Accuracy

As previously mentioned, identical cases have not been run for accuracy comparisons. Rather, the adequacy of each hybrid model component has been checked with more detailed DYNASAR models. The adequacy of a single node core model in providing good vessel outlet temperatures is shown in Figure 9. This compares the vessel outlet temperature with that computed from a detailed digital model (4 axial nodes, 3 fuel nodes plus clad and coolant radially). The adequacy of the simplified flow versus head loss relationship was demonstrated by comparing (as shown in Figure 10) flow decay curves with curves generated by a more detailed hydraulic model which accounted for head losses from bends, entrance, and exits. Finally, the adequacy of the 3 node counter flow dump heat exchanger model as opposed to an 18 mode counter flow model was verified by comparing outlet temperature for transients such as air flow losses of full sodium flow as shown in Figure 11.

After accuracy verification, the hybrid model has been used for (1) providing scoping information for early component conceptual studies, (2) providing consevative "worst case" values for thermal transients, and (3) providing preliminary evaluation of plant control schemes.

Time and Cost

The development of both hybrid and digital models proceeded in response to conceptual design needs of the plant and subject to available hardware and software. Direct time and cost comparative information are not available, but qualitative information suggests that conventional large digital programs would cost at least 100 times more to run than the hybrid computer.[15]

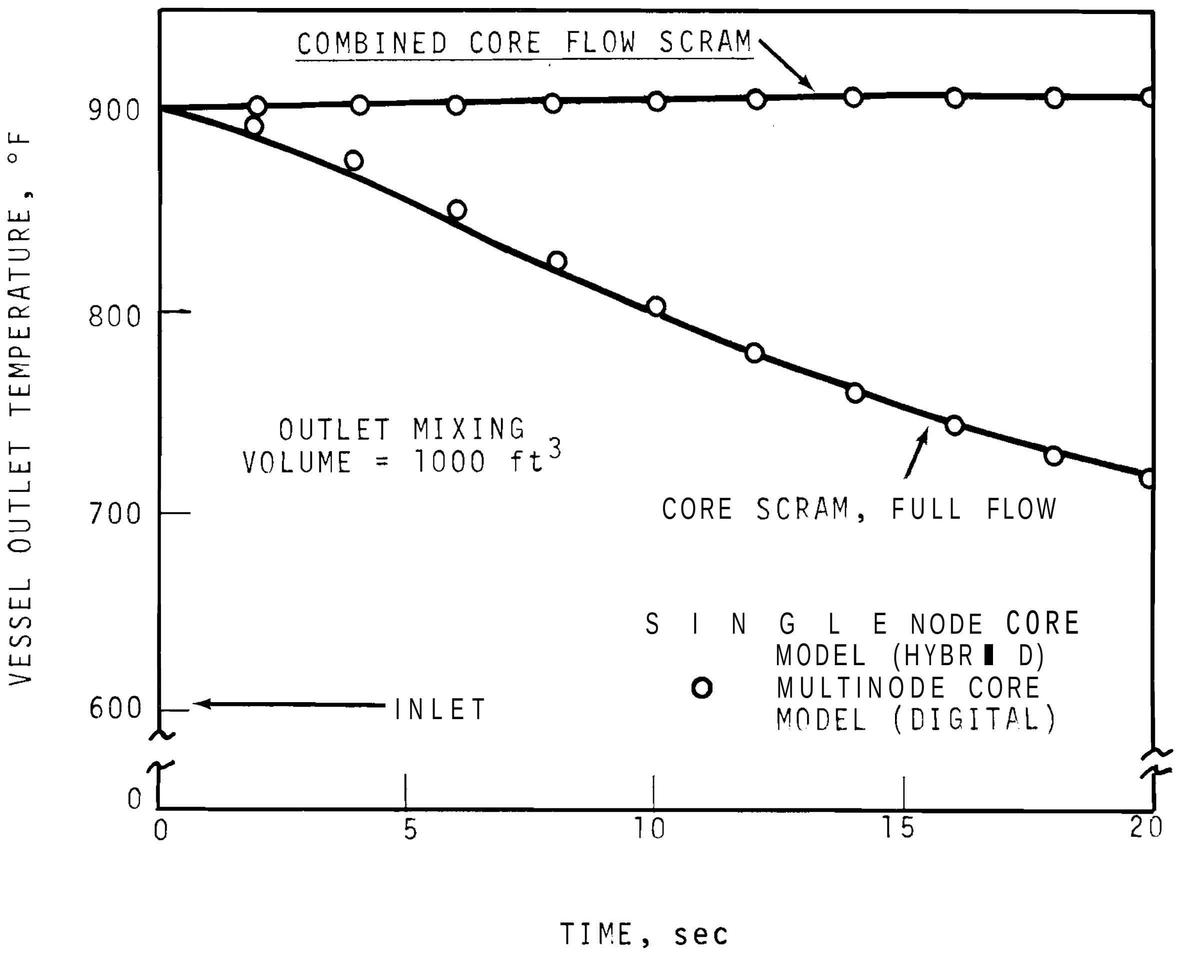


FIGURE 9. Vessel Model Comparison, Outlet Temperature Transient

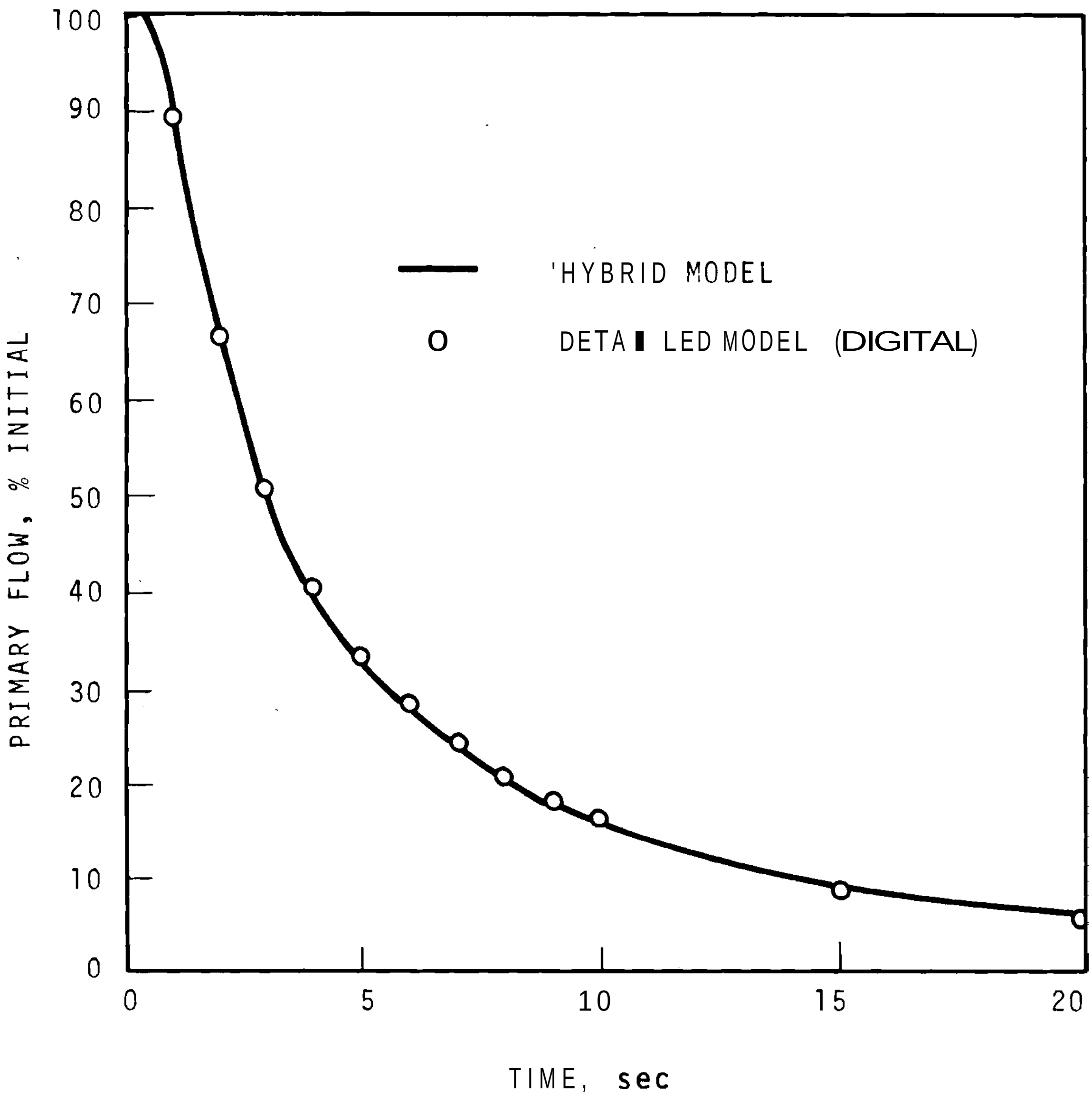


FIGURE 10. Flow Model Comparison: Primary Flow **Decay** for Loss of Pump Motor

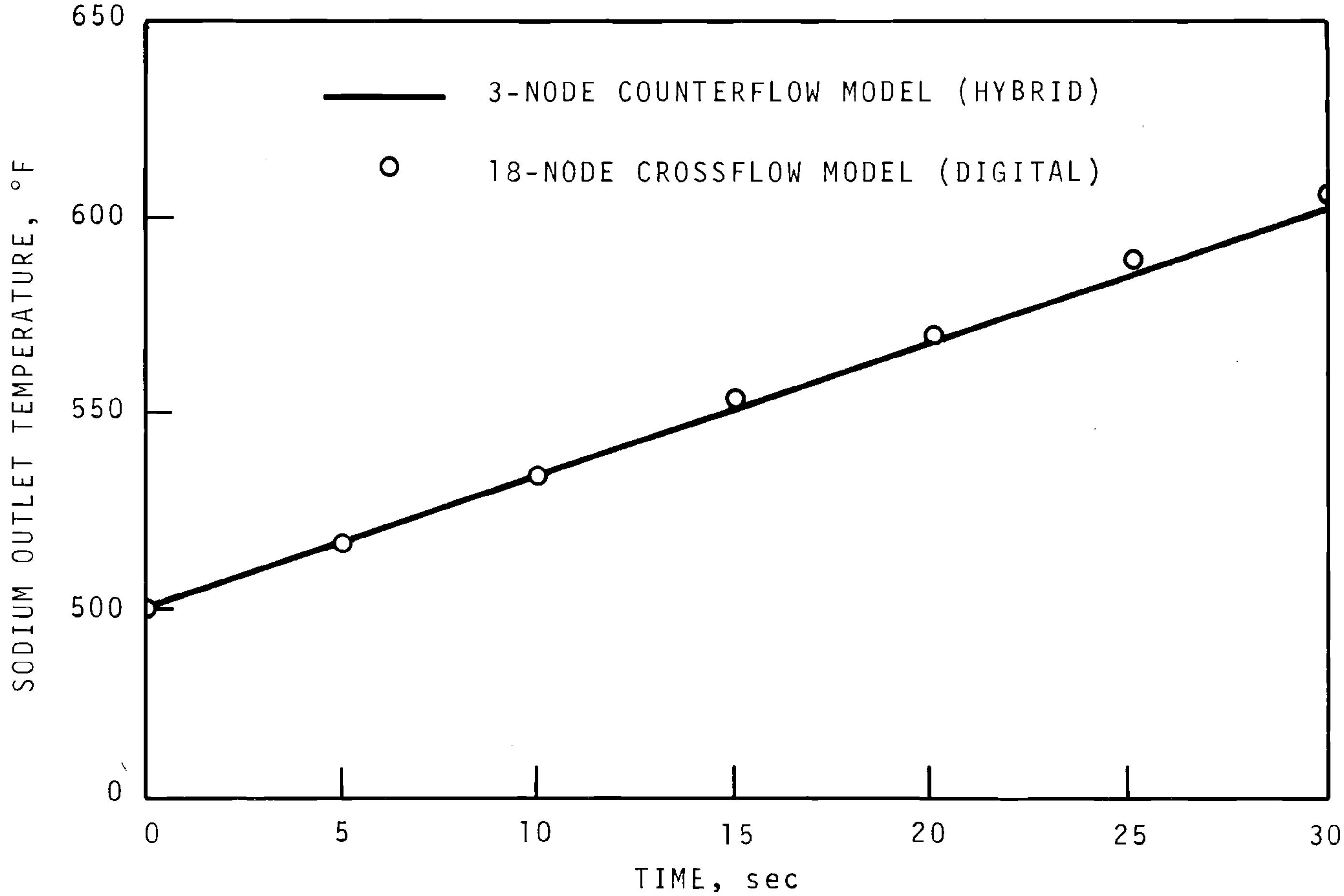


FIGURE 11. DHX Sodium Outlet Response to Loss of Air Flow Full Sodium Flow

Operational Convenience and Flexibility

A dynamic keyboard monitor program (DKM) provides the capability of making on-line decisions to initiate control actions or transients or to alter controller setpoints or safety trip points. This is done by way of the teletype while the computer is in compute mode without returning to initial conditions, and this capability will provide the basis for future operator training. In addition, DKM makes possible the changing of instructions during operation of the simulation, providing a powerful debugging tool. It also allows commands to be given to selectively load any of several support programs from magnetic tape into a buffer portion of memory. These programs (discussed below) can be loaded relocatably and are loaded on an interrupt level so as to not disturb the operation of the simulation. Once they are loaded, DKM can be used to transfer control and initiate program action by these programs.

Several support programs sharing a buffer zone in memory are loaded when needed and replaced by other programs upon completing their functions. The first of these automatically sets potentiometers on the analog computer. This provides for easily changing parameter values or initial conditions when a new study is to be performed.

A separate program is used for monitoring steady-state conditions. It stores the steady-state values of all integrators for use as initial condition settings at a later time. The program includes both digital and analog variables.

To assist in determining whether the simulation is operating correctly, several programs can be loaded to monitor steady-state conditions and calculate energy balances throughout the simulated system. Heat balances are calculated for the vessel, IHX, and DHX including percent error deviation for each component.

When the simulation is operating, a simulated protection system program replaces the preoperational support programs mentioned above. This program monitors any number of variables comparing their values to preset trip points. If a trip point is reached, action is automatically taken as specified by the user. This program is used not only for protective functions but also provides the user with the capability of initiating accident conditions. This prevents the necessity of patching special relays and integrators on the analog patch board merely to initiate a particular transient.

During a transient condition a user-specified number of variables can be monitored and their values can be stored in preselected time increments. These values can then be printed out together with a heading describing the transient.

Computer Requirements

The division of labor between the analog and digital portions of the hybrid computer has been established primarily on the basis that high gain operations function better on the analog computer. If the entire simulation were placed on an analog computer (see Figure 8) 320 amplifiers, 60 integrators, 55 multipliers, 25 function generators, over 250 potentiometers, at least 20 differential relays and 8 variable time delays would be needed. The hybrid simulation uses 120 amplifiers, 36 integrators, 30 multipliers, and 130 potentiometers. The digital computer provides the remainder.

The digital program is broken up into about 20 subprograms, each of which can be entered at a varying rate. The overall frame-time of the digital computer program is about 16.5 msec which corresponds to 0.165 sec problem time. However, many variables are updated three, four, or even five times during this single cycle. The frequency of iteration can be varied for each subprogram to provide stable output signals. For example, high gain integrations, such as pump moter speed, require a higher iteration rate than flow integrations to maintain stability.

The simulation itself occupies about 5000 of the available 8192 core memory locations on the PDP-7. Of the remaining 3000 memory locations, about 1000 are used. by an on-line monitoring program, Dynamic Keyboard Monitor (DKM).

RIVER WATER QUALITY DYNAMICS - (R. T. Jaske, D. G. Daniels, R. A. Burnett)

The water quality simulation (COL HEAT) is a FORTRAN IV program for the UNIVAC 1108 computer. The program calculates a history of the'river temperature at spaced intervals along a specified river reach. The basic mathematical models used in COL HEAT were converted into a hybrid program, the current version of which is called RIVER4. The results of the hybrid study[17] are summarized below:

Accuracy

The hybrid program was as accurate as the all-digital program. The integral of the squared error over the length of the comparison run was slightly lower for the RIVER4 simulation than for the all-digital simulation. Figure 12 is a plot of the results of the comparison run. The hybrid model closely duplicated a set of COL HEAT temperature calculations.

Time and Cost

The total time required to develop, evaluate, and document RIVER4 was 450 manhours and 120 hr of hybrid computer time. The solution time for a run covering 168 days of real-time was 33.6 sec with RIVER4. The COL HEAT solution time on the 1108 for a run of the same magnitude was 1 min, 55 sec.

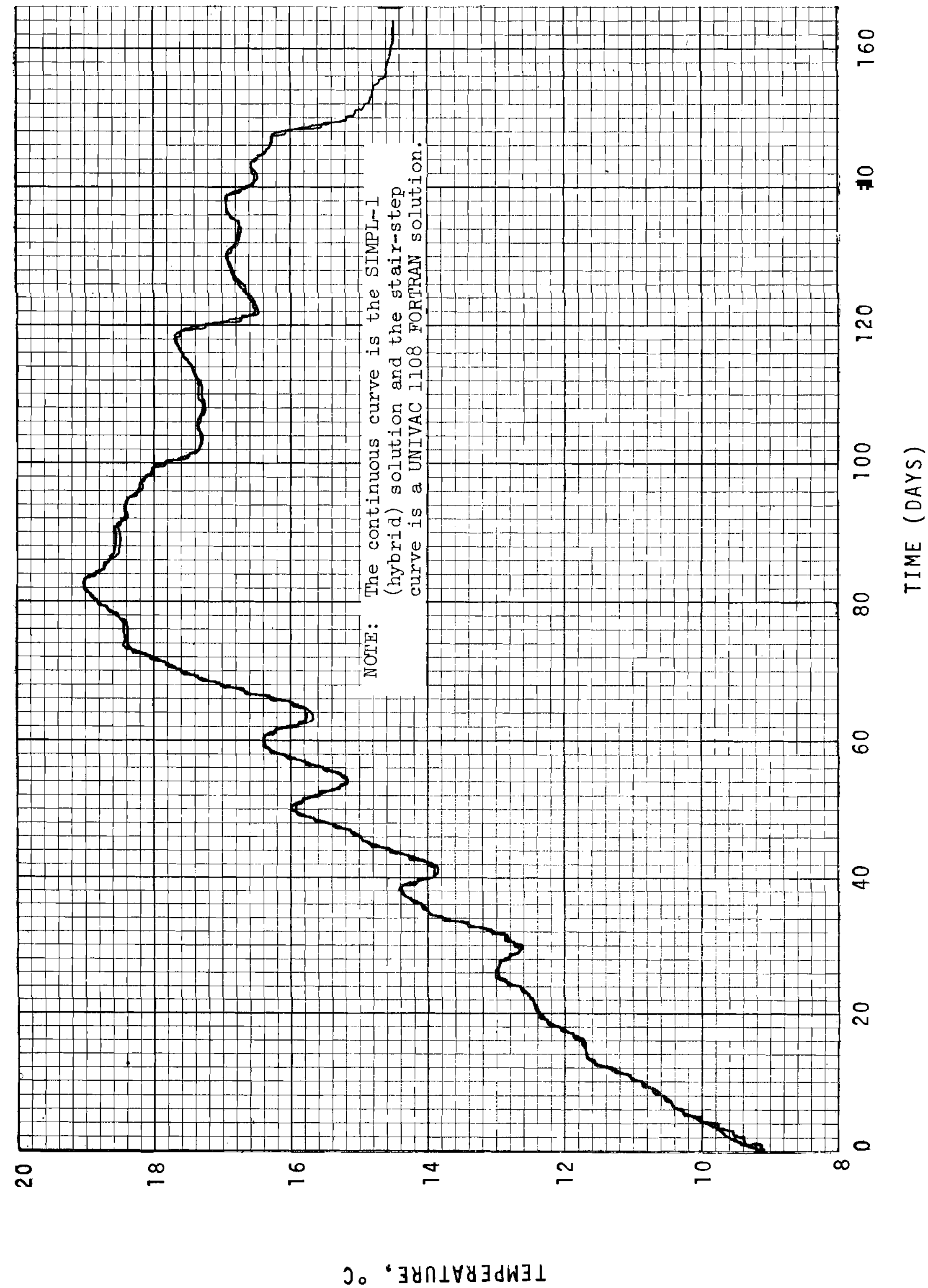


FIGURE 12 Comparison of SIMPL-1 and FORTRAN for Columbia River Water Quality Simulation

The hybrid thus has a 3.6-to-1 minimum speed advantage. At $?/minute for the UNIVAC 1108, the hybrid has a 10.5-to-1 cost advantage for an overall advantage of 36-to-1. However, the time required to set up and initialize RIVER4 (including pot setting and analog checkout) is about 30 min. The cost of obtaining only one set of river temperatures is thus about equal for both models. For parameter surveys and model optimization studies, where a large number of consecutive runs must be made, the increased effectiveness of an engineer should be multiplied by the 36-to-1 machine advantage to produce the overall economic advantage.

Operational Convenience and Flexibility

The present configuration of RIVER4 is not as flexible as COL HEAT for accepting all possible input data. Program changes in RIVER4 require longer setup time. COL HEAT is simple to set up since it is standardized. Turn-around-time Is 6 to 12 hr per run, so consecutive runs take longer than with RIVER4. In addition, graphical output from COL HEAT requires 6 to 12 hr longer per run. The COL HEAT digital model is most effective on a limited production basis while RIVER4 is most effective on an experimental basis. RIVER4 becomes a powerful tool for parameter surveys and optimization studies because of the ability to make rapid parameter and program changes and the availability of graphical output displays for observing the effects of these changes.

Computer Requirements

The hybrid model as presently constituted does not posses all of the capabilities of COL HEAT. However, consideration of the expansion area available and the existence of optimal programming techniques, which can be used to condense the existing program, indicate that capabilities could be added to RIVER4.

Approximately 50% of the 8K memory of the PDP-7 digital computer and 70% of the combined capacity of the EASE 1132 and 2133 analog computers are required by RIVER4 to simulate 21 river sections with two flow troughs in each section. Twelve of the EASE 1132 multipliers are used, with the remainder of the analog portion of the simulation being handled by the EASE 2133 analog computer. Forty-two integrators, seventy summers, and forty-two multipliers were required. About 30K of UNIVAC 1108 core memory was required to solve the problem digitally when three flow troughs and all features of the model were included.

METAL ANNEALING - (R. A. Burnett and D. G. Doran)

ANNEAL is a UNIVAC 1108 FORTRAN program which simulates the annealing of radiation-induced lattice defects in a-iron. The simulation performs a correlated random walk of interstitial and vacancy type point defects on a bcc lattice. The agglomeration of like defects and the mutual annihilation of unlike defects are treated. During one time step, each mobile defect is considered for a jump to a neighboring lattice site; jump probabilities are functions of the detailed positions of nearby defects.

ANNEAL operates in three separate modes. Model 1 is a low temperature simulation (300 °K) in which only interstitial motion occurs. Modes 2 and 3 are operated alternately to perform an elevated temperature simulation. The ratio of time steps in each mode is a function of temperature. Mode 2 permits interstitial motion only but differs from Model 1 in jump probabilities and annihilation criteria. Mode 3 permits vacancy motion only.

A hybrid program, HAP1, (Hybrid Annealing Program, Version 1) was developed to perform the same functions as ANNEAL. The added capability of displaying the relative defect positions on a storage oscilloscope was also provided. Due to limited time and funds, HAPl was programmed for Modes 1 and 2 only. As the programming logic is similar for all three modes, it can be assumed that a Mode 3 hybrid simulation would also be comparable.

The hybrid program (aside from the display capability) is actually an all-digital program which receives one analog input: a signal from a random noise generator. The output voltages of the analog noise generator follow a normal (Gaussian) distribution curve. HAPl contains a subroutine which converts these voltages to a set of random numbers having a uniform distribution. These numbers are then used in the determination of jump directions, jump execution, and order of defect selection.

Accuracy

A Mode 1 problem consisting of an initial population of 105 defects was run for 200 time steps. Fixed number sequences replaced the random number routines such that the results would be deterministic. The HAPl output data agreed perfectly with the ANNEAL output over the entire 200 time steps.

Time and Cost

The HAPl solution time (output listing time excluded) for the deterministic run was 1 min 43 sec. The corresponding ANNEAL solution (written in FORTRAN) time was approximately 6 min, or nearly 3.5 times longer. The random number routines were then reinserted in HAPl, and the running time was recorded for ten runs. Due to the random processes involved, the solution times varied from 13 to 65 sec. The average solution time was 28 sec. Typical ANNEAL solution times for the random case were in the 1.5 to 2 min range. The speed advantage gained by HAPl was thus again in the neighborhood of 3.5-to-1.

This advantage combined with a 10-to-1 computer cost rate reduction results in an economic advantage of 35-to-1. If the cost of a simulation specialist is included, the economic advantage is about 28-to-1 in favor of the SIMPL technique.

It is significant to note that most of the SIMPL-1 hybrid versus FORTRAN-large digital comparison programs involve the solution of many simultaneous equations. The ANNEAL-HAP1 simulation does not contain any differential or algebraic equations and therefore provides a more accurate measure of relative logic programming efficiencies. The relative computer speeds must also be factored in. The cycle times of the UNIVAC 1108 and the PDP-7 are 0.75 and 1.75 μsec, respectively. Combined with the 3.5-to-1 speed advantage, SIMPL-1 efficiency advantage of roughly 8-to-1 over FORTRAN logic programming is thus indicated for machines with equal cycle times.

The time required to develop, debug, and evaluate HAP1 was approximately 540 manhours. A total of 110 hr of computer time was accumulated, much of which was spent in program preparation and editing. The initial programming effort required a lot of time because of the complex interconnected logic and the large amount of bookkeeping involved. Due to the conceptual and sequential evolution of ANNEAL to its present form, a comparable figure for the time required to develop and program ANNEAL cannot easily be obtained.

Operational Convenience and Flexibility

The HAP1 program was combined with a storage oscilloscope display. The operator can then visualize the relative position of the defects as the simulation progresses. The simulation can be temporarily stopped at any point for making photographs of the display. Sample photographs are shown in Figures 13 and 14.

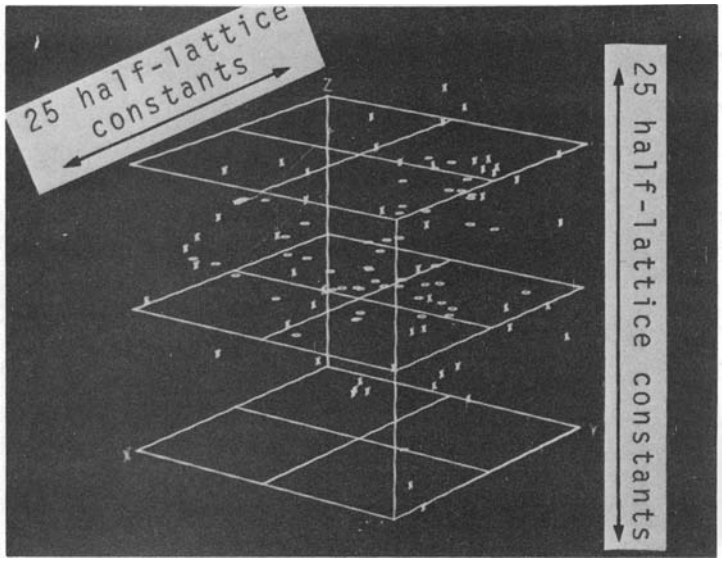


FIGURE 13. HAP1 Display of Initial Defect Distribution.
(X = Interstitial, 0 = Vacancy)

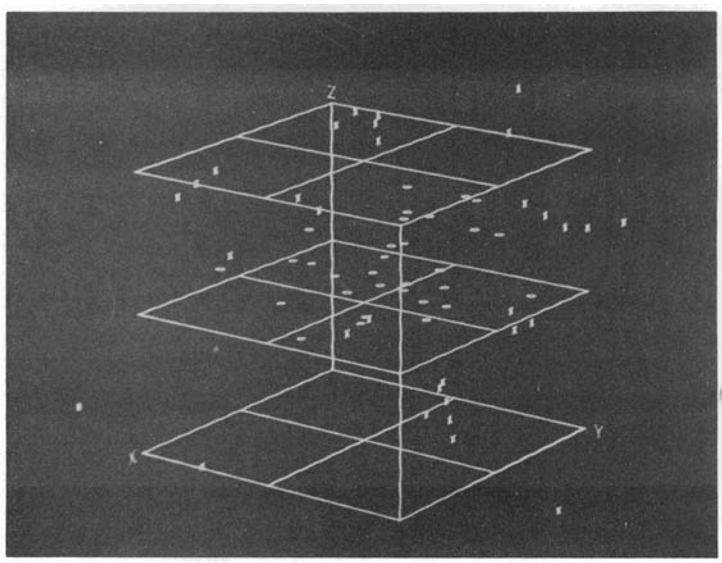


FIGURE 14. HAP1 Display of Defect Distribution After 200 Time Steps.
(X = Interstitial, 0 = Vacancy)

Additional convenience features of HAPl include simplified reprogramming and the ability to make repeated runs with on-the-spot supervision and control of parameters and input data.

Computer Requirements

HAPl consists of approximately 2800 words of instructions and requires an additional data storage area of five words per interstitial and three words per vacancy. If a jump history (a chronological record of the time, direction, and defect involved in each jump) is desired, the present version requires two 512-word memory buffers for use by the subroutines which store this information on a magnetic drum. A buffer size of 128 words could be used at the expense of a slight increase (2 to 4 sec) in computer run time.

The ANNEAL program uses 4000 words of program instructions plus output buffer areas, and an additional eight locations are required per defect of either type. A problem consisting of an initial defect population of 500 vacancies and 500 interstitials would thus require 12K words of UNIVAC 1108 core memory. The same problem solved with HAPl would take up 7.8K core locations. However, ANNEAL contains the capability of Mode 3 operation, and HAPl does not. It is estimated that the addition of Mode 3 operation to HAPl could be accomplished with less than 500 additional memory words. The memory savings achieved by HAPl is thus roughly 30% for a problem of this size. Smaller problems would result in a correspondingly lower percentage of savings.

REACTOR COPE DESIGN - (D. T. Pase, H. P. Foote)

A considerable portion of this study was attempted on both UNIVAC 1108 and IBM 7090 computers. Convergence of integral control loops was requiring more engineering time than available to complete the study using batch processing methods. With two weeks remaining, it was decided to complete it with the hybrid computer. In this time the problem was reprogrammed and checked for accuracy, and all parameter studies, were conducted.

The basic purpose of the study was to establish the sensitivity of power density in a Steam-Cooled Fast Reactor core to certain design and operating parameters. Figure 15 indicates the magnitude of the problem and shows the independent parameters and integral control loops used to maintain the design constraints during the sensitivity studies. Reference 6 presents the format of some of the equations and reference 7 summarizes the results of the study.

Figure 16 shows the procedures necessary to solve the problem using the digital and hybrid approaches. The solid lines in Figure 16 indicate the actual path used to perform the study. MIMIC[18] is a digital analog simulator and it is relatively easy to switch from one approach to the other. In fact, since analog techniques are used in both cases, parallel programs are sometimes written. The MIMIC program gives a preliminary check on program logic and also provides a set of calculations to use in scaling the hybrid program.

Accuracy

Spot checks made with the MIMIC program were used to verify hybrid computer accuracy.

Time and Cost Factors

By the time the gains on two control loops of Figure 15 were set using the digital computer, four weeks of calendar time and a total of approximately $1500 ($660 for computer time) were spent. With the two control loops set at nearly optimum gain, each computer run required 20 min of IBM 7090 time. Setting the gain on the third control loop would have

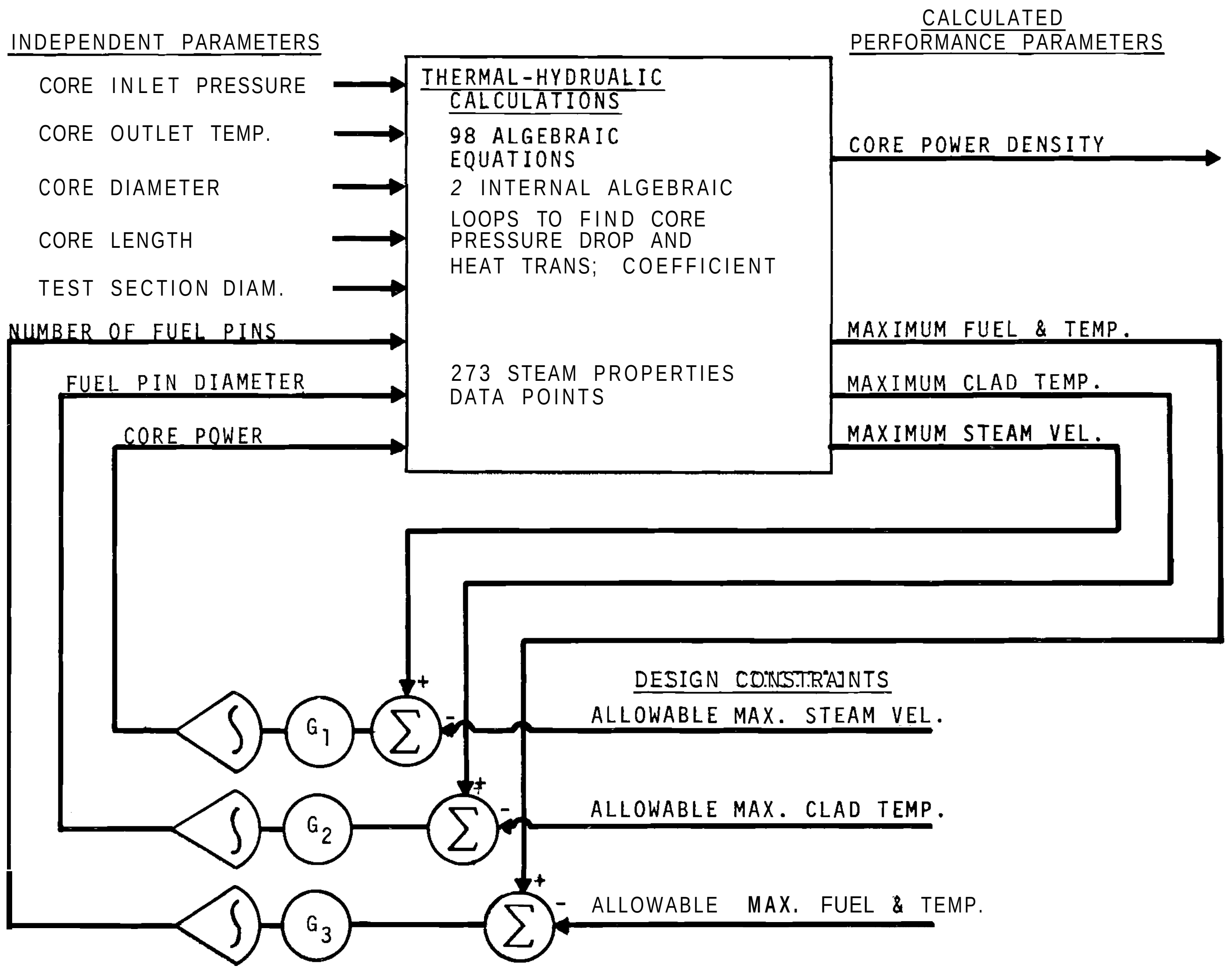


FIGURE 15. Schematic Diagram of SCFTM Parametric Study Model

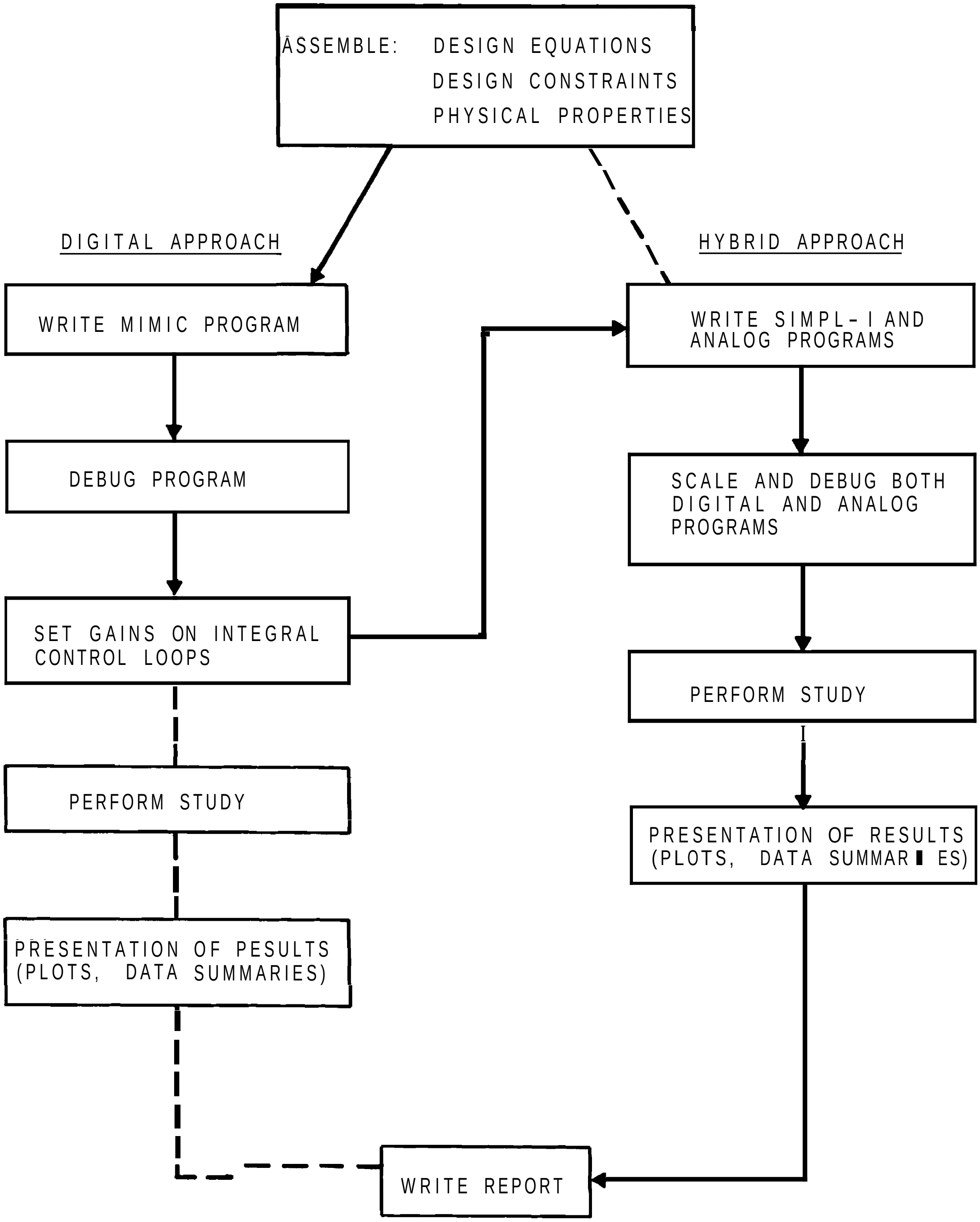


FIGURE 16. **SCFTM** Parametric Study Calculation Procedure

required about two additional hours ($550) of IEM 7090 computer time and 1.5 to 2 weeks of calendar time, or a total cost of approximately $1200. To complete a minimum parametric study beyond that would have required approximately 9 hr of computer time spread out over about 1 month of calendar time and cost of approximately $4200. Thus, the total cost for the digital computer study would have been $6900 and 2.5 months of calendar time.

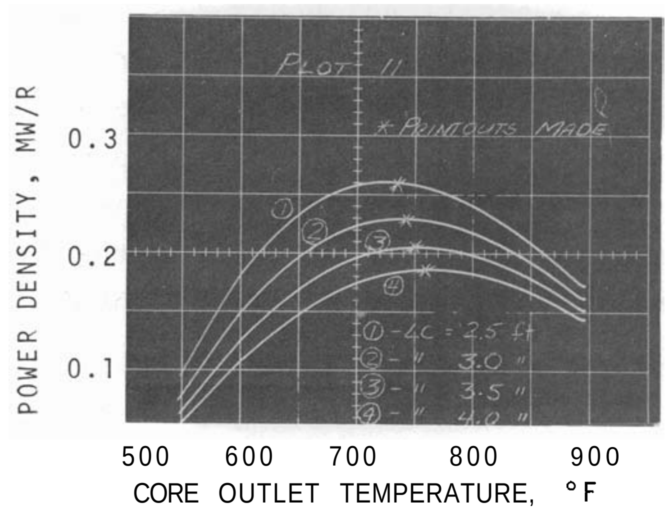
The hybrid computer was employed before the latter two tasks were started, primarily because of the remaining calendar time involved. It was programmed and debugged, and the study was completed with $2140 in 2 weeks of calendar time. Assuming it would have taken $1500 and 2 weeks of additional calendar time to program the problem on the hybrid without the benefit of a debugged MIMIC program, the hybrid approach would have required 1 month of calendar time and about $3600. Table 3 summarizes cost estimates for the two approaches.

TABLE 3. SCFTM Parametric Study Cost and Time Comparison

Approach	Calendar Time, Months	Cost
Digital Computer (MIMIC)	2.5	$6900
Hybrid	1	$3600

Operational Convenience and Flexibility

About three times more information was generated with the hybrid computer than was considered a minimum for parametic design studies. However, because a character generator was not available for labelling results, all information was replotted by hand. Figure 17 shows the comparison of replotted results to computer generator generated photographs.



Photograph of Oscilloscope Output Generated
by Hybrid Computer

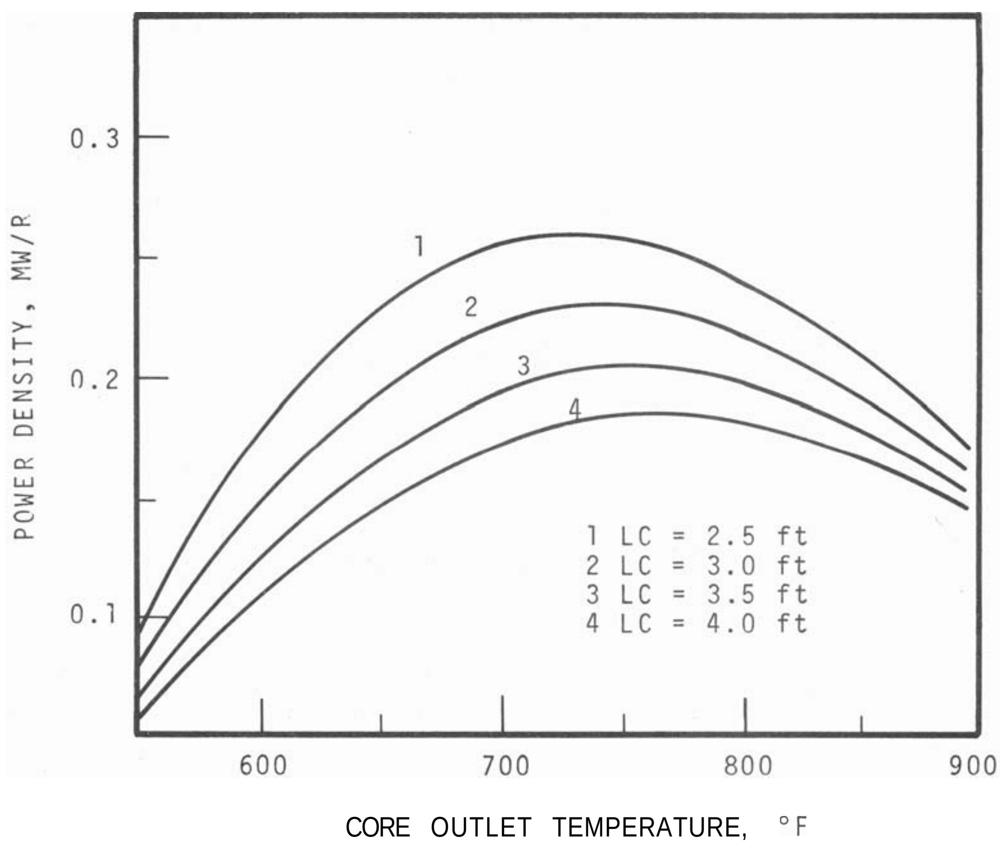


FIGURE 17. Comparison of Hybrid Oscilloscope Output and Replotted Output for Steam-Cooled Reactor Design Problem

Computer Requirements

The problem required 7% of the EASE 2133 analog computer and 45% of the PDP-7 digital computer's 8192 word memory.

STEAM PARTICLE DEPOSITION - (J. M. Hales and P. J. Dionne)

The purpose of this study is to evaluate aerosol transport in a laminar boundary layer of condensing steam. The four equations describing the physical system are coupled, nonlinear differential equations and possess boundary conditions at time zero and infinity.[18] Solution of such problems using available numerical techniques depends on convergence schemes that are inefficient and time-consuming. Hybrid simulation provides efficient iterative solutions with manually (or automatic) controlled convergence through adjustment of initial conditions.

Accuracy

Table 4 compares four hybrid computer solutions with a UNIVAC 1108 digital computer solutions using a Runge-Kutta integration routine. From this appears that the hybrid computer solutions are accurate to within about 1%, based on maximum values of the variables.

TABLE 4. Comparison of Hybrid and Large Digital Computer Results

Run	ξ %dev	Σ_1, %dev	τ, %dev	$\frac{\pi F'}{\phi}$ %dev
1-1	+1.0	-1.0	0	-0.5
2-1	+1.0	+1.0	+0.6	-0.9
1-4	+1.5	-0.4	-0.1	+0.7
2-4	+1.8	-1.1	-0.5	-0.7

Figure 18 is a graphical comparison of one of the computer experiments. The initial conditions were adjusted a few tenths of a percent to obtain the most appropriate solution. This reflects the extreme sensitivity of the solutions to initial conditions values.

Time and Cost

This study was conducted by an engineer who had no prior experience with hybrid simulation techniques, but was introduced to analog computers in college. Three days of instructions from an experienced simulation engineer over a period of three weeks was required to develop the hybrid program and learn the computer operating procedures. During the first week, a basic familiarization of the system along with techniques for circuit layout were stressed.

The second week was devoted to model development and obtaining solutions to less sophisticated equations to form bases for the final model. This requirement is inherent in problem development and bears little relation to interaction with the simulation system except for the insights created through intermediate solutions. A conceptual error in modeling was discovered as a result of the simulation system behavior.

The remaining week was spent in programming and debugging the final equations. The final solutions to the problem were obtained in one day of computer time. An additional three days were required to obtain the comparative accuracy data.

Operational Convenience and Flexibility

Fifteen solutions to the differential equations were obtained. These represented a range of physical conditions expected in post-accident containment systems. Different scaling was used for each of the solutions. Once appropriate scaling factors were chosen, the corresponding potentiometer settings were calculated and tabulated with a UNIVAC 1108 computer program.

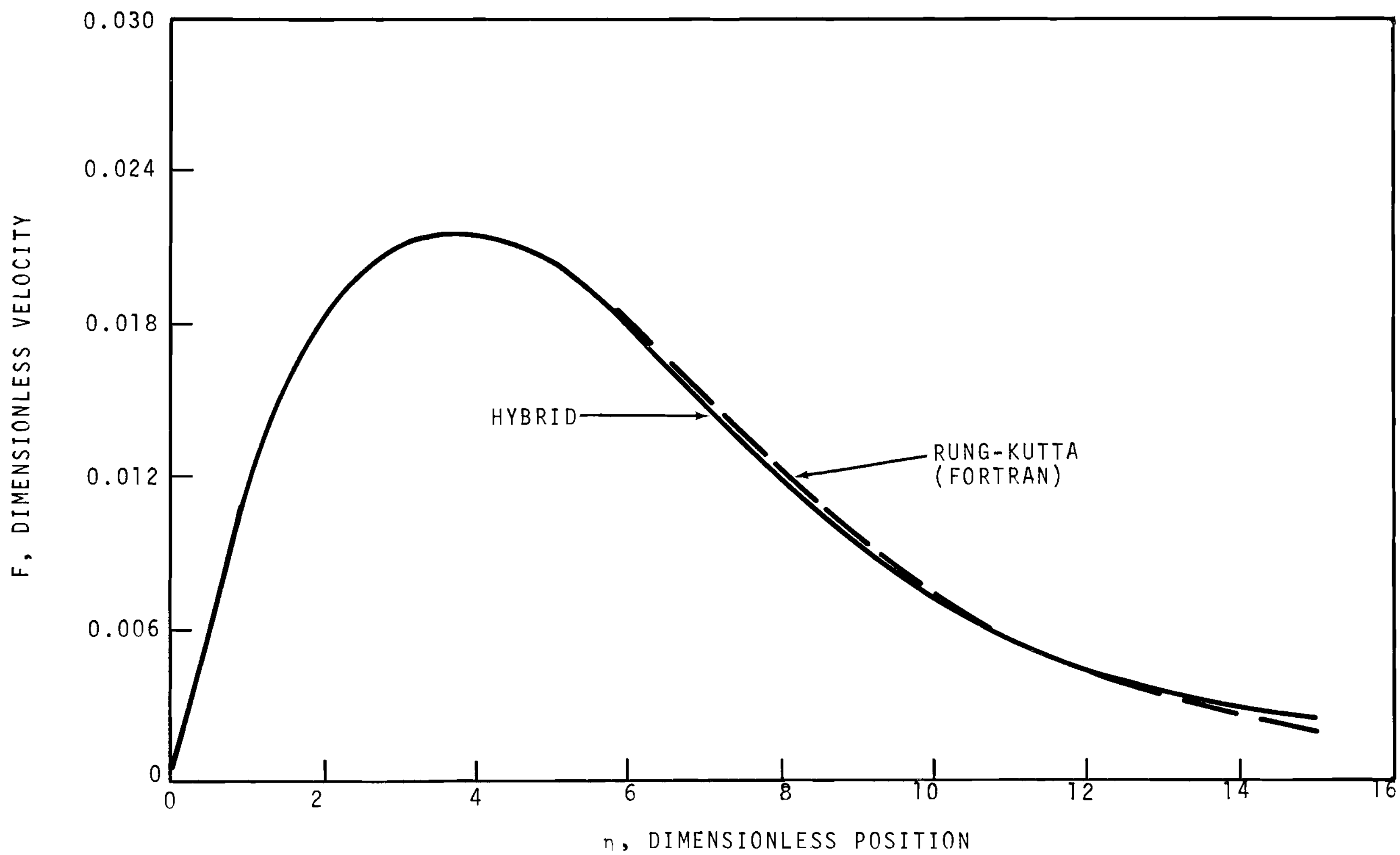


FIGURE 18. Comparison with HYBRID and FORTRAN for Velocity Profiles Adjacent to a Flat Vertical Plate

Once the system is set up, solutions of the equations through repeated iteration on the hybrid computer could be obtained in about 5 min. This compares with an estimated time of 15 min expended in solving similar equations on an IBM 360 model 75. This execution time seems unduly high and probably arose from an inefficient convergence scheme. Nevertheless, the indicated cost advantage of using simulation techniques for solution of this problem is impressive.

Computer Requirements

About 15% of the EASE 2133 analog computer and 5% of the PDP-7 digital computer's 8192 words of core memory were required to solve the problem.

FUEL SINTERING - (R. D. Leggett, R. L. Fish and W. F. Lenzke)

The purpose of the fuel sintering simulation is to investigate the influence of fuel fabrication parameters, irradiation conditions, and basic irradiation behavior on fuel element structure and to display the results for rapid visualization. Early work required hand plotting of computer generated temperature cross sections for hand correlation to fuel structure. Two days to a week were required to generate sufficiently detailed plots to identify the axial void, columnar, equiaxed, and original grain structure. The hybrid computer coupled to a Heath-kit color TV and movie camera were employed to generate a color movie for four different power levels using animated filming techniques. Each power level produced 3600 color cross sections. This movie, to our knowledge, is the first computer-generated color production.

The entire effort required about one calendar month of manpower. About 5% of the analog computer and 37% of the digital computer was required for this study. An accuracy comparison between SIMPL-1 and UNIVAC 1108 FORTRAN is shown in Figure 19. Note, when plotted on 8 1/2 × 11 graph paper the

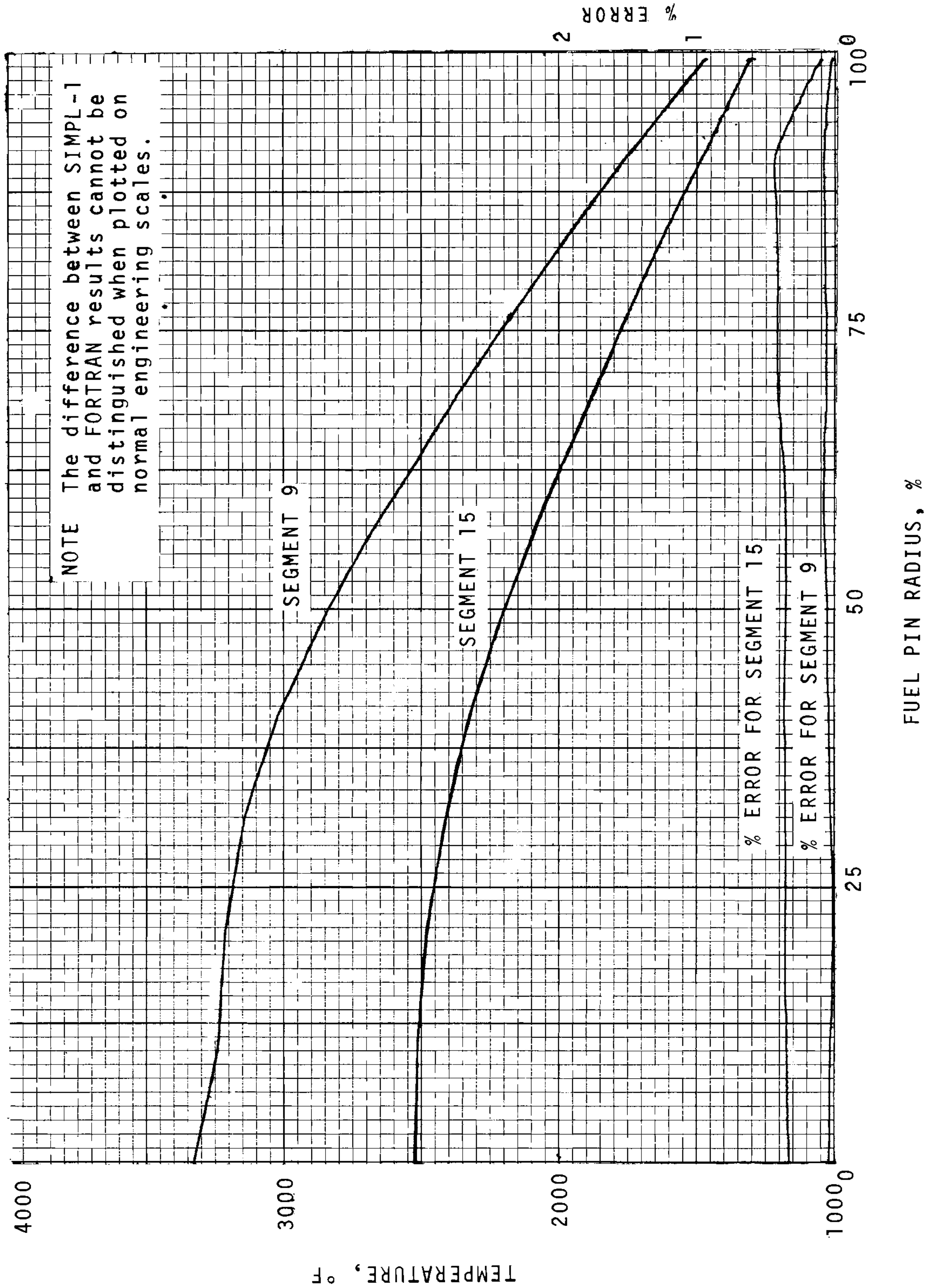


FIGURE 19. Comparison of SIMPL-1 and FORTRAN Results for Fuel Sintering Simulation

0.2 to 0.4% difference in the results cannot be detected by the eye. One plot falls on top of the other,

ULTRA-CENTRIFUGE DATA ANALYSIS - (W. H. Matchett and C. R. Cole)

A slight modification of "pulse-height" methods of qualitative and quantitative analysis of radioactive samples was employed to analyze radioactive ultracentrifuge samples.[9]

The hybrid technique employs an iterative rather than a closed form solution. Computer speed was traded for memory. The "brute-force" hybrid methods required about 3000 iterative solutions to solve the 18 parameter optimization problem. The cost of analyzing one data curve (including man and machine charges) is about $10. Automatic optimization techniques can be developed to reduce the cost further. Typical results from the method are accurate to 0.02%.

About one-man month of effort was required to develop a hybrid computer technique and analyze the first 50 samples. About 30% of the analog and 10% of the digital computer were required to solve the problem by brute-force techniques.

SMOKE POLLUTION - (W. R. McSpadden, Jr. and C. R. Cole)

The following partial differential equation for diffusion of pollutants in the atmosphere was solved using a computer program, and the solution was effectively displayed (see Figure 20) as a surface in time and distance.

$$P(z) \frac{\partial C(z,t)}{\partial t} = S(t) \frac{\partial}{\partial z} \left[\rho(z) K(z) \frac{\partial C(z,t)}{\partial z} \right] \qquad (1)$$

In this equation, $C(z,t)$ is the concentration of the pollutant as the function of the height z and time t. $K(z)$ is the diffusion constant, $P(z)$ is the air density, and $S(t)$ is a periodic time function which accounts for seasonal affects. From previous work, these coefficients were known exponential and gaussian functions. The boundary conditions were as given below:

$$\frac{\partial C(0,t)}{\partial z} = \begin{cases} a & \text{for } 0 < t < 1 \\ 0 & \text{for } t \geq 1 \end{cases} \qquad (2)$$

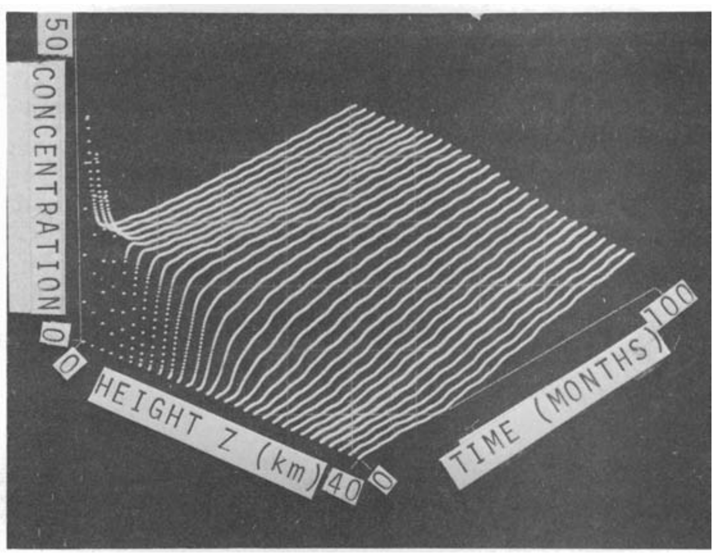


FIGURE 20. The Solution Surface for 100 Months With One Month Continuous Contamination

The diffusion equation was written as a difference equation, and the surface was divided into 10 segments over the range of the distance variable z. The computer program was designed to give solutions as a function of time for each segment. The solution was displayed both on strip-charts with continuous time recordings and on photographs taken from a CRT display.

There is no known analytical solution to this equation, and the use of normal numerical approximation techniques could be quite costly because of the complexity of the time- and distance-varying coefficients. However, the project engineer was able to obtain solutions on the hybrid computer quite inexpensively and to display the solutions in a very effective manner. One of the obvious advantages of this form of the solution was the ease with which parameters could be changed and the corresponding effect immediately observed.

GROUNDWATER SYSTEMS ANALYSIS - (D. B. Cearlock and H. P. Foote)

The need for man-machine interaction and instantaneous visual output (required for efficient development and application of computer routines used in analyzing groundwater flow systems) provided the impetus to use the hybrid computing facility. Figure 21 shows one of the many displays produced by application of the SIMPL concept to groundwater problems.

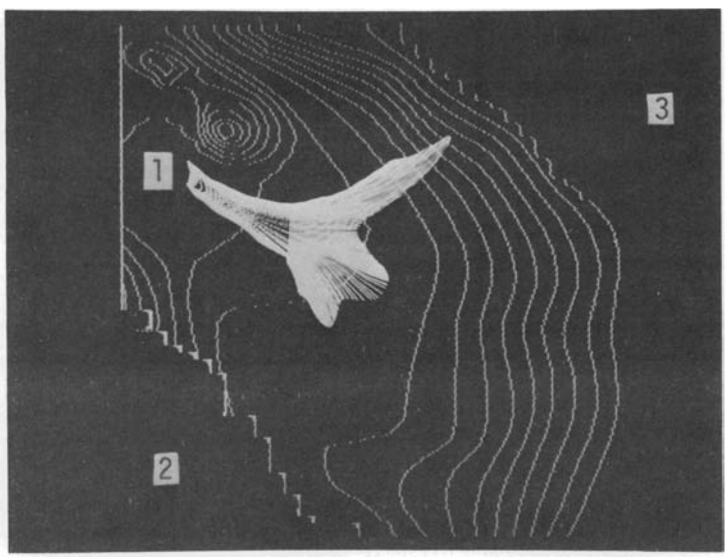


FIGURE 21. Photograph Taken of SIMPL Computer-Drawn Display Showing the Groundwater Contours Under Part of Hanford and the Spread of the Fan-Shape Contamination Front Resulting from a Hypothetical Leak at Position 1. The Project Boundary Along Rattlesnake Mountain is at 2, and the Boundary Along the Columbia River is at 3

In contrast to most of the simulation programs discussed in other parts of this report, the groundwater modelling effort conducted on the hybrid system, in general, had not been previously done on a large computer. It is therefore difficult to obtain quantitative comparisons on the effectiveness of large and small computers. However, since the personnel using these programs developed on the hybrid system have had considerable experience with a UNIVAC 1108, a qualitative evaluation of the benefits of the small computer in a large research and development environment can be made.

To support the qualitative evaluation, a problem involving the numerical solution of LaPlace's equation

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0$$

was run on both the hybrid system and the UNIVAC 1108. On the UNIVAC 1108 it took approximately 2 manhours over a period of a week to produce the graph shown in Figure 22. Approximately 5 manminutes were required to input the data, solve the problem, and produce the photograph shown in Figure 23 on the hybrid system. It took the 1108 approximately 1.75 min and 184 iterations to converge to the same accuracy as that obtained on the PDP-7 after 500 iterations and 2.5 min of computer time. It took approximately 1 additional minute of 1108 computer time to search the data for a plot. Since the data in both programs were scaled, it was concluded that word length differences (36 bit and 18 bit word lengths for the UNIVAC 1108 and PDP-7, respectively) in the two systems resulted in less round-off error in the 1108 which therefore required fewer iterations for convergence.

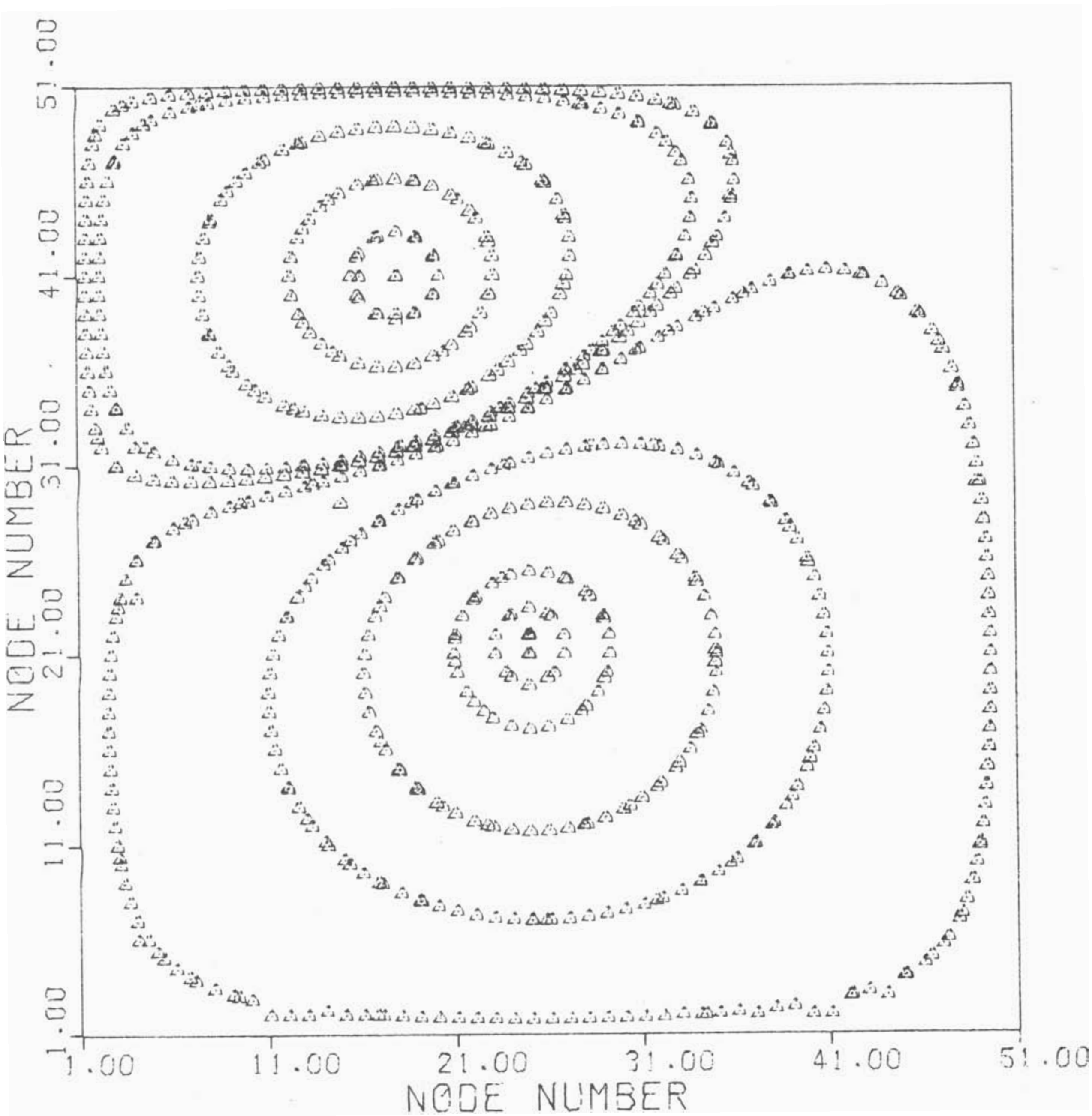


FIGURE 22. CALCOMP Plot of UNIVAC 1108 Solution to LaPlace's Equation

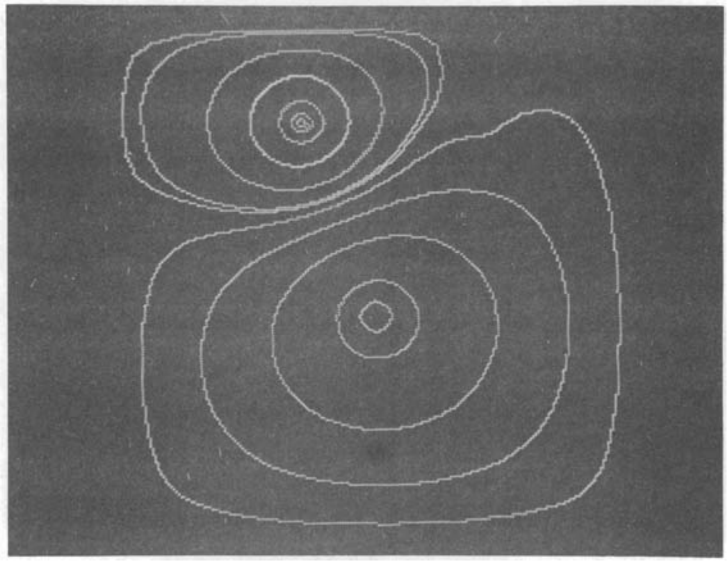


FIGURE 23. Photograph of Hybrid Solution to LaPlace's Equation

Three pertinent conclusions can be drawn from the above information.

First, the PDP-7 can be programmed to perform certain calculations at about the same speed as equivalent calculations programmed in FORTRAN-V on the UNIVAC 1108. It should be noted that the FORTRAN compiler converts mathematical statements, such as LaPlaces's equation, from program language to machine language more efficiently than it converts logical statements. This implies that the computational time, for a program containing more logical statements than the one used in this evaluation, would be less on the PDP-7 than on the UNIVAC 1108, provided the programs were written in SIMPL-1 and FORTRAN for the PDP-7 and UNIVAC 1108, respectively.

Second, the hybrid systems showed a definite advantage in minimizing manpower requirements (2 hr to 5 min or a factor of 24/1). The reduction of manpower associated with the hybrid system is a direct result of using the specially developed analog control devices for inputinp data and program control parameters to the PDP-7. This system has not only proven to be rapid, but also has reduced the chances of input errors and reduced the quantity of input required. In contrast, input to the UNIVAC 1108 requires transferring data to keypunch sheets, keypunching the data, verifying the punched cards with the original data, and then submitting the program for processing.

Third, the hybrid system showed a definite advantage in minimizing analysis time (5 days to 5 min or a factor of 1440/1). The advantage of minimum analysis time associated with the hybrid system is that the low cost of the system time allows the user total machine dedication. When input errors are made, they are readily noticeable and rapidly corrected. Programs required in an analysis sequence can be run in close succession. Results can be immediately displayed and decisions and/or alternatives made while all thought processes are oriented toward the problem being analyzed. The long analysis time associated with the UNIVAC 1108 can be attributed to the mode of operation (batch processing) and the high machine costs. Using the batch processing mode as presently employed on the UNIVAC 1108, a user can expect two turnarounds per day-shift. It usually takes several computer runs to eliminate errors in the input control parameters and data. It also takes a minimum of a day to obtain a plot, and usually two plots are required to obtain the desired output. All of these factors contribute to the long analysis time associated with a large batch processing digital computer.

The only major disadvantage associated with the small computer encountered in the hybrid system was the computer's limited amount of core storage. In the investigators opionion, there are many large simulation models that could not be practically solved on the small computer. However, the small computer can be used effectively to calculate model input, to debug model input, and to analyze the model output.

It is the authors' opinion that the optimum computational capability could be achieved through use of a small computer with display output capability connected (via telephone lines or directly) to a large computer. This would allow scientific productivity to be increased significantly through man-machine interaction and could provide the computational capability of the large computer when necessary.

TWO-GROUP DIFFUSION MODEL

The accuracy of analog, small digital, and hybrid computers, were tested on a one-dimensional two-energy-group diffusion model for an infinitely long cylinder (as shown in Figure 24) that was solved by the following methods:

1) BECKMAN 2133 analog
2) AD/4 analog
3) MIMIC (UNIVAC 1108)
4) **HYBRID** (PDP-7 digital - 2133 Beckman analog)
5) PDP-7 digital using numerical integration techniques

Equations

$$\frac{d^2\phi_1}{dr^2} = -\frac{1}{r}\frac{d\phi_1}{dr} + \frac{\Sigma_1}{D_1}\phi_1 \qquad 0 < r < R_1$$

$$\frac{d^2\phi_2}{dr^2} = -\frac{1}{r}\frac{d\phi_2}{dr} + \frac{\Sigma_2}{D_2}\phi_2 - \frac{\Sigma_1}{D_1}\phi_1 \qquad 0 < r < R_1$$

when $r > R_1$ the first derivatives are changed by the addition of a constant term.

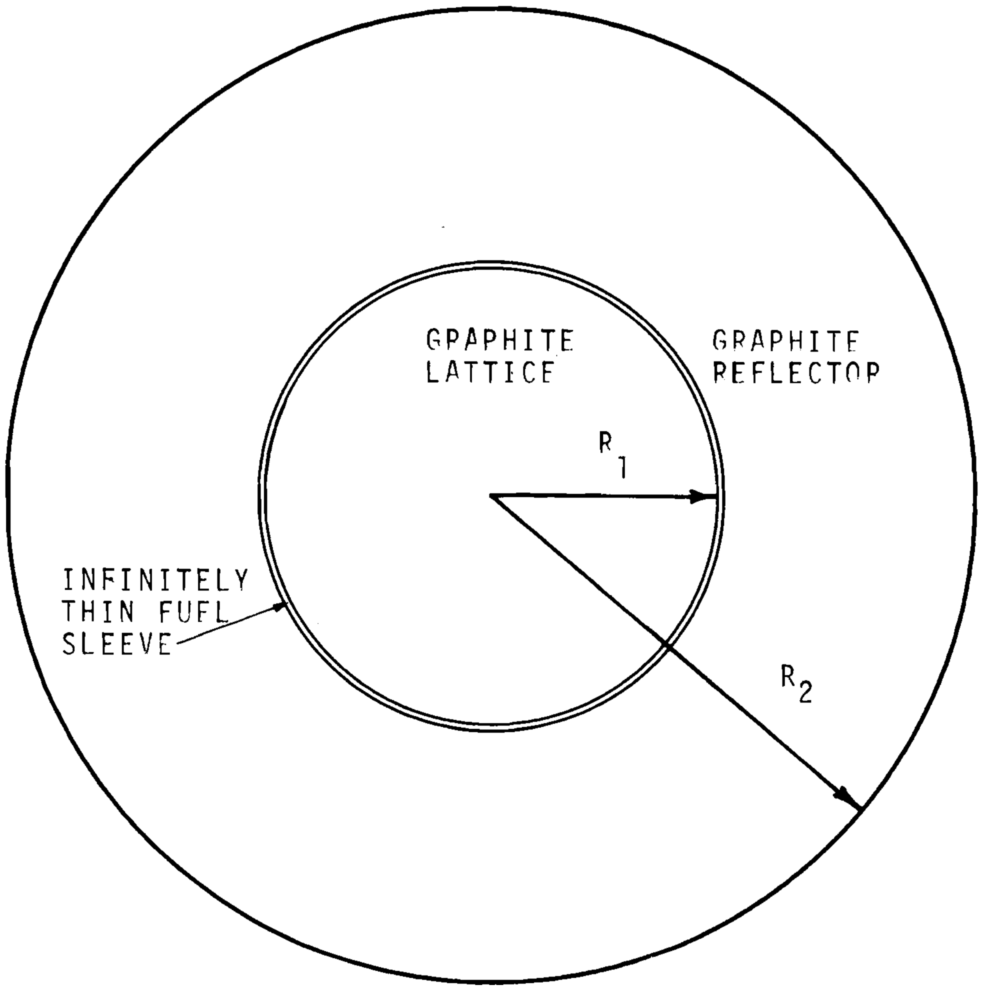


FIGURE 24. **Cross Section of Simulated Reactor**

$$\frac{d\phi_1}{dr}\, r \geq R_1 = \frac{d\phi_1}{dr}\bigg|_{R_1} \quad \frac{\eta\xi\phi_2\,(R_1)}{D_1}$$

$$\frac{d\phi_2}{dr}\, r \geq R_1 = \frac{d\phi_2}{dr}\bigg|_{R_1} + \frac{\xi\phi_2(R_1)}{D_2}$$

The constants have the following values:

$$\frac{\Sigma_1}{D_1} = 2.994 \times 10^{-3} \quad \frac{\Sigma_2}{D_2} = 3.306 \times 10^{-4}$$

$$D_1 = 0.936 = D_2 \qquad \xi = 0.1269$$

$$\eta = 1.7357$$

Comparative Results

A MIMIC compuatation from the UNIVAC 1108 served as an accuracy base for the curves shown in Figure 25 for the AD/4 analog, EASE 2133 analog and PDP-7 (SIMPL-1) computations. Hybrid computer results (not shown) possessed about the same accuracy as the AD/4 or PDP-7 computations. Computer experiments were than performed on the AD/4 analog computer to verify the extreme sensitivity of the problem to parameter changes. A 0.05% change in η is required to compensate for a 1% change in Σ_2/D. In the computer experiment, the boundary conditions ($\phi_1 = \phi_2 = 0$) at $r = 120$ were manually matched with a potentiometer to within 1% while an oscilloscone was used as a readout device. The boundary condition for ϕ_2 at $r = 0$ was automatically matched with an optimizing scheme to within 0.05%. The value of $\phi_1 = 10$ at $r = 0$ was constant. Under this situation the value of η measured from the AD/4 computer (or PDP-7) was accurate to 0.015%. However, the value $\Delta\eta$, the important variable in perturbation studies, was only accurate to 30%.

Conclusions

The results of the study show that fourth generation analog computers, hybrids, or small digital computers are sufficiently accurate for few-group flux and power profile studies. There is still some question about their applicability for perturbation studies. It appears that the only way to completely resolve the problem is for the hybrid computer (or small digital computer) to solve the complete problem of determining reactivity coefficients for accuracy comparison with large digital methods.

The comparative results in Figure 25 shows the limits of accuracy on the most sensitive problem known at the time of this evaluation study. The error in ϕ_1 and ϕ_2 at r = 120 for the AD/4 and PDP/7 computations is about 4% of the maximum values obtained from the 1108 solution. The EASE 2133 analog computer values are in error by 28%. The difference between the EASE 2133 and AD/4 analog computations graphically illustrate the improvements in fourth generation analog computers over third generation machines. This difference is not normally seen because most differential equations solved on an analog computer have sin, cos, and decaying expontentials as major components in their analytical solutions. Precision errors in computing hardware is minimized through negative feedback loops to analog integrators. In this environment, the resolution of an 18 bit word computer (1 part in 130,000) or the resolution of analog computers (1 part in 10,000) coupled with appropriate scaling techniques is more than adequate to solve scientific problems.

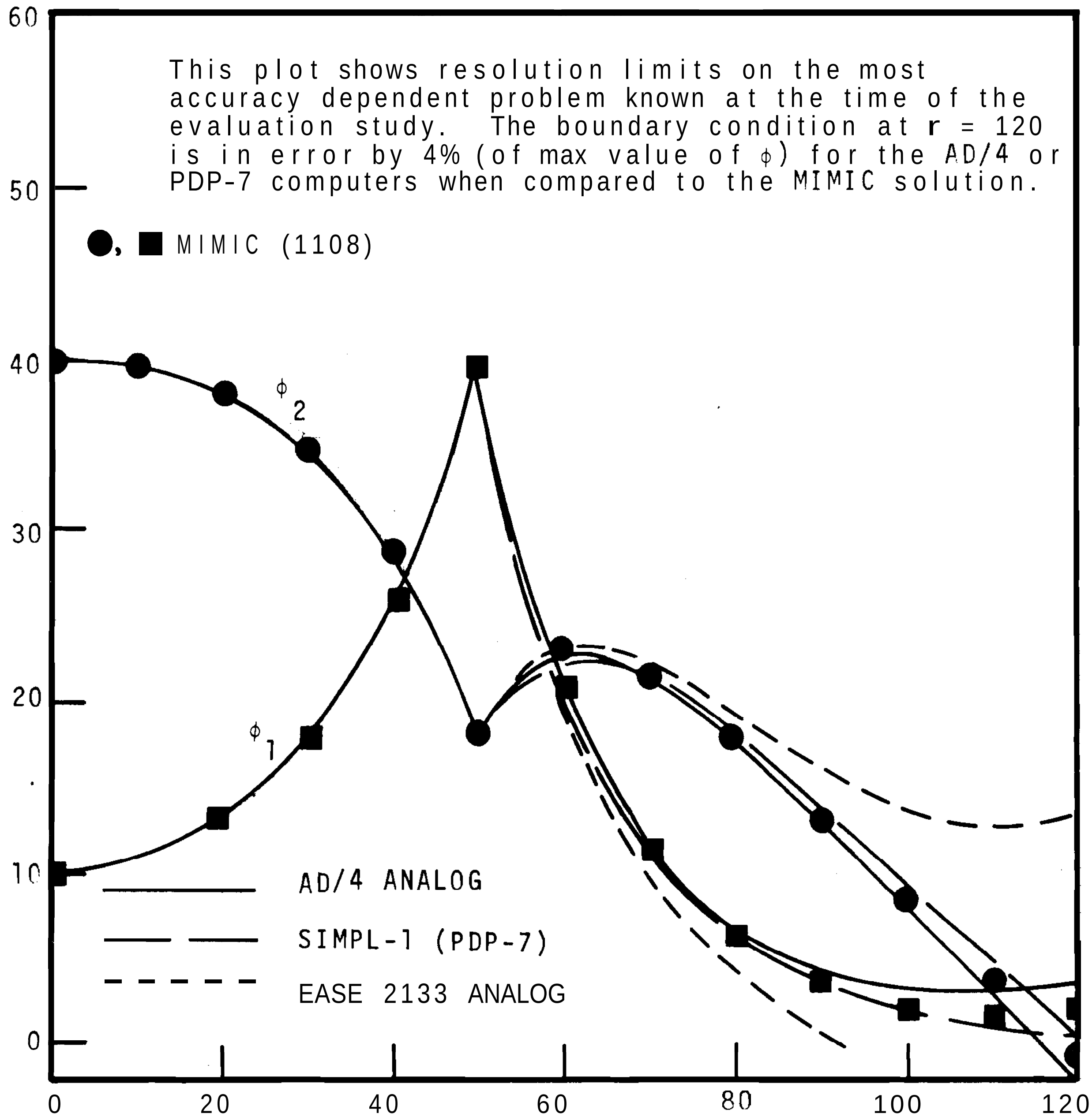


FIGURE 25. Comparison of SIMPL-1, AD/4 Analog, **EASE** 2133 Analog, and MIMIC (UNIVAC 1108), for a Two-energy Group Reactor Physics Problem in Cylindrical Coordinates with the Same Input Data

The reactor diffusion equation, when expressed in cylindrical coordinates and linearized, has sinh and cosh components in its analytical solution. When formulated for a parallel solution as normally required with SIMPL-1, MIMIC, or analog computers, any error in the computer solution is amplified through two integrations in a positive feedback loop. Precision is therefore a paramount problem. Usually sophisticated amplitude scaling, more precise hardware, or double precision techniques will produce the required precision.

LEARNING EFFORT

Direct comparisons of the time required to successfully learn and apply hybrid programming methods as compared to large computer methods were not made. The purpose of this section is to report the learning effort required by two recent chemical and electrical engineering graduates.

Both engineers had prior FORTRAN experience in college. In addition, the electrical engineer attended a one week symposium on hybrid computation. Each engineer required about three weeks to obtain a basic familiarity with analog and SIMPL-1 programming concepts. At the end of three weeks, the engineers solved two or three small problems consisting of 5 to 10 coupled differential equations.

Under the direction of an experienced simulation engineer, each engineer was then assigned a more complex problem that required up to three months to complete. The new engineering graduates gained more confidence with the hybrid system and kept learning right up to the successful completion of their assignments.

The electrical engineer developed a multidecade nuclear reactor simulation using automatic rescaling techniques.(19) The major assignment of the chemical engineer was to become familiar with the mathematical model and hybrid simulation of a waste solidification pilot plant. He then prepared a variable process feed modification to the model and developed the mathematical model and hybrid program for a spray calciner variation to the simulated pilot plant process.

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