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ZØRCH - AN IBM 7090 PROGRAM FOR THE ANALYSIS OF SIMULATED MSRE POWER TRANSIENTS WITH A SIMPLIFIED SPACE-DEPENDENT KINETICS MODEL

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ABSTRACT

The program described in this report is an extended and revised version of the point-model kinetics program MURGATRØYD.[1] In the model used in the present program, the axial space dependence of the fuel and graphite temperatures is calculated, and the effect on reactivity of deviations from the steady state values is assumed to be given by the product of an appropriate temperature coefficient of reactivity times the deviations from the steady state value of the nuclear average temperature (NAT). The NAT is computed using a "sine-squared" weighting function in the axial direction and using an input weighting factor in the radial direction.

The shape of the power density is taken to be time-independent in contrast to the shapes of the temperature distributions, which are time-dependent in the calculation. This program is intended to be used in surveys of reactor behavior under a wide range of conditions. It is therefore based on a simplified model in order to reduce computing time, but should provide a better approximation to reactor behavior than does a purely space-independent calculation.

This report consists of a derivation of the equations used in the program, instructions for its use and sample input and output for a test case. A FØRTRAN source deck and a binary object deck are on file.*

*The desired decks may be obtained either from the author or from T. B. Fowler.

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INTRODUCTION

The conventional space-independent kinetics equations usually consider reactivity compensation to be based on the average temperature rise of the reactor core, independent of the spatial distribution of the temperature. In this report, the spatial temperature distribution is used explicitly in obtaining the reactivity change associated with changes in power level, considering a fundamental-mode power distribution. The program applies to fluid fuel reactors in which fuel moves through the core with slug-type flow; the moderator is assumed to be stationary. Application to the Molten Salt Reactor Experiment is considered in deriving the equations, and so the fluid fuel is referred to as fuel salt, with graphite as the moderator.

DERIVATION OF EQUATIONS AND CALCULATIONAL PROCEDURE

Consider a small disk of fuel salt of thickness Δz and cross sectional area A_f moving through the core with speed u (Fig. 1A). A temperature $T_f(r,z,t)$ is assigned to the disk and a temperature $T_g(r,z,t)$ is assigned to the annular disk of graphite surrounding the disk of fuel salt. Assuming that heat transfer from graphite to fuel may be adequately represented by the product of a heat transfer coefficient times the difference of the temperatures, and neglecting axial heat conduction, the following pair of equations is obtained for the fuel and graphite temperatures: (Symbols are defined in Table 1.)

$$T_f(z + nu\Delta t,\ t + n\Delta t) - T_f(z,t) = \frac{1}{\rho_f C_f} \int_0^{n\Delta t} \Phi_f(z + u\tau,\ t + \tau)\, d\tau$$

$$+ \frac{hL}{A_f \rho_f C_f} \int_0^{n\Delta t} [T_g(z + u\tau,\ t + \tau) - T_f(z + u\tau,\ t + \tau)]\, d\tau \qquad (1a)$$

$$T_g(z + nu\Delta t,\ t + n\Delta t) - T_g(z + nu\Delta t,\ t) = \frac{1}{\rho_g C_g} \int_0^{n\Delta t} \Phi_g(z + nu\Delta t,\ t + \tau) d\tau$$

$$- \frac{hL}{A_g \rho_g C_g} \int_0^{n\Delta t} [T_g(z + nu\Delta t,\ t + \tau) - T_f(z + nu\Delta t,\ t + \tau)]\, d\tau \qquad (1b)$$

(For convenience, the dependence on r has not been explicitly included in the above equations.)

Table 1. Nomenclature

The following quantities have subscripts f, denoting fuel salt, or g, denoting graphite:

A	channel cross sectional area
C	specific heat
$\frac{\partial k_e}{\partial \overline{T}}$	temperature coefficient of reactivity
Q	normalized heat source term
S	heat capacity
T	temperature (referred to initial inlet temperature)
$\overline{T}$	nuclear average temperature
v	volume fraction
ρ	density
Φ	power density

The following quantities have subscript i denoting delayed neutron family:

C	normalized latent power
β_e	effective yield in circulating fuel reactor [The correction for fuel flow is identical to that used in Ref. 1.]
β_s	yield in stationary fuel reactor
γ	effective yield divided by prompt neutron lifetime (β_e/ℓ)
λ	decay constant

The following quantities have subscripts only as indicated:

f	fraction of total power generated in fuel salt
$F(r)$	radial power density distribution

Table 1 - cont'd

F_R	radial peak-to-average ratio of power density
h	heat transfer coefficient
H	core height
$k_e(t)$	effective multiplication constant
ℓ	prompt neutron lifetime
L	channel perimeter
$P(t)$	reactor power at time t
t_c	core residence time
t_L	external loop residence time
T_i	fuel inlet temperature
u	fuel velocity in channel
V	core volume
$x(t)$	$P(t)/P(o)$, relative power at time t
β	total effective delayed neutron yield

It is assumed that the power densities Φ_f and Φ_g are of the form

$$\Phi_f(r,z,t) = \frac{fF(r)\,P(o)\,x(t)}{v_f V}\,\frac{\pi}{2}\sin\frac{\pi z}{H} \tag{2a}$$

$$\Phi_g(r,z,t) = \frac{(1-f)\,F(r)\,P(o)\,x(t)}{(1-v_f)V}\,\frac{\pi}{2}\sin\frac{\pi z}{H}\,. \tag{2b}$$

Consider the fuel channel along which $F(r)$ has the value F_R. Then, with the definitions

$$Q_{f,g} = \frac{1}{\rho_{f,g}C_{f,g}}\int_o^{n\Delta t}\Phi_{f,g}\,(z'(\tau),\ t+\tau)\,d\tau \tag{3}$$

and the power densities of the form given by equation 2, the normalized heat source terms are:

$$Q_f = \frac{1}{\rho_f C_f}\,\frac{fF_R\,P(o)(\frac{\pi}{2})}{v_f\,V}\int_o^{n\Delta t}\sin\frac{\pi(z+u\tau)}{H}\,x(t+\tau)\,d\tau \tag{4a}$$

$$Q_g = \frac{1}{\rho_g C_g}\,\frac{(1-f)\,F_R\,P(o)(\frac{\pi}{2})}{(1-v_f)\,V}\sin\frac{\pi(z+nu\Delta t}{H}\int_o^{n\Delta t}x(t+\tau)\,d\tau. \tag{4b}$$

Using the trigonometric formula for the sine of the sum of two angles, noting that the core residence time t_c is given by

$$t_c = H/u, \tag{5}$$

and that the total heat capacities of fuel and graphite in the core S_f and S_g, respectively, are given by

$$S_f = v_f\,V\,\rho_f C_f \tag{6a}$$

$$S_g = (1-v_f)\,V\,\rho_g C_g \tag{6b}$$

equations 4a and 4b may be written

$$Q_f = \frac{f\, F_R\, P(o)\, (\pi/2)}{S_f} \left[\sin \frac{\pi z}{H} \int_o^{n\Delta t} \cos \frac{\pi \tau}{t_c}\, x(t+\tau)\, d\tau \right.$$

$$\left. + \cos \frac{\pi z}{H} \int_o^{n\Delta t} \sin \frac{\pi \tau}{t_c}\, x(t+\tau)\, d\tau \right] \tag{7a}$$

$$Q_g = \frac{(1-f)\, F_R\, P(o)\, (\pi/2)}{S_g} \sin \frac{\pi(z + nu\Delta t)}{H} \int_o^{n\Delta t} x(t+\tau)\, d\tau \ . \tag{7b}$$

The time dependence of the relative power $x(t)$ is calculated from the same differential equations used in MURGATRØYD,[1] viz:

$$\dot{x}(t) = \frac{k_e(1-\beta) - 1}{\ell}\, x(t) + \sum_{i=1} \lambda_i C_i \tag{8a}$$

$$\dot{C}_i(t) = -\lambda_i C_i(t) + \gamma_i\, x(t)\ , \quad i = 1,N \tag{8b}$$

but the form of temperature feedback has been changed from that used in MURGATRØYD to allow an approximate treatment of space dependence. The effective multiplication constant k_e is taken to be of the form

$$k_e(t) = 1 + \Delta + bt + \frac{\partial k_e}{\partial \overline{T}_f} [\overline{T}_f(t) - \overline{T}_{fo}] + \frac{\partial k_e}{\partial \overline{T}_g} [\overline{T}_g(t) - \overline{T}_{go}] \tag{9}$$

where the average temperatures $\overline{T}_f(t)$ and $\overline{T}_g(t)$ are defined by

$$\overline{T}_j(t) \equiv \frac{\int_o^R \int_o^H T_j(r,z,t)\, I(r) \sin^2 \frac{\pi z}{H}\, r\, dr\, dz}{\int_o^R \int_o^H I(r) \sin^2 \frac{\pi z}{H}\, r\, dr\, dz}\ , \quad j = f,g \tag{10}$$

where $I(r)$ is a radial weighting function.

With the assumption of separability of the time dependence of the power densities and the neglect of axial heat conduction, the radial dependence of the temperatures is proportional to that of the power densities, so that

$$\bar{T}_j(t) = \frac{\int_0^H T_j(z,t)\sin^2\frac{\pi z}{H}\,dz}{\int_0^H \sin^2\frac{\pi z}{H}\,dz} \quad \frac{\int_0^R F(r)\,I(r)\,rdr}{\int_0^R I(r)\,rdr}, \quad j = f,g. \tag{11}$$

The ratio $\int_0^R F(r)\,I(r)\,rdr/\int_0^R I(r)\,dr$ is an input number to the program considered here.

The set of equations 8a and 8b is converted to a set of recursion relations for the relative power x and delayed neutron latent powers C_i by integrating the differential equations over a single time step of length Δt, with the integrals on the right hand side evaluated by means of the trapezoidal rule:

$$x(t+\Delta t) - x(t) = \frac{\Delta t}{2}\left[\alpha(t+\Delta t)\,x(t+\Delta t) + \alpha(t)\,x(t)\right] + \sum_i \frac{\lambda_i\,\Delta t}{2}\left[C_i(t+\Delta t) + C_i(t)\right] \tag{12a}$$

$$C_i(t+\Delta t) - C_i(t) = \frac{\gamma_i\,\Delta t}{2}\left[x(t+\Delta t) + x(t)\right] - \frac{\lambda_i\,\Delta t}{2}\left[C_i(t+\Delta t) + C_i(t)\right] \tag{12b}$$

where $\alpha(t) \equiv (k_e(t)(1-\beta) - 1)/\ell$.

Equations of the form of 12b are solved for $C_i(t+\Delta t)$ for each value of i:

$$C_i(t+\Delta t) = C_i(t)\,\frac{1-\lambda_i\Delta t/2}{1+\lambda_i\Delta t/2} + \frac{\gamma_i\Delta t/2}{1+\lambda_i\Delta t/2}\left[x(t+\Delta t) + x(t)\right] \tag{13b}$$

and the result substituted into 12a to obtain

$$x(t+\Delta t) = \frac{x(t)\left[1 + \frac{\alpha(t)\Delta t}{2} + \sum_i \frac{(\lambda_i\Delta t/2)(\gamma_i\Delta t/2)}{1+\lambda_i\Delta t/2}\right] + 2\sum_i C_i(t)\,\frac{\lambda_i\Delta t/2}{1+\lambda_i\,\Delta t/2}}{1 - \frac{\alpha(t+\Delta t)\,\Delta t}{2} - \sum_i \frac{(\lambda_i\,\Delta t/2)(\gamma_i\,\Delta t/2)}{1+\lambda_i\,\Delta t/2}} \tag{13a}$$

[This technique is a modification of one described by Fox and Goodwin.[2]] The inverse period $\alpha(t + \Delta t)$ is, of course, unknown, since the temperatures depend upon the integrated power. A procedure quite similar to the above is used to derive recursion relations for the temperatures. The integrals of the heat transfer from graphite to fuel were evaluated by means of the trapezoidal rule with the interval of integration being $n\Delta t$ (with n = an integer); this interval was used since the temperature variation is usually considerably slower than the power variation during a power transient. Equations (1) were thus transformed into the pair

$$T_f(z + nu\Delta t,\ t + n\Delta t) - a_f\, T_g(z + nu\Delta t,\ t + n\Delta t) = [Q_f + z_f T_g(z,t) + (1 - z_f)\, T_f\,(z,\ t)]/(1 + z_f) \tag{14a}$$

$$- a_g T_f(z + nu\Delta t,\ t + n\Delta t) + T_g(z + nu\Delta t,\ t + n\Delta t) = [Q_g + z_g\, T_f(z + nu\Delta t,\ t) + (1 - z_g)\, T_g(z + nu\Delta t,\ t)]/(1 + z_g) \tag{14b}$$

where $z_\ell \equiv \frac{hLH}{S_\ell}\frac{n\Delta t}{2}, \quad \ell = f,g$

$$a_\ell = z_\ell/(1 + z_\ell),\ \ell = f,\ g.$$

If R_f and R_g are used to denote the right-hand sides of 14a and 14b, respectively, the solution to the pair of equations 14 may be written as

$$T_f(z + nu\Delta t,\ t + n\Delta t) = (R_f - a_f\, R_g)/(1 - a_f\, a_g) \tag{15a}$$

$$T_g(z + nu\Delta t,\ t + n\Delta t) = (R_g - a_g\, R_f)/(1 - a_f\, a_g)\ . \tag{15b}$$

The calculational procedure used in ZORCH is the following:

1. Temperature profiles and average temperatures are calculated for an initial, steady-state condition.
2. Values of the average temperatures are estimated for time $t + n\Delta t$ by linear extrapolation of the values at $t - n\Delta t$

and t. (If t = o, the slope is taken as o.) The reactivity effect of the change in temperatures is taken to be a linear ramp over the interval t to $t + n\Delta t$.

3. Equations 13a and 13b are used to compute values of $x(t + k\Delta t)$, $k = 1, 2, \ldots, n$, using the computed linear reactivity ramp; trapezoidal rule approximations to the integrals involving $x(t + \tau)$ in equations 7a and 7b are also computed.

4. Equations 15a and 16b are used to generate new temperature profiles; trapezoidal rule approximations to the integrals in equation 11 are also computed, to allow computation of new average temperatures.

5. New ramp reactivity rates are computed, using the new average temperatures from step 4.

6. Steps 3 and 4 are repeated.

7. Advance to next time step ($n\Delta t$) and return to step 2.

The process of temperature calculation is indicated in Fig. 1b. Temperatures $\bar{T}(t - n\Delta t)$ and $\bar{T}(t)$ are used to calculate the slope of line ℓ_1 and temperature $\bar{T}^{(o)}$ for the fuel and graphite; this information is converted into an equivalent ramp reactivity insertion. A power calculation is done at times $t + \Delta t$, $t + 2\Delta t$, ..., $t + n\Delta t$, producing estimates of the heat source terms. The temperature equations are then solved and the averages computed to obtain $\bar{T}^{(1)}$ for the fuel and graphite. $\bar{T}^{(1)}$ and $\bar{T}(t)$ now are used to calculate the slope of line ℓ_2, which is converted to an equivalent ramp. A new power calculation is done at times $t + \Delta t$, $t + 2\Delta t$, ..., $t + n\Delta t$ to obtain new estimates of the heat source terms. The temperature equations are then solved again and the averages $\bar{T}^{(2)}$ for fuel and graphite computed; the process is then repeated for the next time step.

USE OF THE PROGRAM

The basic unit of time in the program is the power time step Δt. As described previously, the fuel and graphite temperatures are calculated at time steps $n\Delta t$ in length, where n is an input number, and the space mesh is obtained by dividing the length of the reactor into M intervals, where M is the largest integer not greater than

$$t_c/n\Delta t.$$

The present version of the program is limited to 250 space intervals, so n should be chosen large enough to ensure that this limit is not exceeded. The size of the power time step must be small enough to prevent the denominator in equation 13a from becoming negative and thus will depend upon the neutron lifetime ℓ and the maximum positive reactivity insertion ρ_M. A useful rule is

$$\Delta t \lesssim \frac{\ell}{2\rho_M} .$$

Some relaxation of this rule may be permitted, since reactivity compensation due to increased temperature always increases the minimum value of period observed during a transient.

Standard input forms are shown in Figs. 2a and 2b. As in the case with MURGATRØYD,[1] the first form contains input describing the reactor system and the second contains input for a particular case. Any number of cases using the same basic system may be run in succession by filling out the first form once and adding a second form for each case. The input reactivity variation is given as an initial step and ramp rate, folfowed by up to 50 ramp rates. Inlet temperature variation is given as an initial value, followed by up to 50 pairs of numbers indicating a time and the value of the inlet temperature at that time. A linear variation of inlet temperature is assumed between the specified times. The symbols used on the input forms are defined in Tables 2 and 3.

Table 2. ZØRCH Input 1

Card		
1	Title card - any 72 characters to describe a series of cases	
Card	**Symbol**	**Meaning**
2	V_c	Volume of fuel salt in core, ft^3
	t_c	Core residence time, sec
	v_f	Fuel volume fraction
	H	Product of heat transfer coefficient by wetted area, megawatts/^oF
	f	Fraction of power generated in fuel salt
	S_f	Fuel heat capacity, megawatt sec/^oF
	S_g	Graphite heat capacity, megawatt sec/^oF
3	$\lvert \partial k_e/\partial T_f \rvert$	Magnitude of fuel temperature coefficient, $(^oF)^{-1}$
	$\lvert \partial k_e/\partial T_g \rvert$	Magnitude of graphite temperature coefficient, $(^oF)^{-1}$
	ℓ	Prompt neutron lifetime, sec
	F_R	Radial peak to average ratio
	BESL	Radial weighting factor for average temperature calculation
	ρ	Fuel salt density, lb/ft^3
	$\left\lvert \frac{1}{\rho} \frac{\partial \rho}{\partial T_f} \right\rvert$	Fuel salt coefficient of expansion, $(^oF)^{-1}$
	λ_1 thru λ_7	Delayed neutron precursor decay constants, sec^{-1}
5	β_1 thru β_7	Delayed neutron precursor static yields
6	t_L	External loop residence time, sec

Table 2 - cont'd

Card	Symbol	Meaning
	A	Outlet pipe cross section, ft^2
	L	Outlet pipe length, ft
	U_o	Steady-state speed of fluid in outlet pipe, ft/sec
	a_f	Friction term, $psi/(ft/sec)^2$
7	$V_p(o)$	Initial gas space volume in pump bowl, ft^3
	$P_p(o)$	Initial pressure in gas space, psi
	n	Ratio of specific heats for gas in gas space

Table 3. ZØRCH Input 2

Card	Symbol	Meaning
1	Case No.	Any six-digit number
	Title	Any 66 characters to describe a particular case
2	P_o	Initial power, watts
	T_{io}	Initial inlet temperature, ^oF
	STØP TIME	Time to end calculation, sec
	STEP Δk	Initial step, per cent
	RAMP	Initial ramp, per cent per sec
	Δt	Power time step, sec
	NPØ	Print out frequency for power calculation
	KCAL	Plotting frequency for CALCØMP plotter. Temperature profiles are plotted at t = o and every KCAL temperature time steps thereafter; if KCAL = o, no plots are done.
3	NPPT	Power time steps per temperature time step
	KPLØ	Printer plot frequency (if o, no plot)
	NRTC	Number of additional ramp rates
	NTIC	Number of additional inlet temperatures

The following card or cards need be supplied only if NRTC $\neq$ o:

Time, sec	Time to change ramp rate	3 pairs/card
New ramp, %/sec	New ramp rate	up to 50 pairs

The following cards need be supplied only if NTIC $\neq$ o:

Time, sec	Time at which inlet temperature has new value
NEW INLET	Value of inlet temperature (in ^oF) at time specified

These are also given 3 pairs to a card, and up to 50 pairs may be specified.

OUTPUT

Output for the test case (input given in Figs. 2a and 2b) is shown in Figs. 3a, b, c, and d. The input describing the reactor system is printed (Fig. 3a), followed by the input for each case (Fig. 3a) with an output of the reactor power, pressure and inverse period (Fig. 3b), similar to that given by MURGATRØYD.[1] The temperature profiles initially and at each temperature time step are printed next (Fig. 3c) and the last item (Fig. 3d) is a rough plot of power vs time, available if desired. An additional option is provided so that the initial fuel and graphite temperature and the fuel and graphite temperature at specified temperature time steps may be plotted using the Calcomp digited plotter. A sample graph for the test case is shown in Fig. 4.

DETAILS OF MACHINE OPERATION

ZØRCH is designed to be run under control of the 7090 Monitor program now in use at the K-25 Data Processing Facility. In addition to the standard input and output tape, three pool tapes must be specified as shown in Table 4.

Table 4. Magnetic Tape Use in ZØRCH

Tape Number	Use	Unit Assignment	Density
5	Storage of power vs time for printer plot	any	high
7	Storage of temperature profiles for printing and plotting	any	high
6	Input to Calcomp plotter	A6	low
Tape card format:	*TAPE (5, PØØL)(7, PØØL)(6, PØØL, SAVE)		

A sample sequence card (Form UCN-2657) and request for Calcomp service (Form UCN-3632) are shown in Fig. 5. The number of plots to be entered on the Calcomp request is the total number of graphs expected.

This number is given by the sum of the number of graphs for each case:

$$1 + \frac{\text{STOP TIME}}{(\text{KCAL})(\text{NPPT})(\Delta t)} \qquad \text{if KCAL} > 0;$$

$$0 \qquad \text{if KCAL} = 0.$$

The maximum number of graphs which the Calcomp tape will accommodate is 49.

REFERENCES

1. C. W. Nestor, Jr., MURGATRØYD - An IBM 7090 Program for the Analysis of the Kinetics of the MSRE, ORNL-TM-203, April 6, 1962, and Addendum, May 25, 1962.

2. L. Fox and E. T. Goodwin, Proc. Cambridge Phil. Soc., 45, 373 (1949).

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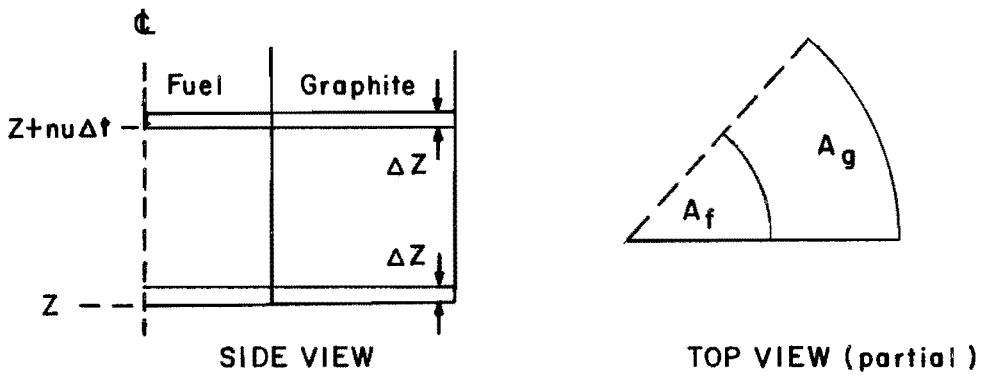

Fig.1a: Model of Fuel Channel

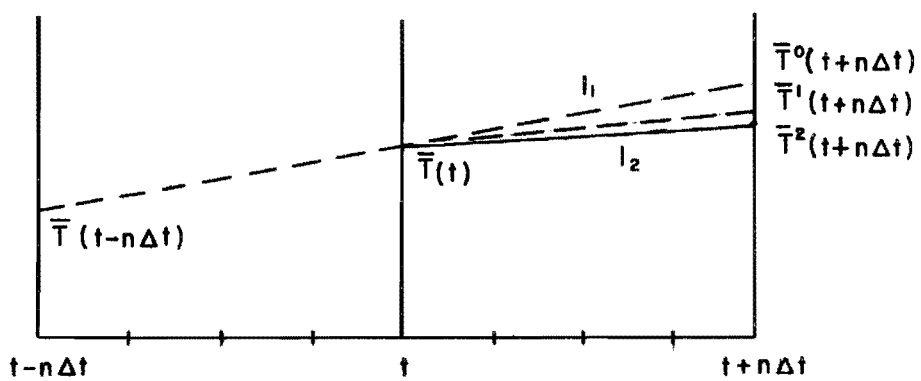

Fig.1b: Calculational Proceedure

Fig. 2a

ZORCH INPUT I

KEYPUNCHING INSTRUCTIONS
Punch all cards

Request No. 2531

1	TITLE FOR SERIES OF CASES	73 80
	MSRE WITH FULLY-ENRICHED FUEL, NO THORIUM	

CORE DATA

1	11	21	31	41	51	61	71	73 80
V_c	t_c	ν_f	h	f	S_f	S_g		
23.5	8.79	.225	.02	.94	1.47	3.53		
$\lvert \partial k_e/\partial T_f \rvert$	$\lvert \partial k_e/\partial T_g \rvert$	ℓ	F_R	BESL	ρ	$\left\lvert \frac{1}{\rho}\frac{\partial \rho}{\partial T_f} \right\rvert$		
3.68 -5	8.43 -5	4.78 -4	1.93	.7235	143.3	1.26 -4		

DELAYED NEUTRON DATA

1	11	21	31	41	51	61	71	73 80
λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7		
.0124	.0305	.1114	.3013	1.14	3.01			
β_1	β_2	β_3	β_4	β_5	β_6	β_7		
2.112 -4	1.402 -3	1.254 -3	2.528 -3	7.4 -4	2.7 -4			

EXTERNAL LOOP DATA

1	11	21	31	41	51	73 80
t_L	A	L	U_o	a_f		
17.03	.139	16.0	19.3	.0203		

PUMP BOWL DATA

1	11	21	31	73 80
$V_p(0)$	$P_p(0)$	n		
2.5	5.0	1.67		

KEYPUNCHING INSTRUCTIONS
Punch all cards having data in columns 73-80

Fig 2b
ZORCH INPUT-2

Request No. 2531

CASE NO. (1)	CASE TITLE (7)	(73-80)
11	PER CENT STEP NO ROD ACTION	TITLE

P_o (1)	T_{io} (11)	STOP TIME (21)	STEP $\Delta\kappa$ (31)	RAMP (41)	Δt (51)	NPO (61)	K CAL (66)	(73-80)
1.0 +7	1175.0	3.0	1.0		0.005	20	2	INITIAL

NPPT (1)	KPLO (6)	NRTC (11)	NTIC (16)	(21)	(73-80)
20	20				CONTROL

TIME, sec. (1)	NEW RAMP, %/sec. (11)	TIME, sec. (21)	NEW RAMP, %/sec. (31)	TIME, sec. (41)	NEW RAMP, %/sec (51)		(73-80)

TIME, Sec (1)	NEW INLET (11)	TIME, Sec. (21)	NEW INLET (31)	TIME, Sec. (41)	NEW INLET (51)		(73-80)

PROGRAM ZORRO

MSRE WITH FULLY-ENRICHED FUEL, NO THORIUM

INPUT EDIT

HEAT TRANSFER RATE (GRAPHITE TO FUEL)	[illegible].020	MW/DEG F
FRACTION POWER GENERATED IN FUEL	[illegible].940	
RADIAL PEAK-TO-AVERAGE POWER RATIO	1.930	
RADIAL WEIGHTING FACTOR FOR NAT	[illegible].723	
PROMPT NEUTRON LIFETIME	4.7[illegible]E-04	SECONDS
HEAT CAPACITIES		
FUEL	1.47	MW*SEC/DEG F
GRAPHITE	3.53	MW*SEC/DEG F
TEMPERATURE COEFFICIENTS (DK/K)		
FUEL	[illegible].6[illegible]E-05	PER DEGREE F
GRAPHITE	[illegible].43E-05	PER DEGREE F
CORE RESIDENCE TIME	[illegible].7[illegible]	SECONDS
LOOP RESIDENCE TIME	17.0[illegible]	SECONDS

DELAYED NEUTRON DATA

DELAY GROUP	LAMBDA, SEC**-1	STATIC BETA	EFFECTIVE BETA
1	.[illegible]4	2.112E-[illegible]	7.2[illegible]E-[illegible]
2	[illegible].5[illegible]5	1.402E-[illegible]	4.[illegible]E- 4
3	.1114	1.254E-[illegible]	5.33[illegible]E- 4
4	.3[illegible]13	2.52[illegible]E-[illegible]	1.[illegible]E- 3
5	1.14[illegible]	7.40[illegible]E-[illegible]	[illegible]E- 4
6	[illegible]	2.7[illegible]E-[illegible]	2.5[illegible]E- 4
TOTAL		[illegible].405E-[illegible]	[illegible]E- 3

DATA FOR PRESSURE CALCULATION

OUTLET PIPE DATA				PUMP BOWL DATA			CORE SALT DATA		
AREA, SQ FT	LENGTH, FT	FLOW SPEED, FT/SEC	FRICTION TERM, PSI/(FT/SEC)**2	GAS VOLUME, CUBIC FT	PRESSURE, PSI	CP/CV	VOLUME, CU FT	DENSITY, LB/CU FT	-(1/V)(DV/DT), PER DEG F
0.139	16.[illegible]	19.	0.[illegible]	2.5	5.[illegible]	1.67	23.5	143.3	1.2[illegible]E-04

Fig. 3a. Edit of Input Describing Reactor System

ZORCH

CASE 1 1 PER CENT STEP NO ROD ACTION

INITIAL CONDITIONS

POWER	1.00E 07	WATTS
TEMPERATURES		
INLET	1 72. 00	DEG F
NUCLEAR AVERAGE		
FUEL	1 15.748	DEG F
GRAPHITE	1 72.002	DEG F
STEP INSERTION	1.00	PER CENT
RAMP RATE	-1.	PER CENT PER SECOND
TIME STEPS		
POWER	5.00E-03	SECONDS
TEMPERATURE	1.00E-02	SECONDS

PRINT EVERY 20 STEPS

Fig. 3a (cont'd). Edit of Input for One Case

TIME, SEC	POWER, WATTS	PRESSURE, PSI	LOGN PI/DT, PER SEC
0.100	5.337E 07	8.832E 00	1.471E 01
0.200	2.1[illegible]2E 08	3.077E 01	1.310E 01
0.300	6.591E 08	1.476E 02	1.043E 01

VALUES AT PRESSURE MAXIMUM

TIME,SEC	PRESSURE RISE,PSI
0.295	1.3745E 3
0.300	1.4761E [illegible]
0.305	1.4732E [illegible]

VALUES AT PRESSURE MINIMUM

TIME,SEC	PRESSURE RISE,PSI
0.300	1.4761E [illegible]
0.305	1.4732E [illegible]
0.310	1.5510E [illegible]

0.400	1.192E 09	3.[illegible]96E 02	3.66[illegible]E 00

VALUES AT POWER MAXIMUM

TIME,SEC	POWER, WATTS	LOGN PI/DT
0.395	1.1705E 09	
		3.6692E 00
0.400	1.1921E 09	
		-1.4723E 00
0.405	1.1[illegible]33E 09	

0.500	8.336E 08	1.240E 02	-5.612E 00
0.600	2.9[illegible]1E 08	1.165E 01	-1.015E 01
0.700	1.[illegible]94E 08	3.[illegible]09E 00	-7.291E 00
0.800	6.558E 07	3.[illegible]04E 00	-3.139E 00
0.900	5.297E 07	3.[illegible]02E 00	-1.431E 00
1.000	4.654E 07	3.[illegible]43E 00	-9.417E-01
1.100	4.295E 07	2.[illegible]14E 00	-7.659E-01
1.200	3.955E 07	2.[illegible]26E 00	-6.639E-01
1.300	3.753E 07	2.473E 00	-5.844E-01
1.400	3.556E 07	2.348E 00	-5.152E-01
1.500	3.343E 07	2.246E 00	-4.559E-01
1.600	3.2[illegible]E 07	2.162E 00	-4.015E-01

Fig. 3b. Power, Pressure, and Inverse Period Output

ZORCH CASE

TIME, SEC	POWER, WATTS	PRESSURE, PSI	D(LN P)/DT, PER SEC
1.700	3.158E 07	2.095E 00	-3.523E-01
1.800	3.061E 07	2.040E 00	-3.070E-01
1.900	2.990E 07	1.997E 00	-2.649E-01
2.000	2.934E 07	1.965E 00	-2.254E-01
2.100	2.891E 07	1.942E 00	-1.880E-01
2.200	2.862E 07	1.927E 00	-1.520E-01
2.300	2.844E 07	1.921E 00	-1.173E-01
2.400	2.838E 07	1.922E 00	-8.351E-02
2.500	2.842E 07	1.931E 00	-5.038E-02
2.600	2.857E 07	1.948E 00	-1.768E-02
2.700	2.883E 07	1.972E 00	1.470E-02
2.800	2.919E 07	2.005E 00	4.689E-02
2.900	2.966E 07	2.045E 00	7.896E-02
3.000	3.024E 07	2.094E 00	1.110E-01

Fig. 3b. (cont'd)

ZORCH CASE 1 1 PER CENT STEP NO ROD ACTION

TIME,SEC	0.	0.100	0.200	0.300	0.400
POWER,WATTS	1.000E 07	5.037E 07	2.102E 08	6.591E 08	1.192E 09

Z/H	FUEL	GRAPHITE								
0.	1175.000	1175.000	1175.000	1175.000	1175.000	1175.000	1175.000	1175.000	1175.000	1175.000
0.011	1175.037	1178.287	1175.120	1178.290	1175.492	1178.309	1176.644	1178.382	1178.557	1178.554
0.023	1175.147	1181.643	1175.349	1181.649	1176.417	1181.689	1179.905	1181.834	1186.679	1182.179
0.034	1175.331	1185.064	1175.653	1185.074	1177.449	1185.133	1183.594	1185.351	1196.403	1185.869
0.046	1175.589	1188.547	1176.025	1188.559	1178.551	1188.638	1187.380	1188.928	1200.534	1189.620
0.057	1175.919	1192.085	1176.472	1192.101	1179.723	1192.199	1191.224	1192.561	1216.732	1193.425
0.068	1176.322	1195.676	1176.991	1195.695	1180.962	1195.812	1195.121	1196.246	1220.951	1197.281
0.080	1176.796	1199.314	1177.580	1199.336	1182.268	1199.472	1199.067	1199.977	1237.177	1201.181
0.091	1177.343	1202.994	1178.241	1203.019	1183.637	1203.175	1203.055	1203.750	1247.397	1205.122
0.102	1177.960	1206.713	1178.971	1206.741	1185.070	1206.915	1207.081	1207.560	1257.599	1209.099
0.114	1178.646	1210.464	1179.769	1210.495	1186.563	1210.689	1211.139	1211.402	1267.769	1213.105
0.125	1179.402	1214.244	1180.635	1214.278	1188.115	1214.490	1215.225	1215.272	1277.894	1217.137
0.137	1180.226	1218.048	1181.568	1218.085	1189.724	1218.315	1219.334	1219.163	1287.961	1221.188
0.148	1181.117	1221.870	1182.566	1221.910	1191.389	1222.158	1223.460	1223.072	1297.958	1225.254
0.159	1182.074	1225.707	1183.628	1225.749	1193.105	1226.014	1227.597	1226.993	1307.871	1229.330
0.171	1183.096	1229.552	1184.752	1229.597	1194.873	1229.879	1231.741	1230.922	1317.689	1233.409
0.182	1184.180	1233.401	1185.936	1233.449	1196.688	1233.748	1235.886	1234.852	1327.398	1237.488
0.193	1185.327	1237.249	1187.184	1237.300	1198.550	1237.615	1240.027	1238.780	1336.966	1241.561
0.205	1186.535	1241.092	1188.488	1241.145	1200.456	1241.476	1244.159	1242.701	1346.440	1245.623
0.216	1187.801	1244.923	1189.845	1244.979	1202.402	1245.326	1248.276	1246.608	1355.750	1249.668
0.228	1189.125	1248.739	1191.253	1248.798	1204.387	1249.160	1252.373	1250.498	1364.902	1253.691
0.239	1190.504	1252.535	1192.731	1252.596	1206.409	1252.972	1256.445	1254.365	1373.866	1257.688
0.250	1191.937	1256.305	1194.256	1256.368	1208.464	1256.759	1260.487	1258.204	1382.689	1261.652
0.262	1193.423	1260.046	1195.815	1260.111	1210.550	1260.515	1264.493	1262.011	1391.360	1265.580
0.273	1194.956	1263.751	1197.433	1263.818	1212.664	1264.236	1268.459	1265.780	1399.769	1269.466

Fig. 3c. Sample Temperature Profile Output

ZIRCH CASE 1 1 PER CENT STEP NO ROD ACTION

TIME,SEC	0.	0.100	0.200	0.300	0.400
POWER,WATTS	1.070E 07	5.537E 07	2.102E 08	6.591E 08	1.192E 09

	FUEL	GRAPHITE								
NUCLEAR AVERAGE	1216.746	1272.602	1216.776	1272.657	1231.352	1272.996	1277.683	1274.250	1387.651	1277.245

Fig. 3c. (cont'd). Nuclear Average Temperature Output

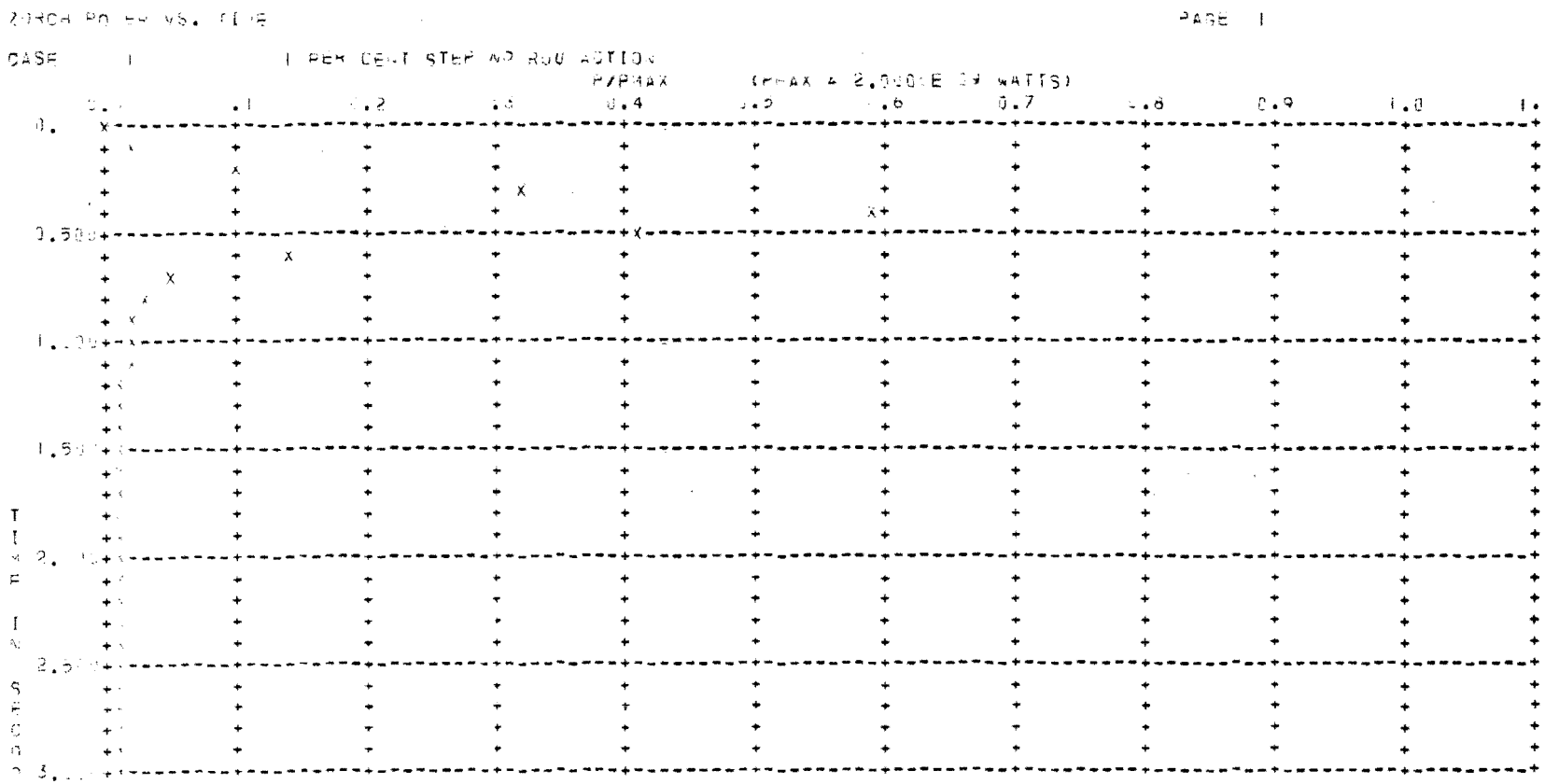

Fig. 3d. Rough Plot of Power vs. Time

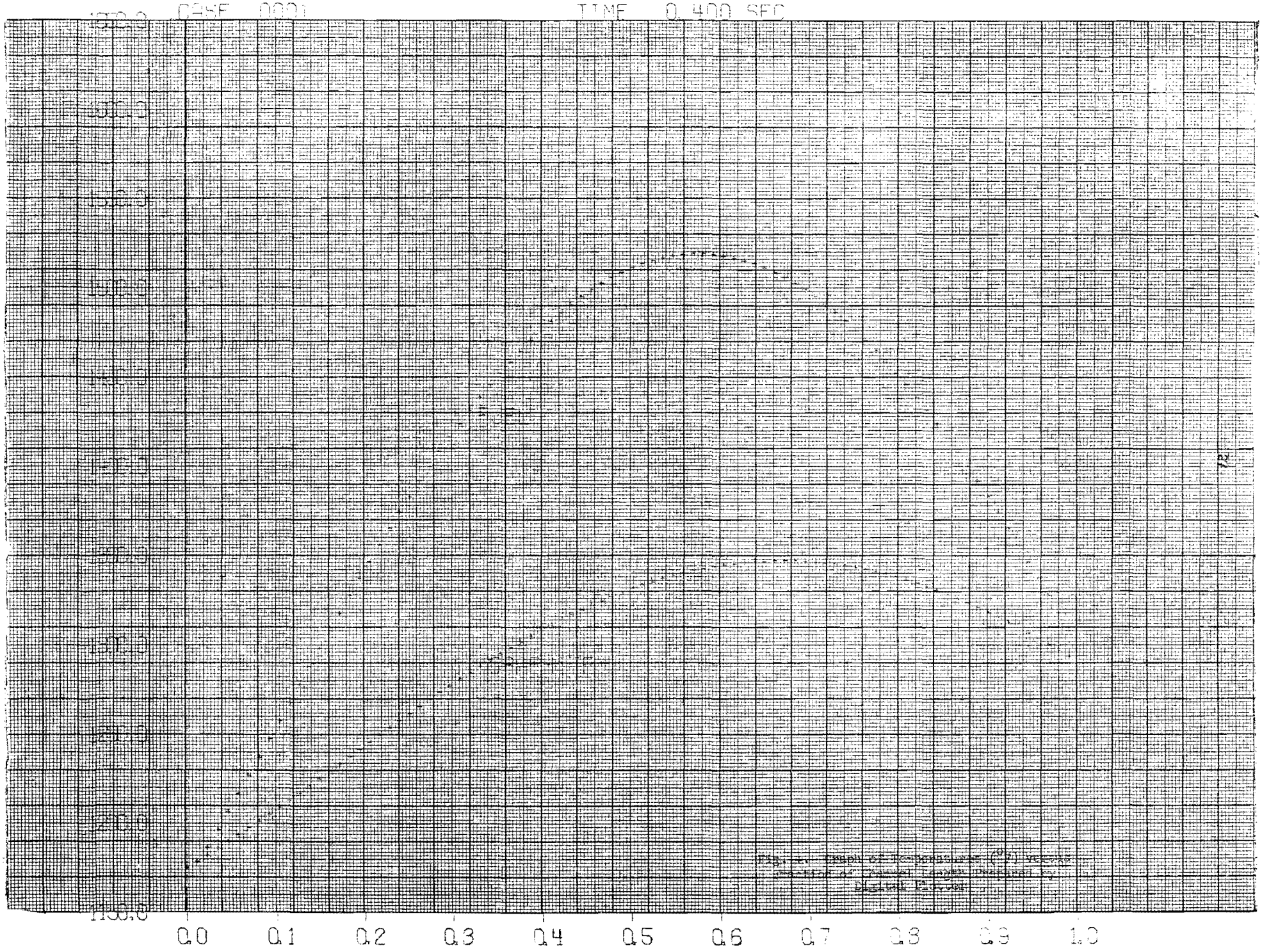

Fig. [illegible] Graph of Temperatures (°F) versus Fraction of Channel Length Prepared by Digital Plotter

7090 SEQUENCE CARD

☐ COMPATIBILITY	☒ ABSOLUTE TAPE ASSIGNMENT	DATE
NAME	REQUEST NO.	SEQUENCE NO.
☐ COMPILE ☐ ASSEMBLE	☒ EXECUTE	RUN NO.
SIZE PAPER 14 x 11 / NO. PARTS 1	RIGHT PERFORATION ON COLUMN	ESTIMATED RUN TIME

CHANNEL A

LOG NO.	REEL NO.	ASSIGN NO.	SAVED TAPE NO.	✓ SAVE	✓ LIST	✓ PNCH	✓ PLOT	DEN	COMMENTS
5	POOL								
7	POOL								
6	POOL	6		✓				LO	Send to X-10 for plotting

CHANNEL B

LOG NO.	REEL NO.	ASSIGN NO.	SAVED TAPE NO.	✓ SAVE	✓ LIST	✓ PNCH	✓ PLOT	DEN	COMMENTS

OPERATOR | STOP LOCATION | ☐ PULLED ON TIME

UCN-2657
(1 1-61)

CALCOMP WORK REQUEST

IN			OUT
	NAME	REQUEST NO.	
	BUILDING NUMBER		
	REEL NUMBER	NUMBER PLOTS	
	INK COLOR	PAPER TYPE 03	
	REEL of		
	WORK DONE BY		

UCN-3632
(3 6-62)

Fig. 5. Sample Sequence Card and Calcomp Service Request.

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66. M. J. Kelley
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