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A HYBRID-COMPUTER PROGRAM FOR TRANSIENT TEMPERATURE CALCULATIONS ON TREAT FAST REACTOR SAFETY EXPERIMENTS

by

Lawrence T. Bryant, Lawrence W. Amiot,
Charles E. Dickerman, and William P. Stephany

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September 1967

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NOMENCLATURE

Symbol

A	Cross-sectional flow area	cm ²
C _p	Heat capacity	J/cc deg C
G	Mass flow rate = $\rho_{co}vA$	g/sec
h	Film coefficient used to calculate heat flux from outer surface of cladding to coolant	W/cm ² deg C
K, K(T)	Thermal conductivity	W/cm deg C
K _{i,i+1}	Linear average of the thermal conductivity between the ith and (i+1)th nodes	W/cm deg C
q	Power density	W/cc
r _i	r-component of the position vector to the ith node point	cm
t	Time	sec
T	Temperature	°C
U	Gap conductivity used to calculate the heat flux from the outer surface of the fuel to the inner surface of the cladding	W/cm ² deg C
v	Average speed of coolant	cm/sec
V	Volume	cc
ΔH_{fusion}	Heat of fusion	J/cc
Δr_c	Cladding thickness	cm
Δr_{co}	Width of coolant annulus	cm
Δr_f	Distance between node points of fuel	cm
Δz	Height of a radial section	cm
ρ	Density	g/cc

Subscripts

c	Cladding
co	Coolant
f	Fuel
i	Node point, i = 1, ..., 9

Superscripts for T₉

i	Outlet of the ith section
i-1	Inlet for the ith section

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SUMMARY

This report gives a detailed description of a hybrid-computer program for calculating temperatures in a multiregion, axisymmetric, cylindrical configuration consisting of solid materials bounded by flowing coolant. Included is an explanation of the mathematical methods, together with a discussion of special features, input-output descriptions, and several sample problems.

The number of concentric regions allowed by the program is limited by the amount of analog computer equipment available. Each region may contain either stationary or turbulently flowing material with temperature-dependent properties. The temperatures are calculated at node points equally spaced within a region. The system described here uses nine radial node points and ten axial increments.

The variation of conductivity and temperature along the radius is assumed linear between adjacent node points over a region. Thermal conductivity is assumed to be a continuous finite function of temperature. Phase change in the fuel is considered, with heats of transformation added to the material at the transformation temperatures.

The hybrid computer consists of a stored-program digital computer, with an 8K core memory, connected through a link to an analog computer. The analog computer solves the ordinary differential equations arising from a finite-difference approximation of the heat-transfer equations.

The duties of the digital computer are: (1) parameter input, (2) arithmetic computation of the coefficients of the system, (3) analog potentiometer setting, (4) system check, (5) control, and (6) storage and memory.

The physical parameters, initial conditions, and scale factors are the input parameters to the digital computer. The digital computer calculates the potentiometer settings of the analog computer, sets all analog potentiometers, resets the analog computer, performs a system check, and makes a

decision to "go" or "not go." The reset, hold, and operate analog modes are "slaved" to those of the link, so that the analog is under the control of the digital computer. The analog components are multiplexed, and great savings of analog hardware are realized.

The digital computer sets the initial conditions of the problem and gives the "operate" order to the link, which initiates the first iteration.

The exit coolant temperature of an increment $(\Delta \ell)_i$, where ℓ is the length of the fuel pin (or cell), is computed by the analog, sampled in time, and stored in the memory of the digital computer. This becomes the inlet temperature of the next axial increment $(\Delta \ell)_{i+1}$, and so on, until

$$\sum_{i=1}^n (\Delta \ell)_i = \ell \quad (\text{axial conduction of heat is neglected}).$$

Thus, by multiplexing, only one set of temperature equations is programmed on the analog computer to obtain the radial and axial temperature profiles.

The analog and digital programs are described in Appendix A, and sample problems are included in the body of the text. Special features are discussed in Appendix B.

I. MATHEMATICAL ANALYSIS

Calculation of transient temperatures in various experimental configurations is part of the Fast Reactor Safety Program. The configuration usually consists of fuel cells in the form of a right cylinder with axially flowing coolant. A typical fuel cell consists of a cylindrical rod of fissionable material with concentric bonding material, cladding, and coolant.

The equations for calculating temperatures in concentric cylindrical configurations are derived below. The regions may contain either stationary or flowing material, with heat generation permitted in the stationary region. Axial conduction of heat is neglected. Therefore, the temperature equations are coupled in the direction of flow only through the variation of the coolant temperature along the z -axis. This variation in temperature is dictated by energy transport due to coolant flow. Thus the equation for radial heat flow is the same (in form) at any axial location.

The general diffusion equation describing the thermal behavior of stationary (nonconvective) materials is¹

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T) + q(\vec{r}, t). \quad (1)$$

Assuming that T is a function of r and t only, Eq. 1, in cylindrical coordinates, reduces to

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r} \left[\frac{\partial}{\partial r} \left(K r \frac{\partial T}{\partial r} \right) \right] + q(r, z, t). \quad (2)$$

Most codes use a finite-difference form of Eq. 2 attained by assuming conductivity $K = \text{constant}$, yielding the equation

$$\rho C_p \frac{\partial T}{\partial t} = K \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) + q(r, z, t). \quad (3)$$

Equation 3 neglects $(\partial K / \partial T)(\partial T / \partial r)^2$ implicitly contained in Eq. 2. This, in general, is not correct.

Rather than solving Eq. 3, we can put Eq. 2 into finite-difference form, and the result is equivalent to applying the principle of conservation of energy directly to the system. This is the method used in the development of the problem for the hybrid system.

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Fig. 1. Radial Segment of Annulus

Consider a homogeneous material with an internal heat source. A typical geometric representation for the i^{th} interior node point is shown in Fig. 1. Equation 2 can be put directly into finite-difference form, giving results identical to those of the method presented here (the integral formulation being more explicit). Integrating both members of Eq. 2 over the volume V_i associated with the i^{th} node, we get

$$\int_{V_i} \rho C_p \frac{\partial T}{\partial t} dV = \int_{V_i} \frac{1}{r} \frac{\partial}{\partial r} \left(r K \frac{\partial T}{\partial r} \right) dV + \int_{V_i} q dV, \quad (4)$$

with $dV = r dr d\theta dz$.

For unit height, an angular segment of one radian, and excluding θ dependence, $dV = 2\pi r dr$. Therefore,

$$\int_{r_i - \Delta r/2}^{r_i + \Delta r/2} (\rho C_p)_i \frac{\partial T}{\partial t} r dr = \int_{r_i - \Delta r/2}^{r_i + \Delta r/2} \frac{\partial}{\partial r} \left(r K \frac{\partial T}{\partial r} \right) dr + \int_{r_i - \Delta r/2}^{r_i + \Delta r/2} q_i r dr, \quad (5)$$

or

$$(\rho C_p)_i \frac{\partial T_i}{\partial t} \Delta r r_i = r K \frac{\partial T}{\partial r} \Big|_{r_i - \Delta r/2}^{r_i + \Delta r/2} + q_i \Delta r r_i, \quad (6)$$

where $\rho C p_i$ and q_i are assumed constant over V_i , and $\partial T / \partial t$ for V_i is assumed to be $\partial T_i / \partial t$. Evaluating the first term on the right side of Eq. 6 gives

$$rK \frac{\partial T}{\partial r} \bigg|_{r_i - \Delta r/2}^{r_i + \Delta r/2} = \left(r_i + \frac{\Delta r}{2} \right) K_{i,i+1} \frac{T_{i+1} - T_i}{\Delta r} - \left(r_i - \frac{\Delta r}{2} \right) K_{i,i-1} \frac{T_i - T_{i-1}}{\Delta r}.$$

The variation of K and T with r is assumed to be linear over the region. Therefore,

$$K_{i,i+1} \equiv \frac{K(T_i) + K(T_{i+1})}{2},$$

where $K(T)$ is assumed to be a continuous, finite function of temperature. A similar definition holds for $K_{i,i-1}$.

We have thus derived the "working" differential equation,

$$\begin{aligned} \frac{dT_i}{dt} = & \frac{1}{(\rho C p)_i r \Delta r^2} \left[K_{i,i+1} \left(r_i + \frac{\Delta r}{2} \right) (T_i - T_{i+1}) \right. \\ & \left. - K_{i,i-1} \left(r_i - \frac{\Delta r}{2} \right) (T_{i-1} - T_i) \right] + \frac{q_i}{(\rho C p)_i}. \end{aligned} \quad (7)$$

Applying the laws of conservation of energy and assuming $T_0 = T_1$, we obtain the following set of simultaneous differential equations:

$$\frac{dT_1}{dt} = - \frac{1}{r_1 (\rho C p)_f \Delta r_f^2} K_{1,2} \left(r_1 + \frac{\Delta r_f}{2} \right) (T_1 - T_2) + \frac{q}{(\rho C p)_f}; \quad (8)$$

$$\begin{aligned} \frac{dT_2}{dt} = & - \frac{1}{r_2 (\rho C p)_f \Delta r_f^2} \left[K_{2,3} \left(r_2 + \frac{\Delta r_f}{2} \right) (T_2 - T_3) \right. \\ & \left. - K_{1,2} \left(r_2 - \frac{\Delta r_f}{2} \right) (T_1 - T_2) \right] + \frac{q}{(\rho C p)_f}; \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{dT_3}{dt} = & - \frac{1}{r_3 (\rho C p)_f \Delta r_f^2} \left[K_{3,4} \left(r_3 + \frac{\Delta r_f}{2} \right) (T_3 - T_4) \right. \\ & \left. - K_{2,3} \left(r_3 - \frac{\Delta r_f}{2} \right) (T_2 - T_3) \right] + \frac{q}{(\rho C p)_f}; \end{aligned} \quad (10)$$

$$\begin{aligned} \frac{dT_4}{dt} = & - \frac{1}{r_4(\rho C_p)_f \bar{\Delta r}_f^2} \left[K_{4,5} \left(r_4 + \frac{\Delta r_f}{2} \right) (T_4 - T_5) \right. \\ & \left. - K_{3,4} \left(r_4 - \frac{\Delta r_f}{2} \right) (T_3 - T_4) \right] + \frac{q}{(\rho C_p)_f}; \end{aligned} \quad (11)$$

$$\begin{aligned} \frac{dT_5}{dt} = & - \frac{1}{r_5(\rho C_p)_f \bar{\Delta r}_f^2} \left[K_{5,6} \left(r_5 + \frac{\Delta r_f}{2} \right) (T_5 - T_6) \right. \\ & \left. - K_{4,5} \left(r_5 - \frac{\Delta r_f}{2} \right) (T_4 - T_5) \right] + \frac{q}{(\rho C_p)_f}; \end{aligned} \quad (12)$$

$$\begin{aligned} \frac{dT_6}{dt} = & - \frac{2}{\left(r_6 - \frac{\Delta r_f}{4} \right) (\rho C_p)_f \bar{\Delta r}_f^2} \left[U r_6 \Delta r_f (T_6 - T_7) \right. \\ & \left. - K_{5,6} \left(r_6 - \frac{\Delta r_f}{2} \right) (T_5 - T_6) \right] + \frac{q}{(\rho C_p)_f}; \end{aligned} \quad (13)$$

$$\begin{aligned} \frac{dT_7}{dt} = & - \frac{2}{\left(r_7 + \frac{\Delta r_c}{4} \right) (\rho C_p)_c \bar{\Delta r}_c^2} \left[K_c \left(r_7 + \frac{\Delta r_c}{2} \right) (T_7 - T_8) \right. \\ & \left. - U r_7 \Delta r_c (T_6 - T_7) \right]; \end{aligned} \quad (14)$$

$$\begin{aligned} \frac{dT_8}{dt} = & - \frac{2}{\left(r_8 - \frac{\Delta r_c}{4} \right) (\rho C_p)_c \bar{\Delta r}_c^2} \left[h r_8 \Delta r_c (T_8 - T_9) \right. \\ & \left. - K_c \left(r_8 - \frac{\Delta r_c}{2} \right) (T_7 - T_8) \right]; \end{aligned} \quad (15)$$

$$\frac{dT_9}{dt} = \frac{h r_8 (T_8 - T_9)}{\Delta r_{co} (\rho C_p)_{co} \left(r_8 + \frac{\Delta r_{co}}{2} \right)} - \frac{G f(t) (T_9^i - T_9^{i-1})}{2\pi \Delta z \rho_{co} \Delta r_{co} \left(r_8 + \frac{\Delta r_{co}}{2} \right)}; \quad (16)$$

where $T_9 = (T_9^{i-1} + T_9^i)/2$, and for the first axial section, $T_9^{i-1} = \text{constant}$ inlet coolant temperature.

This original formulation which considers the fuel as a hollow cylinder, reduces to the solid cylindrical case by setting $r_1 = \Delta r_f/2$ in Eq. 8. Figure 2 shows the radial subdivisions for a typical axial section.

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Fig. 2. Radial Subdivision of an Axial Section

The fuel cell is divided into "small" increments, Δz_i , where the length of the cell is

$$\ell = \sum_1^n \Delta z_i,$$

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Fig. 3. Model of a Typical Fuel Cell

as shown in Fig. 3. The radial temperature distribution in the fuel, bond, and cladding is considered to be invariant over the distance Δz . The coolant temperature is assumed to vary linearly along Δz . The conductivity at the boundary between the radial section i and $i+1$ of the fuel, denoted by $K_{i,i+1}$, is evaluated at the boundary temperature $T_{i,i+1} = (T_i + T_{i+1})/2$. Conductivity across the fuel boundary is given by a quadratic function of temperature. For the problem given here, the function is

$$K_{i,i+1} = 4.756 \times 10^{-2} - 3.7165 \times 10^{-5} T_{i,i+1} + 8.8405 \times 10^{-9} T_{i,i+1}^2$$

in W/cm deg C for $0 < T_{i,i+1} < 2200^\circ\text{C}$. This equation was obtained by a polynomial approximation of the conductivity curve shown in Fig. 4. This curve was obtained by using the data of Hedge and Fieldhouse,²

Kingery *et al.*,³ and Reiswig,⁴ together with appropriate correction factors to correct for deviation from theoretical density and to compensate for plutonium content. [In our problem, $(\rho C_p)_f$ was 3.52 J/cc deg C, which is 95% of the heat capacity of fully dense UO_2 . The correction factor used for plutonium content was 0.7.]

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Fig. 4. Thermal-conductivity Curve

The melting point of the fuel is assumed to be 2600°C and $\Delta H_{\text{fusion}} = 2990 \text{ J/cc}$. Using a semiempirical relationship, the ΔH_{fusion} of fully dense UO_2 was estimated to be 3150 J/cc.⁵ This value will be used for the $(\text{U} + \text{Pu})\text{O}_2$. Since the mixed oxide is 95% of theoretical density,

$$\Delta H_{\text{fusion}} = 0.95 \times 3150 \text{ J/cc} \approx 2990 \text{ J/cc}.$$

The gap conductivity is taken as a constant. The value used is $0.5 \text{ W/cm}^2 \text{ deg C}$ and is based on previous UO_2 experiments.⁶

The cladding and coolant are stainless steel and sodium, respectively. The thermal properties of the cladding are the same as those of Type 304 stainless steel;⁷ the coolant properties are presented in Ref. 8.

The equations developed thus far define the mathematical model. With this model, the phenomena are described quantitatively. This system can be simulated on purely analog or digital equipment; but simulation on a hybrid computer has an outstanding advantage in terms of programming effort and computer equipment.

II. DESCRIPTION OF THE HYBRID SIMULATION

The Argonne Hybrid Computer System consists of a stored-program PDP-7 digital computer connected through a control and interfacing unit to the analog-computer consoles.⁹

The interfacing electronics handles the control between computers, the conversion of digital information to analog voltages, the conversion of analog voltages to digital information, and special functions, such as automatic potentiometer settings on the analog consoles. The conversion equipment consists of 10 channels in each direction: analog-to-digital (A-to-D) and digital-to-analog (D-to-A).

Analog computers are efficient in handling ordinary differential equations of the type presented here. However, the analog computing equipment required to effect a solution is enormous. The nature of the equations suggests multiplexing the analog equipment. This can be done since the equations for the radial temperature profile are the same at any axial increment.

Since axial conduction of heat is neglected, the thermal coupling between successive axial increments (Δz) is only through the flowing coolant. The inlet coolant temperature to an axial segment is the exit coolant temperature from the segment immediately preceding it. This temperature must be "remembered" from run to run (section to section) to be used as input data to the succeeding section. It is in this "remembering" that the digital system plays a most vital role. Thus, only the simulation of one set of Eqs. 8-16 is necessary.¹⁰

The two-dimensional temperature profile in a fuel cell is determined in the following manner: The flow rate and inlet coolant temperatures are known functions of time. The radial temperature profile of the first axial segment is computed on the analog computer. The exit coolant temperature T_{co1} from this segment is sampled in time at a rapid rate and stored as sampled binary numbers in the memory of the digital computer. The temperature profile is plotted on X-Y recorders during each iteration. This was necessary because of lack of storage space on the digital computer. Thus, the digital computer need only retain the exit-coolant temperature function (T_{co1}) from the previous iteration. By making T_{co1} available as the inlet temperature to the next axial section, and using the same analog equipment again, we compute the radial temperature profile of this next segment. This process is then repeated for all axial divisions of the fuel cell, thus enabling the entire radial and axial temperature profiles of the cell to be calculated.

Change of state (melting) of the fuel is handled by a system of transistorized switches and energy storage mechanisms on the analog. As a fuel node reaches its melting point, the node temperature is held constant while the energy needed to melt the node is stored by the system. When the storage mechanism determines that the prescribed amount of energy has been stored, the node temperature is released for continued temperature increase. The energy can be released in the solidifying of the molten material. Other fuel cells may be treated simultaneously, if enough hardware is available, or sequentially in the same manner as described.

The PDP-7 digital computer is not only important in the basic method of solution of the problem, but is also involved in the overall control of the hybrid system. In addition to providing for operator intervention during the solution process, the digital system also provides for initial setup of the problem, automatic potentiometer setting on the analog computer, checkout of the system, input of the problem parameters, control of the operation of the analog computers, and general control of the problem solution. The digital machine is controlled by stored digital program written specifically for this problem. In addition to this mainline program, several routines resident in the computer memory can be entered to allow for special features. Among these are routines to print out potentiometer settings and to debug the program.

The digital programs are written in assembly language, the assembler for the PDP-7 being run on the CDC-3600.¹¹ The language for the assembler is essentially that used by the Digital Equipment Corp. assembler for the PDP-7, with certain mnemonics, macroinstructions, and subroutines added to handle the hybrid system. The output of the CDC-3600 for the assembled object code is on magnetic tape suitable for input to the PDP-7 at run time. These programs are discussed in Appendix A.

To ensure that the Eqs. 8-16 do not exceed the limits of the machine, the equations must be scaled. The following relationships define the scale factors of the various variables:

$$at = t', \quad bT_i = T'_i, \quad cq = q',$$

where the primed variables are analog machine voltages and analog machine time, and a, b, and c are predetermined constants which ensure that our analog variables do not exceed the computer limit over the period of interest. Substitution of these "scaled" variables yields the so-called machine equations. Figure 5 shows the analog circuit diagram for these equations.

A flow diagram of the digital program used in the problem solution is shown in Fig. 6. The program shown is necessary to process the iterations for a temperature profile for one set of input parameters.

The input parameters to the digital computer are the initial conditions, dimensions, and thermal properties of the system, together with all analog scale factors. This enables the materials, dimensions, or scale to be changed readily so that other materials can be investigated. The following is a list of the input data to the digital program:

A. Dimensions of the system and scale factors

$$\begin{array}{lcl} \Delta z \text{ cm} & \parallel & r_5 \text{ cm} \parallel r_{co} \text{ cm} \\ r_1 \text{ cm} & \parallel & r_6 \text{ cm} \parallel a \text{ V/sec} \\ r_2 \text{ cm} & \parallel & r_7 \text{ cm} \parallel b \text{ V/deg C} \\ r_3 \text{ cm} & \parallel & r_8 \text{ cm} \parallel c \text{ V cc/W} \\ r_4 \text{ cm} & \parallel & \Delta r_f \text{ cm} \parallel \end{array}$$

B. Thermal properties

1. Fuel

$$\begin{array}{ll} K_f & \text{W/cm deg C} \\ (\rho C_p)_f & \text{J/cc deg C} \end{array}$$

Fig. 5
Analog Circuit Diagram

Fig. 6. Digital Flow Chart

2. Cladding

$$K_c \quad W/cm \text{ deg } C$$

$$(\rho C_p)_c \quad J/cc \text{ deg } C$$

3. Coolant

ρ_{co}	g/cc	G	g/sec
$C_{p_{co}}$	J/g deg C	h	W/cm ² deg C
U	W/cm ² deg C	Initial temperatures of the system in °C.	
Inlet coolant temperature °C.			

The power density is input data to the analog computer.

The first portion of the program allows for initialization of the machine, program, and associated hardware. Problem parameters are entered from the console keyboard. The parameters describe the physical constants of the problem to be run as indicated above. The parameters are inputted as floating-point numbers into the magnetic-core storage. Once parameters are entered, a special routine may be used to punch them onto paper tape. This paper tape can then be used in place of the typewriter on subsequent reruns of the problem. Once the paper tape has been entered, any parameters may be changed by the typewriter.

After the problem parameters are correctly entered, GO is typed and the digital computer calculates potentiometer values via programmed algorithms, using the inputted parameters. These values are stored in digital form in a table in core storage. The potentiometer values can be produced by:

1. Direct typing of coefficients from the typewriter.
2. Calculation from typed parameters.
3. Stored coefficients programmed into the problem.

Once all values have been calculated, they are sequentially converted to analog voltages by D-to-A conversion orders, and the corresponding potentiometers are set to these values under control of the digital machine.

A system static check is made on the analog computer, and the status of the system is indicated. Two manual switches on the analog console are interrogated. The first indicates whether the operator wishes the computer to proceed with the problem solution or to continue to loop and reinterrogate the switches. The second indicates whether the program should reinitialize

itself or continue iterations along the axis upon signal from the first switch. The switches have plus or minus voltages on the poles to control the computer's interrogation.

When the program is allowed to proceed with the problem solution, it sets the clock sampling rate and places the analog consoles in the operate mode. The exit temperature for the present iteration on segment Δz_i is sampled, converted A-to-D, and put into a list in core storage. At the same time, a sample is taken from the list. This sample relates to the exit temperature of the previous section from the previous iteration. Samples are repetitively taken at a rate corresponding to the clock until the list is filled with samples. The number of samples taken, divided by the sample rate, then gives the total time for one iteration. This can be varied by changing a location in core memory which controls the clock sample rate.

This iterative procedure is carried on in this fashion over each axial segment, Δz_i , until

$$\sum_{i=1}^n \Delta z_i = \ell.$$

The resulting temperature distributions of each segment are plotted on X-Y recorders, resulting in the two-dimensional temperature distribution of the cell.

The inlet temperature for the first section is constant (supplied by analog). The digital computer must then supply a zero inlet value during the first iteration. This is done by initially converting A-to-D with zero and then bypassing further A-to-D conversions on the first iteration.

To conserve core storage, we keep only one list for sampled data, and it is shared by both inlet and outlet temperature data. In concept, it acts as a push-down list, inlet temperature data being pushed in one end and outlet temperature data emptying out the other. Actually, as we move down the fixed list, inlet temperature data are first moved from the list and converted A-to-D, and then the D-to-A converted outlet data are stored in their place. As we move down the list, the front part will contain outlet temperature data and the last part will contain inlet temperature data. The outlet data will become the inlet data for the next iteration.

Nine radial and ten axial segments gave good results.

III. SYSTEM MONITOR

The system library contains an Automatic Debug Program (ADP), which was written to allow for operator control over the program in the initial phases of debugging. This program, however, also provides a convenient and powerful means for the experimenter to control the problem during the actual hybrid problem solution.

ADP provides the following facilities:

1. The means to interrogate individual locations or list of consecutive locations in memory and print them on the console typewriter.
2. The means to interrogate locations and, if desired, change these locations with the typewriter.
3. The means to punch consecutive locations onto paper tape.
4. The means to put breakpoints (programmed jumps back into ADP) at any desired point in the program (up to eight).
5. The means to continue the program at the breakpoint in the program.

Although problem parameters are inputted through the normal program in floating-point form, ADP allows seldom-changed parameters to be easily modified. We thus use ADP to modify the sampling rate, the number of samples per iteration, or the number of segments to be analyzed. The switches on the analog console that control restart and continue along with the breakpoints that can be added at random provide for pauses in the program, at which time values can be interrogated, results studied, etc.

IV. RESULTS

The examples that follow represent typical problems that were solved using the hybrid system. In some cases, digital or analytic results are compared with the hybrid solution.

A. Example 1

Data for the first problem to be used as a machine check are as follows:

Input Data

$$\Delta z = 3.76 \text{ cm}$$

$$r_1 = 0.092 \text{ cm}$$

$$r_2 = 0.1236 \text{ cm}$$

$$r_3 = 0.1552 \text{ cm}$$

$$r_4 = 0.1868 \text{ cm}$$

$$r_5 = 0.2184 \text{ cm}$$

$$r_6 = 0.25 \text{ cm}$$

$$r_7 = 0.25 \text{ cm}$$

$$r_8 = 0.2921 \text{ cm}$$

$$\rho_{co} = 0.833 \text{ g/cc}$$

$$Cp_{co} = 1.2636 \text{ J/g deg C}$$

$$G = 93.4 \text{ g/sec}$$

$$a = 100$$

$$b = 0.02$$

$$c = 0.01$$

$$\Delta r_f = 0.0316 \text{ cm}$$

$$\Delta r_c = 0.0421 \text{ cm}$$

$$\Delta r_{co} = 0.0859 \text{ cm}$$

$$K_f = 4.756 \times 10^{-2} \text{ W/cm deg C}$$

$$K_c = 0.228 \text{ W/cm deg C}$$

$$(\rho Cp)_f = 3.52 \text{ J/cc deg C}$$

$$(\rho Cp)_c = 4.7 \text{ J/cc deg C}$$

$$U = 0.5 \text{ W/cm}^2 \text{ deg C}$$

$$h = 18.3 \text{ W/cm}^2 \text{ deg C}$$

Initial temperatures = 400°C; power density $q = 2000 \text{ W/cc}$.

Using the above data, we calculated steady-state temperatures for the first axial section of the system using both the analytic form of the diffusion equation and the equations programmed on the hybrid computer. Fuel conductivity was held constant in this example. Figure 7 compares the hybrid computer solution with the calculated results, for the first segment.

145-915

Fig. 7. Steady-state Temperature Calculations (Example 1)

B. Example 2

Example 2 is presented as a check of the hybrid response to a normalized power transient of the form given in Fig. 8. As in Example 1, the conductivity of the fuel was held constant. This was done to check our results with the results obtained

using the ARGUS program. The ARGUS program uses only five axial increments for this calculation. The results for the innermost node and the edge of the fuel are shown in Figs. 9 and 10, respectively. Note that the axial rather than the radial temperature profiles of the various segments (Δz) of the fuel are shown.

145-914

Fig. 8. Normalized Power Transient
(Example 2)

145-913

Fig. 9. Power-transient Response of Innermost Node

145-912

Fig. 10. Power-transient Response of Edge of Fuel

C. Example 3

This example shows the response of the system when the fuel conductivity is a continuous function of fuel temperature. Figure 11 compares the radial temperature profile with an analytic solution of the partial differential equations.

V. DISCUSSION

The outstanding feature of this method for calculating the transient temperature response of multiregion, axisymmetric, cylindrical configurations is the great saving of computer equipment. This is accomplished by

145-911

Fig. 11. Response with Variable Thermal Conductivity

multiplexing the analog equipment of the hybrid computer, allowing great savings of analog circuitry. Without this economy, the ten sets of nine simultaneous differential equations that represented our model could not have been handled.

Phase change (melting) of the fuel is handled by a system of transistorized switches and energy-storing mechanisms (integrators), as shown in the analog circuit diagram (Fig. 5). When a node of the fuel reaches its melting point (2600°C), the derivative of the differential equation representing the node is made zero, holding the node temperature and the node conductivity constant. The energy-storing integrator then calculates the amount of

energy necessary to melt the node, and, when the proper amount of energy has been stored, the temperature of the node is allowed to increase.

We used a simple experiment to arrive at the sampling rate used in the system. We observed the true analog response to a power function in excess of any power we would use in our calculations. We sampled this response over the interval at a rate that exhausted the rest of the digital memory. We reconverted the sampled response D-A and compared it with the observed analog response. We then decreased the sampling rate and repeated the process until we found a sampling rate that caused the sampled-reconverted D-A curve to differ from the true analog curve. Since a sampling rate that exhausted the memory over any interval of interest was more than adequate, we chose that rate in all cases.

Thus, the time interval is limited by the amount of memory available, and this will determine the sampling rate. If a longer interval is to be considered, the interval can be subdivided into smaller intervals (whose lengths are compatible with the machine limitations) and the responses computed sequentially.

In this simulation, the speed of the digital computer is not a factor. This is true since no arithmetic calculations are made during sampling intervals or iterative runs.

APPENDIX A

Details of Operation of the Digital-computer Program1. Introduction

This appendix gives a detailed description of the digital portion of the hybrid computer program. Since the digital computer controls the hybrid system, the control features of the program are emphasized. The hybrid program was designed to run as an automatic production-type analysis program. We recognized that an interaction between the experimenter and the simulation process was needed, and programmed the digital control so that a "hands on" feature was available.

Table I gives a listing of the assembly language for the mainline program. Library subroutine calls are executed by micro and macro instructions. The routines are loaded into the program at assembly time by the assembler from a library magnetic tape and thus do not appear in the source language listing.

The arithmetic subroutines are single-precision floating-point routines. Communication of parameters via the teletype is in floating-point notation. The floating-point numbers are "fixed" before conversion (D-to-A) or "floated" after conversion (A-to-D).

The digital program can be grouped into three categories:

1. A general program, which allows parameter input, calculation of coefficients and initial conditions (potentiometer settings), and the control program for initiating and running the multiplexed hybrid simulation.
2. A set of subprograms, which allow the experimenter to perform special functions such as, "hands on."
3. ADP, which serves as a limited monitor control program.
(See Appendix B.)

TABLE I. Source Language Listing of Mainline Program

	RES	1	
	LAC	=ATD	INTERRUPT LOCATION
	DAC	=BINA	
	CLAD		
FRED	JMP	PAST	
	LAC*	=L ISTA	
	DAC	=DTA	
	C1DAO	=DTA	
PAST	ION		
	LAC	=BINA	
	DAC*	=L ISTA	
	ISZ	=L ISTA	
	ISZ	=CT1	
	JMP	*	
	LAC	=740000B	
	DAC	FRED	
	HRTC		
	LAC	=BINB	
	DAC	=L ISTA	
	DZM*	=L ISTA	
	LAC	SAMPCT	
	DAC	=CT1	
	ICG2		
	LAC	ORDA	
	DAC	001	
GU	C1ADO	=ATD	
	JMP	*	
TEST	CLAD		
	ION		
	LAC	=ATD	
	SMA		
	JMP	SIG	
	LAC	URDD	
	DAC	001	
	C1AD2	=ATD	
	JMP	*	
TESTB	CLAD		
	ION		
	LAC	=ATD	
	SPA		
	JMP	GO-2	
	JMP	CONT	
SIG	LAC	ORDB	
	DAC	001	
	RRTC		
	ICG2		
	SCK1	10	
	C1AD1C	=ATD	
	URTC		
	JMP	*	
START	IOF		
	ICRTC		
	RRTC		
KEYS	LAM	-33	SET UP TABLE COUNT
	STA	=KEYE	
	TCR		CARRIAGE RETURN LINE FEED
	RWORD	=KEY	GET FIRST 3 CHARACTERS
	LAC	KEYTZ	
	DAC	=KEYA	SET UP ADDRESS OF TABLE
KEY	LAC	=KEY	
	SAD*	=KEYA	COMPARE TYPED WORD TO TABLE
	JMP	KEYM	

TABLE I (Contd.)

	LAC	=KEYA	INCREMENT ADDRESS OF TABLE
	ACD	=2	
	STA	=KEYA	
	ISZ	=KEYE	END OF TABLE
	JMP	KEY	TRY NEXT WORD
	JMP	KEYS	NO MATCH IN TABLE
KEYM	ISZ	=KEYA	MATCH FOUND
	XCT*	=KEYA	
KEYTZ	CAL	KEYI	
C1	FDEC	1E-1	
C2	FDEC	37165E-2	
C3	FDEC	88405E-4	
C4	FDEC	5E0	
C5	FDEC	1E0	
C6	FDEC	2E1	
C7	FDEC	-25E0	
C8	FDEC	25E0	
C9	FDEC	-5E0	
C10	FDEC	159E-1	
C11	FDEC	2E0	
FIEMP1	RES	2	
FIEMP2	RES	2	
FIEMP3	RES	2	
FIEMP4	RES	2	
POTT	RES	9	INITIAL CONDITION POTS
	RES	6	POT 9 - 14
	DEC	200000B	POT 15 = .5
	DEC	200000B	POT 16 = .5
	DEC	171564B	POT 17
	RES	1	POT 18
	RES	1	POT 19
	RES	2	POT 20 , 21
	DEC	200000B	POT 22
	DEC	200000B	POT 23
	DEC	171564B	POT 24
	RES	1	POT 25
	RES	1	POT 26
	RES	2	POT 27 , 28
	DEC	200000B	POT 29
	DEC	200000B	POT 30
	DEC	171564B	POT 31
	RES	1	POT 32
	RES	1	POT 33
	RES	2	POT 34 , 35
	DEC	200000B	POT 36
	DEC	200000B	POT 37
	DEC	171564B	POT 38
	RES	1	POT 39
	RES	1	POT 40
	RES	2	POT 41 , 42
	DEC	200000B	POT 43
	DEC	200000B	POT 44
	DEC	171564B	POT 45
	RES	1	POT 46
	RES	1	POT 47
	RES	9	POT 48 - 56
C	LAW	CZ	SET UP PARAMETERS
	STA	=ADDZ	
	JMP	INPUT	
B	LAW	BZ	
	JMP	C+1	
G	LAW	GZ	

TABLE I (Contd.)

	JMP	C+1	
U	LAW	UZ	
	JMP	C+1	
H	LAW	HZ	
	JMP	C+1	
LA	LAW	LAZ	
	STA	=ADDZ	
	JMS	RCHAR	
	JMP	INPUT	
R1	LAW	R1Z	
	JMP	LA+1	
R2	LAW	R2Z	
	JMP	LA+1	
R3	LAW	R3Z	
	JMP	LA+1	
R4	LAW	R4Z	
	JMP	LA+1	
R5	LAW	R5Z	
	JMP	LA+1	
R6	LAW	R6Z	
	JMP	LA+1	
R7	LAW	R7Z	
	JMP	LA+1	
R8	LAW	R8Z	
	JMP	LA+1	
BA	LAW	BAZ	
	JMP	LA+1	
DZ	LAW	DZZ	
	JMP	LA+1	
PF	LAW	PFZ	
	JMP	LA+1	
KC	LAW	KCZ	
	JMP	LA+1	
DHF	LAW	DHFZ	
	STA	=ADDZ	
	JMS	RCHAR	
	JMS	RCHAR	
	JMP	INPUT	
DRF	LAW	DRFZ	
	JMP	DHF+1	
PCU	LAW	PCUZ	
	JMP	DHF+1	
DRC	JMS	RCHAR	
	SAD	=000275B	COMPARE TO =
	JMP	*+3	
	LAW	DRCUZ	
	JMP	DHF+1	
	LAW	DRCZ	
	JMP	LA+1	
PCP	JMS	RCHAR	
	SAD	=000303B	COMPARE TO C
	JMP	*+3	
	LAW	PCPFZ	
	JMP	DHF+1	
	JMS	RCHAR	
	SAD	=000275B	COMPARE TO =
	JMP	*+3	
	LAW	PCPCUZ	
	JMP	DHF+1	
	LAW	PCPCZ	
	JMP	LA+1	
INPUT	JMS	RFDEC	TYPE FLOATING NUMBER INTO F. AC

TABLE I (Contd.)

	LAC	=FACE	
	STA*	=ADDZ	
	ISZ	=ADDZ	
	LAC	=FACE	
	STA*	=ADDZ	
	JMP	KEYS	GET NEXT PARAMETER
IC0	LAW	IC0Z	
	JMP	DHF+1	
IC1	LAW	IC1Z	
	JMP	DHF+1	
IC2	LAW	IC2Z	
	JMP	DHF+1	
IC3	LAW	IC3Z	
	JMP	DHF+1	
IC4	LAW	IC4Z	
	JMP	DHF+1	
IC5	LAW	IC5Z	
	JMP	DHF+1	
IC6	LAW	IC6Z	
	JMP	DHF+1	
IC7	LAW	IC7Z	
	JMP	DHF+1	
IC8	LAW	IC8Z	
	JMP	DHF+1	
KEYT	OCT	037540	
	JMP	C	
	OCT	027540	
	JMP	B	
	OCT	077540	
	JMP	G	
	OCT	257540	
	JMP	U	
	OCT	107540	
	JMP	H	
	OCT	140175	
	JMP	LA	
	OCT	226175	
	JMP	R1	
	OCT	226275	
	JMP	R2	
	OCT	226375	
	JMP	R3	
	OCT	226475	
	JMP	R4	
	OCT	226575	
	JMP	R5	
	OCT	226675	
	JMP	R6	
	OCT	226775	
	JMP	R7	
	OCT	227075	
	JMP	R8	
	OCT	020175	
	JMP	BA	
	OCT	043275	
	JMP	DZ	
	OCT	200675	
	JMP	PF	
	OCT	130375	
	JMP	KC	
	OCT	041006	
	JMP	DHF	

TABLE I (Contd.)

	OCT	042206
	JMP	DRF
	OCT	042203
	JMP	DRC
	OCT	200360
	JMP	PC0
	OCT	200320
	JMP	PCP
	OCT	071717
	JMP	GG0
	OCT	110360
	JMP	IC0
	OCT	110361
	JMP	IC1
	OCT	110362
	JMP	IC2
	OCT	110363
	JMP	IC3
	OCT	110364
	JMP	IC4
	OCT	110365
	JMP	IC5
	OCT	110366
	JMP	IC6
	OCT	110367
	JMP	IC7
	OCT	110370
	JMP	IC8
CZ	RES	2
BZ	RES	2
LAZ	RES	2
R1Z	RES	2
R2Z	RES	2
R3Z	RES	2
R4Z	RES	2
R5Z	RES	2
R6Z	RES	2
R7Z	RES	2
R8Z	RES	2
DRFZ	RES	2
DRCZ	RES	2
DRC0Z	RES	2
BAZ	RFS	2
GZ	RES	2
DZZ	RES	2
PFZ	RES	2
PCPFZ	RES	2
UZ	RES	2
PCPCZ	RES	2
KCZ	RFS	2
HZ	RES	2
PC0Z	RES	2
PCPC0Z	RES	2
DHFZ	RES	2
IC0Z	RES	2
IC1Z	RES	2
IC2Z	RES	2
IC3Z	RES	2
IC4Z	RES	2
IC5Z	RES	2
IC6Z	RES	2
IC7Z	RES	2

TABLE I (Contd.)

IC8Z GCU	RES	2
	FLAC	C1
	FMPY	BZ
	FSTA	FTEMP1
	FMPY	IC0Z
	UNFLTF	POTT
	FLAC	FTEMP1
	FMPY	IC1Z
	UNFLTF	POTT+1
	FLAC	FTEMP1
	FMPY	IC2Z
	UNFLTF	POTT+2
	FLAC	FTEMP1
	FMPY	IC3Z
	UNFLTF	POTT+3
	FLAC	FTEMP1
	FMPY	IC4Z
	UNFLTF	POTT+4
	FLAC	FTEMP1
	FMPY	IC5Z
	UNFLTF	POTT+5
	FLAC	FTEMP1
	FMPY	IC6Z
	UNFLTF	POTT+6
	FLAC	FTEMP1
	FMPY	IC7Z
	UNFLTF	POTT+7
	FLAC	FTEMP1
	FMPY	IC8Z
	UNFLTF	POTT+8
	FLAC	LAZ
	FMPY	PCPFZ
	FSTA	FTEMP1
	FMPY	CZ
	FSTA	FTEMP2
	FLAC	BZ
	FDIV	FTEMP2
	UNFLTF	POTT+9
	LAC	POTT+9
	DAC	POTT+10
	DAC	POTT+11
	DAC	POTT+12
	DAC	POTT+13
	DAC	POTT+14
	FLAC	C2
	FDIV	BZ
	UNFLTF	POTT+18
	LAC	POTT+18
	DAC	POTT+25
	DAC	POTT+32
	DAC	POTT+39
	DAC	POTT+46
	FLAC	C3
	FDIV	BZ
	FDIV	BZ
	UNFLTF	POTT+19
	LAC	POTT+19
	DAC	POTT+26
	DAC	POTT+33
	DAC	POTT+40
	DAC	POTT+47
	FLAC	FTEMP1

TABLE I (Contd.)

FMPY	DRFZ
FMPY	DRFZ
FSTA	FTEMP2
FMPY	R1Z
FSTA	FTEMP3
FLAC	DRFZ
FMPY	C4
FSTA	FTEMP4
FADD	R1Z
FDIV	FTEMP3
FMPY	C5
UNFLTF	POTT+20
FLAC	R2Z
FSUB	FTEMP4
FMPY	C5
FDIV	FTEMP2
FDIV	R2Z
UNFLTF	POTT+21
FLAC	R2Z
FADD	FTEMP4
FDIV	FTEMP2
FDIV	R2Z
FMPY	C5
UNFLTF	POTT+27
FLAC	R3Z
FSUB	FTEMP4
FMPY	C5
FDIV	FTEMP2
FDIV	R3Z
UNFLTF	POTT+28
FLAC	R3Z
FADD	FTEMP4
FMPY	C5
FDIV	FTEMP2
FDIV	R3Z
UNFLTF	POTT+34
FLAC	R4Z
FSUB	FTEMP4
FMPY	C5
FDIV	FTEMP2
FDIV	R4Z
UNFLTF	POTT+35
FLAC	R4Z
FADD	FTEMP4
FMPY	C5
FDIV	FTEMP2
FDIV	R4Z
UNFLTF	POTT+41
FLAC	R5Z
FSUB	FTEMP4
FMPY	C5
FDIV	FTEMP2
FDIV	R5Z
UNFLTF	POTT+42
FLAC	R5Z
FADD	FTEMP4
FMPY	C5
FDIV	FTEMP2
FDIV	R5Z
UNFLTF	POTT+48
FLAC	DRFZ
FMPY	C7

DRF OVER TWO

TABLE I (Contd.)

FADD	R6Z
FSTA	FTEMP3
FLAC	R6Z
FSUB	FTEMP4
FMPY	C11
FDIV	FTEMP2
FDIV	FTEMP3
UNFLTF	POTT+49
FLAC	C6
FMPY	R6Z
FMPY	DRFZ
FMPY	UZ
FDIV	FTEMP2
FDIV	FTEMP3
UNFLTF	POTT+50
FLAC	DRCZ
FMPY	C8
FADD	R7Z
FSTA	FTEMP3
FLAC	C6
FDIV	LAZ
FDIV	PCPCZ
FDIV	DRCZ
FDIV	DRCZ
FSTA	FTEMP2
FDIV	FTEMP3
FSTA	FTEMP3
FMPY	UZ
FMPY	R7Z
FMPY	DRCZ
UNFLTF	POTT+51
FLAC	DRCZ
FMPY	C4
FADD	R7Z
FMPY	KCZ
FMPY	FTEMP3
UNFLTF	POTT+52
FLAC	DRCZ
FMPY	C7
FADD	R8Z
FSTA	FTEMP3
FLAC	FTEMP2
FDIV	FTEMP3
FSTA	FTEMP3
FLAC	DRCZ
FMPY	C9
FADD	R8Z
FMPY	KCZ
FMPY	FTEMP3
UNFLTF	POTT+53
FLAC	HZ
FMPY	R8Z
FMPY	DRCZ
FMPY	FTEMP3
FMPY	C5
UNFLTF	POTT+54
FLAC	DRCZ
FMPY	C4
FADD	R8Z
FSTA	FTEMP3
FLAC	HZ
FMPY	C5

TABLE I (Contd.)

	FMPY	R8Z	
	FDIV	FTEMP3	
	FDIV	LAZ	
	FDIV	PCPCOZ	
	FDIV	DRCOZ	
	UNFLTF	POTT+55	
	FLAC	GZ	
	FDIV	FTEMP3	
	FMPY	C10	
	FDIV	LAZ	
	FDIV	DZZ	
	FDIV	PCOZ	
	FDIV	DRCOZ	
	UNFLTF	POTT+56	
	LAM	-57	
	STA	=KEYE	SET UP COUNT OF POTS TO BE SET
	LAW	POTT	
	STA	=POTAD	SET UP ADDRESS OF POT VALUE
	DZM	=POTNU	SET UP POT NUMBER
NXTPOT	LAC*	=POTAD	
	STA	CALLS+1	GET VALUE
	LAC	=POTNU	
	STA	CALLS+2	GET POT NUMBER
	JMS	POTSX	ENTER POT SET ROUTINE
CALLS	OCT	777377B	CONSOLE A
	RES	2	CALLING SEQUENCE
	ISZ	=KEYE	SET ALL POTS -
	JMP	*+2	
	JMP	CONT	
	ISZ	=POTAD	INCREMENT POT VALUE ADDRESS
	ISZ	=POTNU	INCREMENT POT NUMBER
	LAC	=000017B	
	AND	=POTNU	
	SAD	=10	
	JMP	BCD	
	JMP	NXTPOT	
BCD	LAC	=POTNU	
	AND	=777760B	
	ADD	=000020B	
	DAC	=POTNU	
	JMP	NXTPOT	
CONT	DZM	=DTA	
	ICRTC		
	RRTC		
	C1DAC	=DTA	
	LAC	URDA	
	DAC	001	
	LAC	ORDC	
	DAC	FREC	
	LAC	SAMPCT	
	DAC	=CT1	
	LAW	LISTA	
	AND	=C17777B	
	DAC	=LISTA	
	DAC	=BINB	
	IGN		
	JMP	GO	
ORDA	JMP	TEST	
ORDB	LAC	=ATD	
ORDC	JMP	PAST	
ORDC	JMP	TESTB	
	JMS	ADP	

TABLE I (Contd.)

PCTSX	RES	1	POT SET SUBROUTINE
	IUF		INTERRUPT OFF
	LAC*	*-2	GET CONSOLE A OR B CODE
	AND	=200400B	
	STA	POTS3	
	ISZ	*-5	
	LAC*	*-6	GET VALUE TO BE SET
	STA	POTS1	TEMP STGRE
	CLDA4	POTS1	
	LAC	=777700B	
	STA	POTS2	
	ISZ	POTS2	
	JMP	*-1	
	CLDA		CLEAR INTERRUPT
	ISZ	POTSX	
	LAC*	POTSX	GET POT NUMBER
	XOR	POTS3	
	RTCO		POT SET
	LAC	=400000B	
	STA	POTS2	
	LAC	=777740B	
	STA	POTS1	
	LAC	ORD	
	STA	OC1	
	ICN		INTR ON
	ISZ	POTS2	
	JMP	*-1	
	ISZ	POTS1	
	JMP	*-3	
	CLAP		
	IUF		INTERRUPT OFF
	LAC	=201000B	
	RTCO		CLEAR POT ORDER
	LAC	=400000B	
	STA	POTS2	
	JMS	TCR	
	LAC*	PCTSX	
	JMS	TDEC	
	ISZ	POTS2	
	JMP	*-1	
POTS4	LAC	=400000B	
	DAC	POTS2	
	ISZ	POTS2	
	JMP	*-1	
	CLAP		
	ISZ	POTSX	
	JMP*	POTSX	
ORD	JMP	POTS4	
POTS1	RES	1	
POTS2	RES	1	
POTS3	RES	1	
TYPE	LAM	-57	
	DAC	=TYPEC	
	LAW	POTT	
	DAC	=TYPEA	
	JMS	TCR	
	DZM	=TYPEP	
TYPEE	LAC	=TYPEP	
	JMS	TDEC	
	LAC	=404040B	
	JMS	TWORD	
	LAC*	=TYPEA	

TABLE I (Contd.)

	JMS	IFRAC
	JMS	TCR
	ISZ	=TYPEP
	ISZ	=TYPEA
	ISZ	=TYPEC
	JMP	TYPEE
	JMP	ADP
SAMPCF	DEC	764220B
	SUBR	
	LITLS	
LISTA	RES	1
	JMP	ADP
	END	

2. Details of Operation

Once the program has been loaded, control is transferred to ADP. While the main program is under control of ADP, we type 105G to enter this program at symbolic location START. This sets up the digital part of the hybrid computer program and effects a pause with the keyboard request active. Valid parameter names (see Table II) and their signed floating-point values can now be entered through the keyboard. The program stays in this loop until the experimenter wishes to proceed with the simulation. The mnemonic GOO is entered through the keyboard, and the program proceeds to symbolic location GOO. Potentiometer values are calculated using the programmed algorithms and the parameters that were entered by the experimenter. These values are stored as fixed-point binary numbers in a table in the program starting at symbolic location POTT.

TABLE II. Valid Parameter Names

System Parameter	Typed Parameter	Scale Factors	Typed Parameters
G	G	a	LA
U	U	b	B
h	H	c	C
r ₁	R1		
r ₂	R2		
r ₃	R3	Initial Condition	
r ₄	R4	First fuel segment	IC0
r ₅	R5	Second fuel segment	IC1
r ₆	R6	Third fuel segment	IC2
r ₇	R7	Fourth fuel segment	IC3
r ₈	R8	Fifth fuel segment	IC4
A	BA	Final edge	IC5
Δz	DZ	Homogenized bond and	
ρ_f	PF	cladding	IC6
K _c	KC	Edge of cladding	IC7
ΔH_{fusion}	DHF	Coolant temperature	IC8
Δr_f	DRF		
ρ_{co}	PCO		
Δr_c	DRC		
ρ_{Cp}	PCP		
Δr_{co}	DRCO		
$(\rho_{Cp})_c$	PCPC		
$(\rho_{Cp})_{co}$	PCPCO		

The automatic potentiometer-setting routine is entered, and the servo-set potentiometers of the analog computer are set, via the hybrid orders, to the values stored in the POTT table. If a potentiometer fails to set, an error message is indicated for it, describing the potentiometer number and the value to which it should be set.

The program proceeds to symbolic location CONT, and the hybrid system is restarted. A D-to-A conversion is made on channel 0, which represents the initial inlet temperature. The program then proceeds to symbolic location GO, where two checks are made on the analog console:

1. Should the program proceed, or should it continue to loop and check on the two conditions.
2. Should the program restart at location CONT, or should it continue to loop and check on the two conditions.

The two conditions are controlled by two switches, on the analog console, which are under manual control of the operator.

If the program is to proceed, it branches to location SIG. An iteration is performed using a predetermined clock-sampling rate and total sample count. On each "beat" of the clock, an A-to-D conversion is made on the change in outlet coolant temperature, and the converted data are stored in core in a list. Simultaneously, a D-to-A conversion is made on the inlet-coolant-temperature change, which was stored in the outlet-coolant-temperature change list during the previous run. The first iteration is made using zero as the inlet-coolant-temperature change.

At the end of an iteration, the program returns to GO, where the continue and restart switches are tested. Iterations are continued along the axial length until the maximum number of axial segments have been iterated and/or a restart is signaled. As noted before, temperatures of interest to the experimenter are plotted by X-Y recorders during each iteration. Thus we achieve the radial and axial temperature profiles of our fuel cell.

APPENDIX B

Special Features Allowed by ADP

The use of ADP in conjunction with the program allows certain special functions to be performed. ADP may be entered at any time by manually starting the computer at 1637 (octal).

ADP allows the insertion of up to eight breakpoints at any desired point in the program. They are inserted by typing ZZZBX, where X is the breakpoint number and $0 \leq X \leq 7$, while the system is under control of ADP. ZZZ (octal) is the memory address where the breakpoint is to be inserted. When the main program is executed and proceeds to ZZZ, a branch back to ADP will be effected. Any ADP function can now be performed, including entering a C via the typewriter keyboard; this causes the main program to continue execution at the point where the breakpoint occurred.

Frequently it is desirable to know the value of the potentiometer settings. While the system is under ADP control, a routine at location TYPE may be entered by typing 1614G. The potentiometer numbers and corresponding values will be typed out in decimal form. Upon completion, control is returned to ADP.

To relieve the operator of the task of entering the parameters every time the program is to be reloaded for subsequent runs, the parameters may be punched out from core memory onto paper tape. The paper tape can then be loaded after the main program is loaded. The paper tape is punched out under control of ADP by typing 522P106P. The paper tape is read in under computer manual load control starting at address 522 (octal). Any or all parameters may then be modified through the typewriter keyboard.

The clock, which controls the sampling rate of the conversion equipment, is programmed to sample every 10 msec. Six thousand samples are taken per iteration. The clock time can be varied in millisecond increments by storing the octal binary number in milliseconds in location 73 octal. This is also facilitated by using ADP. For example, 73/XXXXXX000017 will change the value of XXXXXX to 15 msec.

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