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MURGATROYD - AN IBM 7090 PROGRAM FOR THE ANALYSIS OF THE KINETICS OF THE MSRE

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ABSTRACT

The IBM 7090 program MURGATROYD is a revised and extended version of the IBM 704 program PET-I, which solves (by a fifth-order Runge-Kutta procedure) the coupled first-order differential equations for power, delayed neutron concentration and temperature in a one-region reactor as a function of time, given an input reactivity variation represented by a series of linear ramps. The basic extensions were those which were necessary to include the effects of the separate heat capacities and temperature coefficients of the fuel salt and graphite in the MSRE, and of heat transfer between the fuel and graphite. In addition, the input and output sections of the previous program were modified to facilitate the use of the program in extensive parameter studies, and a calculation of the pressure rise in the core was included. Typical running times are of the order of 12 milliseconds per time step; a calculation of a 30-second power history using a 10 millisecond time step requires about 36 seconds of machine time.

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MURGATROYD - AN IBM 7090 PROGRAM FOR THE ANALYSIS OF
THE KINETICS OF THE MSRE

I. Introduction

This report is a description of an IBM 7090 program based on a particular model of the Molten Salt Reactor Experiment. The differential equations of motion are discussed in Section II; since much of the derivation has appeared elsewhere,¹ only the additional derivations necessary in the present problem are included. The fifth-order Runge-Kutta procedure is a standard one which can be found in many numerical analysis textbooks.² Its previous successful use in the 704 program PET³ indicated applicability to the present problem and no revision has as yet been found either desirable or necessary. The use of the program is discussed in Section III, with instructions for the preparation of input data; sample input forms and output sheets are included.

II. Differential Equations of Motion

A. Power, Fuel and Graphite Temperatures

The reactor model used as the basis of the program is a one-point, one-energy group representation, with up to seven delayed neutron precursors, which is described by the following set of differential equations: (all symbols are defined in the Nomenclature; a dot over a symbol denotes time derivative)

$$\dot{P} = \frac{k_e(1-\beta)-1}{\ell} P + \sum_{i=1}^N \lambda_i \Gamma_i \quad (1)$$

$$\dot{\Gamma}_i = \frac{\beta_i P}{\ell} - \lambda_i \Gamma_i, \quad i = 1, N \quad (2)$$

The effective multiplication constant k_e is assumed to be of the form

$$k_e = 1 + \Delta + bt - \left| \frac{\partial k_e}{\partial T_f} \right| (T_f - T_{fo}) - \left| \frac{\partial k_e}{\partial T_g} \right| (T_g - T_{go}). \quad (3)$$

(The subscript zero denotes the steady state value.)

$$S_f \dot{T}_f = fP - WC_P(T_2 - T_1) + h(T_g - T_f) \quad (4)$$

$$S_g \dot{T}_g = (1-f)P - h(T_g - T_f) \quad (5)$$

It is now necessary to specify some connection between the mean fuel temperature T_f , the inlet temperature T_1 and the outlet temperature T_2 . The assumption is made that the mean fuel temperature is a weighted mean of the inlet and outlet; i.e., that

$$T_f = aT_1 + (1-a)T_2 \quad ; \quad (6)$$

the weight $a(0 < a < 1)$ is an input number in the 7090 program. Further it is assumed that the inlet temperature T_1 is a constant. With the definitions

$$y_f \equiv \frac{S_f(T_f - T_{fo})}{fP_o} \quad (7)$$

$$y_g \equiv \frac{S_g(T_g - T_{go})}{(1-f)P_o} \quad (8)$$

and the initial condition

$$h(T_{go} - T_{fo}) = (1-f)P_o \quad (9)$$

the following equations may be obtained

$$fP_o \dot{y}_f = f(P - P_o) - \frac{fP_o}{S_f} y_f \left(\frac{WC_P}{1-a} + h \right) + \frac{h(1-f)P_o}{S_g} y_g \quad (10)$$

$$(1-f)P_o \dot{y}_g = (1-f)(P - P_o) - \frac{h(1-f)P_o}{S_g} y_g + \frac{hfP_o}{S_f} y_f \quad (11)$$

which, with the definition

$$x \equiv P/P_o \quad (12)$$

may be further transformed to obtain the equations used in Murgatroyd:

$$\dot{y}_f = x-1 - \left[\frac{1}{(1-a)t_c} + \frac{h}{S_f} \right] y_f + \frac{h}{S_g} \frac{1-f}{f} y_g \quad (13)$$

$$\dot{y}_g = x-1 - \frac{h}{S_g} y_g + \frac{h}{S_f} \frac{f}{1-f} y_f \quad (14)$$

Similarly equations 1 thru 6 may be transformed with the definitions

$$C_i \equiv \Gamma_i/P_o$$

$$\text{and } \gamma_i \equiv \beta_i/\ell$$

to

$$\dot{x} = \frac{k_e(1-\beta) - 1}{\ell} x + \sum_{i=1}^N \lambda_i C_i \quad (15)$$

$$\dot{C}_i = \gamma_i x - \lambda_i C_i, \quad i = 1, N. \quad (16)$$

If the definitions of y_f and y_g , equations (7) and (8), are introduced into equation (3) the effective multiplication constant becomes

$$k_e = 1 + \Delta + bt - \left| \frac{\partial k_e}{\partial T_f} \right| \frac{fP_o}{S_f} y_f - \left| \frac{\partial k_e}{\partial T_g} \right| \frac{(1-f)P_o}{S_g} y_g; \quad (17)$$

with the definitions

$$W_f^2 \equiv \left| \frac{\partial k_e}{\partial T_f} \right| \frac{fP_o}{S_f \ell} \quad (18)$$

$$W_g^2 \equiv \left| \frac{\partial k_e}{\partial T_g} \right| \frac{(1-f)P_o}{S_g \ell} \quad (19)$$

[These are similar to the parameter W_N^2 in reference 1.]

the equation for the normalized power becomes

$$\dot{x} = \left[\frac{(1 + \delta + bt)(1 - \beta) - 1}{\ell} - (1 - \beta)(W_f^2 y_f + W_g^2 y_g) \right] x + \sum_{i=1}^N \lambda_i C_i \quad (20)$$

The differential equations actually used in the program are the set 20, 16, 13, and 14.

B. Pressure

The simplified model of the primary fuel salt system is shown in Fig. III. It is assumed that compression of the gas in the pump bowl is adiabatic, and that the behavior of the molten salt is adequately described by the linear equation of state

$$\rho(T_f) = \rho_o + \frac{\partial \rho}{\partial T_f} (T_f - T_{fo}) . \quad (21)$$

A force balance on the liquid in the outlet pipe yields the equation

$$\frac{M_r}{144 g_c} \dot{U} = A(p_c - p_p - a_f U^2) ; \quad (22)$$

in steady state

$$p_c(o) = p_p(o) + a_f U_o^2 . \quad (23)$$

The assumption that compression of the gas in the pump bowl is adiabatic can be stated as

$$p_p V_p^n = p_p(o) [V_p(o)]^n ; \quad (24)$$

if we assume that $V_p - V_p(o) \ll V_p(o)$ and neglect second order terms, we obtain

$$p_p = p_p(o) \left[1 - \frac{n \Delta V_p}{V_p(o)} \right] . \quad (25)$$

The change ΔV_p in the pump bowl gas space volume is now assumed to be equal to the change in volume of the core fuel salt due to the change in temperature of the core fuel salt during a transient; i.e., compression of the molten salt is neglected, as is heating of the external loop. The change in volume ΔV_c is expressed as

$$\begin{aligned} -\Delta V_p = \Delta V_c &= -v_c \frac{\Delta \rho}{\rho_o} \\ &\approx -v_c \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} (T_f - T_{fo}) \end{aligned}$$

and substituting in (25) we obtain

$$p_p = p_p(o) \left[1 + \frac{nV_c}{V_p(o)} \left| \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} \right| (T_f - T_{fo}) \right] . \quad (26)$$

Solving equation (22) for the core pressure we obtain

$$p_c = p_p + a_f U^2 + \frac{M_r}{144 g_c A} \dot{U} ;$$

subtracting equation (23), we obtain

$$\Delta p = p_c - p_c(o) = p_p - p_p(o) + a_f (U^2 - U_o^2) + \frac{M_r}{144 g_c A} \dot{U} ; \quad (27)$$

the term $p_p - p_p(o)$ is due to the compression of gas in the pump bowl, the term $a_f(U^2 - U_o^2)$ is due to the increase in friction losses, and the last term is the contribution from the inertia of the fluid in the outlet pipe.

In order to proceed, a relation between outlet velocity and fluid density change is needed. The equation of continuity for the fuel salt in the core is approximately

$$\dot{\rho} = - \frac{A}{V_c} \rho_o (U - U_o) ; \quad (28)$$

solving for the velocity U we obtain

$$U = U_o - \frac{V_c}{A} \frac{\dot{\rho}}{\rho_o}$$

and substituting the equation of state (21) we obtain

$$U = U_o - \frac{V_c}{A} \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} \dot{T}_f ; \quad (29)$$

and taking time derivatives

$$\dot{U} = - \frac{V_c}{A} \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} \ddot{T}_f . \quad (30)$$

We now substitute equations (29) and (30) into (27); after some re-arrangement we obtain

$$\Delta p = - \frac{V_c}{A} \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} \left[\frac{M_r}{144 g_c A} \ddot{T}_f + p_p(o) \frac{nA}{V_p(o)} (T_f - T_{fo}) \right. \\ \left. + 2 U_o a_f \dot{T}_f \left(1 - \frac{V_c}{2AU_o} \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} \dot{T}_f \right) \right] \quad (31)$$

With the definitions of y_f and x (equations 11 and 16) equation (31) is transformed into*

$$\Delta p = - \frac{V_c}{A} \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} \frac{fP_o}{S_f} \left[\frac{M_r}{144 g_c A} \dot{x} + p_p(o) \frac{nA}{V_p(o)} y_f \right. \\ \left. + 2U_o a_f \dot{y}_f \left(1 - \frac{V_c}{2AU_o} \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} \frac{fP_o}{S_f} \dot{y}_f \right) \right] \quad (32)$$

With the definitions

$$d_1 \equiv - \frac{V_c}{A} \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} \frac{M_r}{144 g_c A} \frac{fP_o}{S_f} \\ d_2 \equiv - p_p(o) \frac{nA}{V_p(o)} \frac{144 g_c A}{M_r} \\ \alpha_1 \equiv 2U_o a_f \frac{144 g_c A}{M_r}$$

and

$$d_3 \equiv - \frac{V_c}{2AU_o} \frac{1}{\rho_o} \frac{\partial \rho}{\partial T_f} \frac{fP_o}{S_f}$$

we obtain the equation used in the program:

$$sp = d_1 \left[\dot{x} + d_2 y_f + \alpha_1 \dot{y}_f (1 + d_3 \dot{y}_f) \right] \quad (33)$$

In terms of the dimensional groups of reference 1 and the parameter W_f^2 defined in equation (18), the constants, d_1 , d_2 , and d_3 may be written

* It is assumed that $\ddot{T}_f = f\dot{P}/S_f$.

$$\left. \begin{aligned}
 d_1 &= \frac{rW_f^2}{\gamma_2 W_H^2} \\
 d_2 &= W_H^2 C_2 \\
 d_3 &= W_f^2 / 2\gamma_3
 \end{aligned} \right\} \quad (34)$$

C. Effective Delayed Neutron Yields

In order to account for the reduction in delayed neutron production in the core due to fluid flow, an effective yield is calculated for each precursor, assuming constant flux and slug flow. The fraction v_i of delayed neutrons of the i th group which are released in the core is given by⁽⁴⁾

$$v_i = 1 - \frac{1 - e^{-\lambda_i t_c}}{\lambda_i t_c} \frac{1 - e^{-\lambda_i t_L}}{1 - e^{-\lambda_i (t_c + t_L)}} \quad (35)$$

where t_c is the core residence time, λ_i is the decay constant of the i th precursor and t_L is the external loop transit time.

III. Organization and Use of the Machine Program

The program is designed for use in parameter studies; therefore the calculation is separated into two parts, the first of which deals with the characteristics of the reactor which remain constant for a series of cases, and the second of which deals with the characteristics which change from case to case. Input forms are shown in Figures Ia and Ib; in the usual procedure the first form would be filled out once to describe the characteristics of the reactor, and a second form would be filled out to describe each set of initial conditions and ramp insertions. The input data symbols appearing on the input forms are listed in Tables 3 and 4, with their definitions, the names given them in the program, and the format with which they are read from the input tape.

The standard CDPF Monitor input (logical 10) and output (logical 9) tapes are used; no other tapes are required.

Output for a typical case is displayed in Figures IIa and IIb. Figure IIa is an edit of the input describing the reactor system, with the calculated effective delayed neutron yields; Figure IIb is the input for a particular case, and the continuations of Figure IIb show the time behavior of the reactor. The two columns headed

PCT DK REMOVED BY
FUEL GRAPHITE

show the percent reactivity removed from the system by the temperature rise of the fuel salt and graphite, respectively. The quantity labeled "(1/P)(DP/DT)" is calculated from the expression

$$\alpha = \frac{P(t) - P(t - \Delta t)}{\Delta t} \cdot \frac{2}{P(t) + P(t - \Delta t)}$$

and is therefore approximately the inverse period at $t - \Delta t/2$, where Δt is the input time step.

Since the frequency of printing is an input number, special provision has been made for indicating the first power maximum, the first pressure maximum and the subsequent pressure minimum. ("Maximum" and "minimum" are to be taken here in the mathematical sense of points of zero first derivative and negative or positive second derivative, respectively.) The values labeled "VALUES AT POWER MAXIMUM" are the values at the time t_3 when the power has first decreased, and the values at the two previous times, t_1 and t_2 , as shown in Table 1.

Table 1. Power Maximum Indication

Time	Power	(1/P)(DP/DT)
t_1	$P(t_1)$	
t_2	$P(t_2)$	$\alpha_{1,2}$
t_3	$P(t_3)$	$\alpha_{2,3}$

The criterion for printing is

$$P(t_1) < P(t_2) \geq P(t_3)$$

and the quantities $\alpha_{i,j}$ are

$$\alpha_{i,j} = \frac{P(t_j) - P(t_i)}{\Delta t} \cdot \frac{2}{P(t_j) + P(t_i)}$$

Similar remarks apply, mutatis mutandis, to the values labeled "VALUES AT PRESSURE MAXIMUM" and "VALUES AT PRESSURE MINIMUM."

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References

1. P. R. Kasten, Operational Safety of the Homogeneous Reactor Test, ORNL-2088, July 3, 1956.
2. R. G. Stanton, Numerical Methods for Science and Engineering, Prentice-Hall, Inc., 1961.
3. S. Jaye and M. P. Lietzke, Power Response Following Reactivity Additions to the HRT, ORNL CF-58-12-106, Dec. 30, 1958.
4. P. R. Kasten, Dynamics of the Homogeneous Reactor Test, ORNL-2072, June 7, 1956.

Table 2. Nomenclature

<u>Symbol</u>	<u>Definition</u>	<u>Equation</u>
A	area of outlet pipe, ft ²	22
a _f	friction factor, psi/(ft/sec) ²	22
b	initial ramp reactivity input	3
C _P	specific heat of fuel salt	4
f	fraction of power generated in fuel salt	4
g _c	conversion factor	22
h	product of heat transfer coefficient times wetted area of graphite	4
k _e	effective multiplication constant	1
l	prompt neutron lifetime	1
M _r	mass of fluid in outlet pipe, lb	22
n	ratio of specific heats (C _P /C _V) for pump bowl gas	24
P	power	1
p _c	core pressure, psi	22
p _p	pump bowl pressure, psi	22
p _c (o)	initial core pressure, psi	23
p _p (o)	initial pump bowl pressure, psi	23
S _f	fuel salt heat capacity	4
S _g	graphite heat capacity	5
T _f	fuel temperature	4
T _g	graphite temperature	4
t	time	3
t _c	core residence time	13
T ₁	fuel salt inlet temperature	4
T ₂	fuel salt outlet temperature	4

Table 2. - Cont'd

<u>Symbol</u>	<u>Definition</u>	<u>Equation</u>
U	outlet speed in pipe, ft/sec	22
$V_p(o)$	initial gas space volume in pump bowl, ft ³	24
W	mass flow rate of fuel through core	4
β	total delayed neutron yield	1
β_i	yield of ith delayed neutron precursor	2
Γ_i	latent power due to ith precursor	1
Δ	initial step reactivity input	3
ρ	fuel salt density	21

Table 3. Input for Description of Reactor System

<u>Title</u>	<u>Fortran Name</u>
1. Core characteristics	HØLM
V_c salt volume, ft ³	VC
t_c residence time, sec (if fuel is not circulating, enter zero)	TCØRE
a weighting factor for mean temperature	ATMX
h heat transferred from graphite to sale per unit temperature difference, Mw sec/ ^o F	HTRAN
f fraction of power generated in salt	FRACT
S_f fuel heat capacity, Mw sec/ ^o F	HCAPF
S_g graphite heat capacity, Mw sec/ ^o F	HCAPG
$\left \frac{\partial k_e}{\partial T_f} \right $ fuel temperature coefficient of reactivity, (^o F) ⁻¹	TCØF
$\left \frac{\partial k_e}{\partial T_g} \right $ graphite temperature coefficient of reactivity, (^o F) ⁻¹	TCØG
l prompt neutron lifetime, sec	FLT
ρ_o fuel density, lb/ft ³	DENSE
$\left (1/\rho)(\partial\rho/\partial T_f) \right $ fuel expansion coefficient, (^o F) ⁻¹	EXPCØ
λ_i delayed neutron precursor decay constants, sec ⁻¹	FLAM(I)
β_i delayed neutron precursor yields	BETAS(I)
2. External loop characteristics	
t_L residence time, sec (if fuel is not circulating, enter zero)	TLØØP
A outlet pipe area, ft ²	AREA
L outlet pipe length, ft	PLGTH
U_o steady state outlet velocity, ft/sec	VELØX
a_f friction factor, psi/(ft/sec ²)	AFR

Table 3. Cont'd

<u>Title</u>		<u>Fortran Name</u>
3. Pump bowl characteristics		
$V_p(o)$	initial gas volume, ft ³	VPRS
$p_p(o)$	initial pressure, psi	PPRS
N	ratio of specific heat at constant pressure to specific heat at constant volume for gas in pump bowl	CP ϕ CV

Title card is read with format 12AG; others with 7E10.0.

Table 4. Input for Individual Cases

		<u>Fortran name</u>	<u>Format</u>
Case number		ICASE	16, 11AC
Title		HØLC	
<u>Symbol</u>	<u>Definition</u>		
P_o	initial power, watts	PZERØ	6E10.0, 2I5
T_{fo}	initial fuel mean temperature, °F	TFO	
T_{go}	initial graphite mean temperature, °F	TGO	
$\Delta k(o)$	initial step insertion, %	STEP	
$b(o)$	initial ramp rate, %/sec	RATE	
δt	time step, sec	HH	
NPØ	printout frequency	NPØ	
KSTØP	number of time steps to be run after power peak	KSTØP	
STØP TIME	total time to run	YEND	E10.0, I5
NTC	number of ramp rate changes	NTC	
	time to change ramp rate, sec	TC	6E10.0
	new ramp rate, %/sec	BNEW	

MURGATROYD INPUT - 2

CASE NO.	7																																																																			CASE TITLE	73	80
P_0	T_{fo}	T_{go}	$\Delta k (0)$	b_0	δt	NPO	K STOP	73	80																																																													
STOP TIME, sec	NTC							73	80																																																													
TIME, sec.	NEW RAMP, %/sec.	TIME, sec.	NEW RAMP, %/sec.	TIME, sec.	NEW RAMP, %/sec.			73	80																																																													

FIG 1b. INPUT FOR ONE CASE

IIa.
FIG. 2. SAMPLE OUTPUT

PROGRAM MURGATROYD-II

MSRE NORMAL FLOW NO SOAK-UP 3/27/62

INPUT EDIT

HEAT TRANSFER RATE (GRAPHITE TO FUEL) 0.020 MW/DEG F

FRACTION OF POWER GENERATED IN FUEL 0.940

RESIDENCE TIMES

CORE 7.318 SEC
LOOP 17.334 SEC

HEAT CAPACITY, GRAPHITE FUEL
MW*SEC/DEG F 3.530E 00 1.470E 00

DK/DT, /DEG F 6.000E-05 2.800E-05

DELAYED NEUTRON DATA

DELAY GROUP	LAMBDA, SEC**-1	STATIC BETA	EFFECTIVE BETA	GAMMA(I), SEC**-1	INITIAL C(I)	**GAMMA#BETA/LIFETIME C # GAMMA/LAMBDA
1	0.0124	2.112E-04	5.294E-05	2.170E-01	1.750E 01	
2	0.0305	1.402E-03	4.258E-04	1.468E 00	4.813E 01	
3	0.1114	1.254E-03	4.706E-04	1.623E 00	1.457E 01	
4	0.3013	2.528E-03	1.513E-03	5.216E 00	1.731E 01	
5	1.1400	7.400E-04	6.513E-04	2.246E 00	1.970E 00	
6	3.0100	2.700E-04	2.577E-04	8.888E-01	2.953E-01	

TOTAL 6.405E-03 3.381E-03

NEUTRON LIFETIME 2.900E-04 SEC

FUEL TEMPERATURE # 0.50*INLET + 0.50*OUTLET

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	16.0	19.3	0.0203	2.5	5.0	1.67	19.6	154.5	1.26E-04	

Fig. II b.

CASE I

PROMPT CRITICAL STEP AT 10 MW

INITIAL VALUES

POWER	1.000E 07 WATTS
FUEL TEMP	1200.000 DEGREES F
GRAPHITE TEMP	1230.000 DEGREES F
STEP DELTA K	0.338 PERCENT
RAMP RATE	-0. PERCENT PER SECOND
TIME STEP	5.000E-03 SECONDS

PRINT EVERY 20 STEPS

Fig II b. (Cont.)

MURGATROYD II CASE I

TIME, SEC	POWER, WATTS	FUEL TEMP, DEG F	GRAPHITE TEMP, DEG F	PRESSURE RISE, PSI	DELTA K INPUT, PCT	PCT DK REMOVED BY		(1/P)(DP/DT), PER SECOND
						FUEL	GRAPHITE	
0.100	2.170E 07	1200,369	1230,010	7.677E-01	0.3381	0.0010	0.0001	5.468E 00
0.200	3.388E 07	1201,479	1230,041	9.016E-01	0.3381	0.0041	0.0002	3.687E 00
0.300	4.673E 07	1203,346	1230,093	1.040E 00	0.3381	0.0094	0.0006	2.811E 00
0.400	6.006E 07	1205,988	1230,170	1.159E 00	0.3381	0.0168	0.0010	2.233E 00
0.500	7.331E 07	1209,396	1230,270	1.235E 00	0.3381	0.0263	0.0016	1.769E 00

VALUES AT PRESSURE MAXIMUM

TIME, SEC	PRESSURE RISE, PSI							
0.560	1.2503E 00							
0.565	1.2504E 00							
0.570	1.2503E 00							
0.600	8.562E 07	1213,519	1230,395	1.246E 00	0.3381	0.0379	0.0024	1.350E 00
0.700	9.601E 07	1218,245	1230,541	1.184E 00	0.3381	0.0511	0.0032	9.576E-01
0.800	1.036E 08	1223,410	1230,706	1.058E 00	0.3381	0.0655	0.0042	5.926E-01
0.900	1.081E 08	1228,809	1230,883	8.922E-01	0.3381	0.0807	0.0053	2.677E-01

VALUES AT POWER MAXIMUM

TIME, SEC	POWER, WATTS	D(LN P)/DT						
0.990	1.0938E 08							
		4.6791E-05						
0.995	1.0938E 08							
		-1.3430E-05						
1.000	1.0938E 08							
1.000	1.094E 08	1234,234	1231,069	7.172E-01	0.3381	0.0959	0.0064	-2.685E-03
1.100	1.081E 08	1239,503	1231,257	5.594E-01	0.3381	0.1106	0.0075	-2.090E-01
1.200	1.050E 08	1244,483	1231,445	4.335E-01	0.3381	0.1246	0.0087	-3.492E-01
1.300	1.010E 08	1249,093	1231,629	3.420E-01	0.3381	0.1375	0.0098	-4.300E-01
1.400	9.653E 07	1253,301	1231,807	2.797E-01	0.3381	0.1492	0.0108	-4.634E-01
1.500	9.214E 07	1257,110	1231,981	2.384E-01	0.3381	0.1599	0.0119	-4.637E-01
1.600	8.805E 07	1260,544	1232,149	2.105E-01	0.3381	0.1695	0.0129	-4.440E-01
1.700	8.436E 07	1263,635	1232,313	1.903E-01	0.3381	0.1782	0.0139	-4.143E-01
1.800	8.108E 07	1266,420	1232,472	1.744E-01	0.3381	0.1860	0.0148	-3.812E-01
1.900	7.818E 07	1268,932	1232,627	1.607E-01	0.3381	0.1930	0.0158	-3.487E-01

Fig. II b (cont.)

MURGATROYD II CASE 1								
TIME, SEC	POWER, WATTS	FUEL TEMP, DEG F	GRAPHITE TEMP, DEG F	PRESSURE RISE, PSI	DELTA K INPUT, PCT	PCT OK REMOVED BY FUEL	PCT OK REMOVED BY GRAPHITE	(1/P)(DP/DT), PER SECOND
2.000	7.562E-07	1271.201	1232.779	1.483E-01	0.3381	0.1994	0.0167	-3.184E-01
2.100	7.336E-07	1273.255	1232.928	1.356E-01	0.3381	0.2051	0.0176	-2.911E-01
2.200	7.135E-07	1275.116	1233.074	1.256E-01	0.3381	0.2103	0.0184	-2.668E-01
2.300	6.955E-07	1276.805	1233.218	1.152E-01	0.3381	0.2151	0.0193	-2.452E-01
2.400	6.794E-07	1278.390	1233.360	1.053E-01	0.3381	0.2194	0.0202	-2.260E-01
2.500	6.648E-07	1279.734	1233.500	9.606E-02	0.3381	0.2233	0.0210	-2.088E-01
2.600	6.516E-07	1281.002	1233.638	8.737E-02	0.3381	0.2268	0.0218	-1.934E-01
2.700	6.396E-07	1282.155	1233.775	7.924E-02	0.3381	0.2300	0.0227	-1.795E-01
2.800	6.287E-07	1283.203	1233.911	7.164E-02	0.3381	0.2330	0.0235	-1.670E-01
2.900	6.187E-07	1284.156	1234.045	6.456E-02	0.3381	0.2356	0.0243	-1.555E-01
3.000	6.095E-07	1285.021	1234.176	5.798E-02	0.3381	0.2381	0.0251	-1.451E-01
3.100	6.010E-07	1285.806	1234.310	5.186E-02	0.3381	0.2403	0.0259	-1.356E-01
3.200	5.932E-07	1286.518	1234.440	4.616E-02	0.3381	0.2423	0.0266	-1.268E-01
3.300	5.859E-07	1287.163	1234.570	4.087E-02	0.3381	0.2441	0.0274	-1.188E-01
3.400	5.793E-07	1287.745	1234.699	3.597E-02	0.3381	0.2457	0.0282	-1.114E-01
3.500	5.730E-07	1288.271	1234.827	3.141E-02	0.3381	0.2472	0.0290	-1.045E-01
3.600	5.673E-07	1288.745	1234.955	2.718E-02	0.3381	0.2485	0.0297	-9.822E-02
3.700	5.619E-07	1289.170	1235.081	2.327E-02	0.3381	0.2497	0.0305	-9.236E-02
3.800	5.569E-07	1289.551	1235.207	1.964E-02	0.3381	0.2507	0.0312	-8.694E-02
3.900	5.522E-07	1289.890	1235.332	1.627E-02	0.3381	0.2517	0.0320	-8.189E-02
4.000	5.479E-07	1290.192	1235.456	1.316E-02	0.3381	0.2525	0.0327	-7.722E-02
4.100	5.438E-07	1290.458	1235.580	1.028E-02	0.3381	0.2533	0.0335	-7.284E-02
4.200	5.399E-07	1290.693	1235.703	7.608E-03	0.3381	0.2539	0.0342	-6.881E-02
4.300	5.364E-07	1290.897	1235.826	5.133E-03	0.3381	0.2545	0.0350	-6.507E-02
4.400	5.330E-07	1291.074	1235.948	2.853E-03	0.3381	0.2550	0.0357	-6.151E-02

Fig II b. (cont)

MURGATROYD II CASE

TIME, SEC	POWER, WATTS	FUEL TEMP, DEG F	GRAPHITE TEMP, DEG F	PRESSURE RISE, PSI	DELTA K INPUT, PCT	PCT DK REMOVED BY		(1/P)(DP/DT), PER SECOND
						FUEL	GRAPHITE	
4.500	5.298E 07	1291,225	1236,070	7,413E-04	0,3381	0,2554	0,0364	-5,827E-02
4.600	5,268E 07	1291,353	1236,191	-1,213E-03	0,3381	0,2558	0,0371	-5,523E-02
4.700	5,240E 07	1291,459	1236,311	-3,018E-03	0,3381	0,2561	0,0379	-5,239E-02
4.800	5,213E 07	1291,545	1236,431	-4,676E-03	0,3381	0,2563	0,0386	-4,972E-02
4.900	5,188E 07	1291,613	1236,551	-6,219E-03	0,3381	0,2565	0,0393	-4,726E-02
5.000	5,164E 07	1291,663	1236,670	-7,641E-03	0,3381	0,2567	0,0400	-4,496E-02
5.100	5,142E 07	1291,697	1236,789	-8,956E-03	0,3381	0,2568	0,0407	-4,283E-02
5.200	5,120E 07	1291,717	1236,907	-1,017E-02	0,3381	0,2568	0,0414	-4,083E-02
5.300	5,100E 07	1291,723	1237,025	-1,128E-02	0,3381	0,2568	0,0422	-3,894E-02
5.400	5,080E 07	1291,717	1237,143	-1,231E-02	0,3381	0,2568	0,0429	-3,722E-02
5.500	5,062E 07	1291,699	1237,260	-1,325E-02	0,3381	0,2568	0,0436	-3,559E-02
5.600	5,044E 07	1291,670	1237,376	-1,413E-02	0,3381	0,2567	0,0443	-3,408E-02
5.700	5,028E 07	1291,631	1237,493	-1,494E-02	0,3381	0,2566	0,0450	-3,269E-02
5.800	5,012E 07	1291,584	1237,609	-1,567E-02	0,3381	0,2564	0,0457	-3,135E-02
5.900	4,996E 07	1291,528	1237,724	-1,634E-02	0,3381	0,2563	0,0463	-3,013E-02
6.000	4,982E 07	1291,464	1237,839	-1,697E-02	0,3381	0,2561	0,0470	-2,898E-02
6.100	4,967E 07	1291,393	1237,954	-1,755E-02	0,3381	0,2559	0,0477	-2,794E-02
6.200	4,954E 07	1291,315	1238,069	-1,806E-02	0,3381	0,2557	0,0484	-2,693E-02
6.300	4,941E 07	1291,232	1238,183	-1,854E-02	0,3381	0,2554	0,0491	-2,601E-02
6.400	4,928E 07	1291,143	1238,297	-1,898E-02	0,3381	0,2552	0,0498	-2,515E-02
6.500	4,916E 07	1291,048	1238,410	-1,939E-02	0,3381	0,2549	0,0505	-2,437E-02
6.600	4,904E 07	1290,949	1238,524	-1,975E-02	0,3381	0,2547	0,0511	-2,359E-02
6.700	4,893E 07	1290,846	1238,637	-2,009E-02	0,3381	0,2544	0,0518	-2,292E-02
6.800	4,882E 07	1290,739	1238,749	-2,039E-02	0,3381	0,2541	0,0525	-2,225E-02
6.900	4,871E 07	1290,628	1238,861	-2,067E-02	0,3381	0,2538	0,0532	-2,165E-02

Fig. 2b (cont)

MURGATROYD II CASE

1

TIME, SEC	POWER, WATTS	FUEL TEMP, DEG F	GRAPHITE TEMP, DEG F	PRESSURE RISE, PSI	DELTA K INPUT, PCT	PCT DK REMOVED BY		(1/P)(DP/DT), PER SECOND
						FUEL	GRAPHITE	
7.000	4.861E 07	1290.513	1238.973	-2.093E-02	0.3381	0.2534	0.0538	-2.111E-02
7.100	4.851E 07	1290.396	1239.085	-2.115E-02	0.3381	0.2531	0.0545	-2.057E-02
7.200	4.841E 07	1290.276	1239.196	-2.136E-02	0.3381	0.2528	0.0552	-2.010E-02
7.300	4.831E 07	1290.153	1239.307	-2.155E-02	0.3381	0.2524	0.0558	-1.966E-02
VALUES AT PRESSURE MINIMUM								
TIME, SEC	PRESSURE RISE, PSI							
7.320	-2.1584E-02							
7.325	-2.1598E-02							
7.330	-2.1595E-02							
7.400	4.822E 07	1290.028	1239.418	-2.172E-02	0.3381	0.2521	0.0565	-1.924E-02
7.500	4.813E 07	1289.900	1239.529	-2.186E-02	0.3381	0.2517	0.0572	-1.882E-02
7.600	4.804E 07	1289.771	1239.639	-2.201E-02	0.3381	0.2514	0.0578	-1.847E-02
7.700	4.795E 07	1289.640	1239.749	-2.213E-02	0.3381	0.2510	0.0585	-1.813E-02
7.800	4.786E 07	1289.507	1239.858	-2.223E-02	0.3381	0.2506	0.0592	-1.781E-02
7.900	4.778E 07	1289.373	1239.968	-2.233E-02	0.3381	0.2502	0.0598	-1.754E-02
8.000	4.770E 07	1289.238	1240.077	-2.241E-02	0.3381	0.2499	0.0605	-1.726E-02
8.100	4.761E 07	1289.101	1240.186	-2.250E-02	0.3381	0.2495	0.0611	-1.703E-02
8.200	4.753E 07	1288.963	1240.294	-2.256E-02	0.3381	0.2491	0.0618	-1.678E-02
8.300	4.745E 07	1288.824	1240.402	-2.261E-02	0.3381	0.2487	0.0624	-1.656E-02
8.400	4.738E 07	1288.685	1240.510	-2.266E-02	0.3381	0.2483	0.0631	-1.637E-02
8.500	4.730E 07	1288.544	1240.618	-2.270E-02	0.3381	0.2479	0.0637	-1.618E-02
8.600	4.722E 07	1288.403	1240.725	-2.273E-02	0.3381	0.2475	0.0644	-1.600E-02
8.700	4.715E 07	1288.261	1240.833	-2.276E-02	0.3381	0.2471	0.0650	-1.584E-02
8.800	4.707E 07	1288.119	1240.939	-2.278E-02	0.3381	0.2467	0.0656	-1.569E-02
8.900	4.700E 07	1287.976	1241.046	-2.279E-02	0.3381	0.2463	0.0663	-1.554E-02
9.000	4.693E 07	1287.833	1241.152	-2.281E-02	0.3381	0.2459	0.0669	-1.542E-02
9.100	4.686E 07	1287.689	1241.258	-2.281E-02	0.3381	0.2455	0.0676	-1.528E-02

Fig. 2b (cont)

MURGATROYD II CASE 1

TIME, SEC	POWER, WATTS	FUEL TEMP, DEG F	GRAPHITE TEMP, DEG F	PRESSURE RISE, PSI	DELTA K INPUT, PCT	PCT DK REMOVED BY		(1/P)(DP/DT), PER SECOND
						FUEL	GRAPHITE	
9,200	4.678E 07	1287,545	1241,364	-2.283E-02	0,3381	0,2451	0,0682	-1,522E-02
9,300	4.671E 07	1287,401	1241,470	-2,283E-02	0,3381	0,2447	0,0688	-1,513E-02
9,400	4.664E 07	1287,257	1241,575	-2,282E-02	0,3381	0,2443	0,0695	-1,502E-02
9,500	4.657E 07	1287,112	1241,680	-2,282E-02	0,3381	0,2439	0,0701	-1,494E-02
9,600	4.650E 07	1286,967	1241,785	-2,280E-02	0,3381	0,2435	0,0707	-1,485E-02
9,700	4.643E 07	1286,822	1241,889	-2,278E-02	0,3381	0,2431	0,0713	-1,475E-02
9,800	4.637E 07	1286,677	1241,994	-2,277E-02	0,3381	0,2427	0,0720	-1,469E-02
9,900	4.630E 07	1286,532	1242,098	-2,276E-02	0,3381	0,2423	0,0726	-1,465E-02
10,000	4.623E 07	1286,387	1242,201	-2,274E-02	0,3381	0,2419	0,0732	-1,459E-02
10,100	4.616E 07	1286,242	1242,305	-2,272E-02	0,3381	0,2415	0,0738	-1,453E-02
10,200	4.610E 07	1286,097	1242,408	-2,270E-02	0,3381	0,2411	0,0744	-1,448E-02
10,300	4.603E 07	1285,952	1242,511	-2,267E-02	0,3381	0,2407	0,0751	-1,441E-02
10,400	4.596E 07	1285,807	1242,614	-2,265E-02	0,3381	0,2403	0,0757	-1,440E-02
10,500	4.590E 07	1285,662	1242,716	-2,263E-02	0,3381	0,2399	0,0763	-1,437E-02
10,600	4.583E 07	1285,517	1242,819	-2,260E-02	0,3381	0,2394	0,0769	-1,432E-02
10,700	4.577E 07	1285,372	1242,921	-2,257E-02	0,3381	0,2390	0,0775	-1,427E-02
10,800	4.570E 07	1285,228	1243,022	-2,254E-02	0,3381	0,2386	0,0781	-1,425E-02
10,900	4.564E 07	1285,083	1243,124	-2,252E-02	0,3381	0,2382	0,0787	-1,425E-02
11,000	4.557E 07	1284,939	1243,225	-2,249E-02	0,3381	0,2378	0,0793	-1,421E-02

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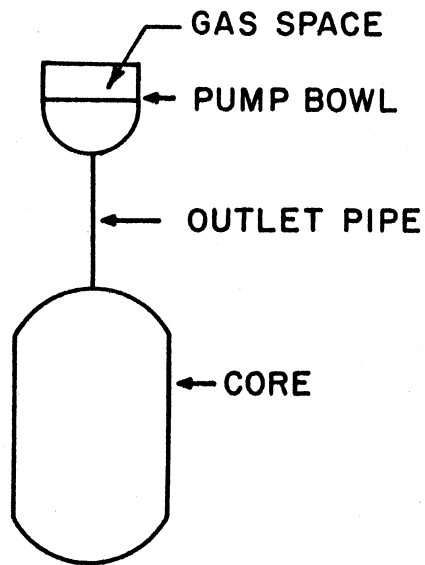


FIG. III SIMPLIFIED MODEL FOR PRESSURE CALCULATIONS

Internal Distribution

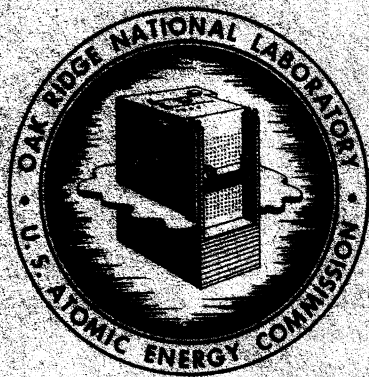
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MURGATROYD - AN IBM 7090 PROGRAM FOR THE ANALYSIS OF THE KINETICS OF THE MSRE

C. W. Nestor, Jr.

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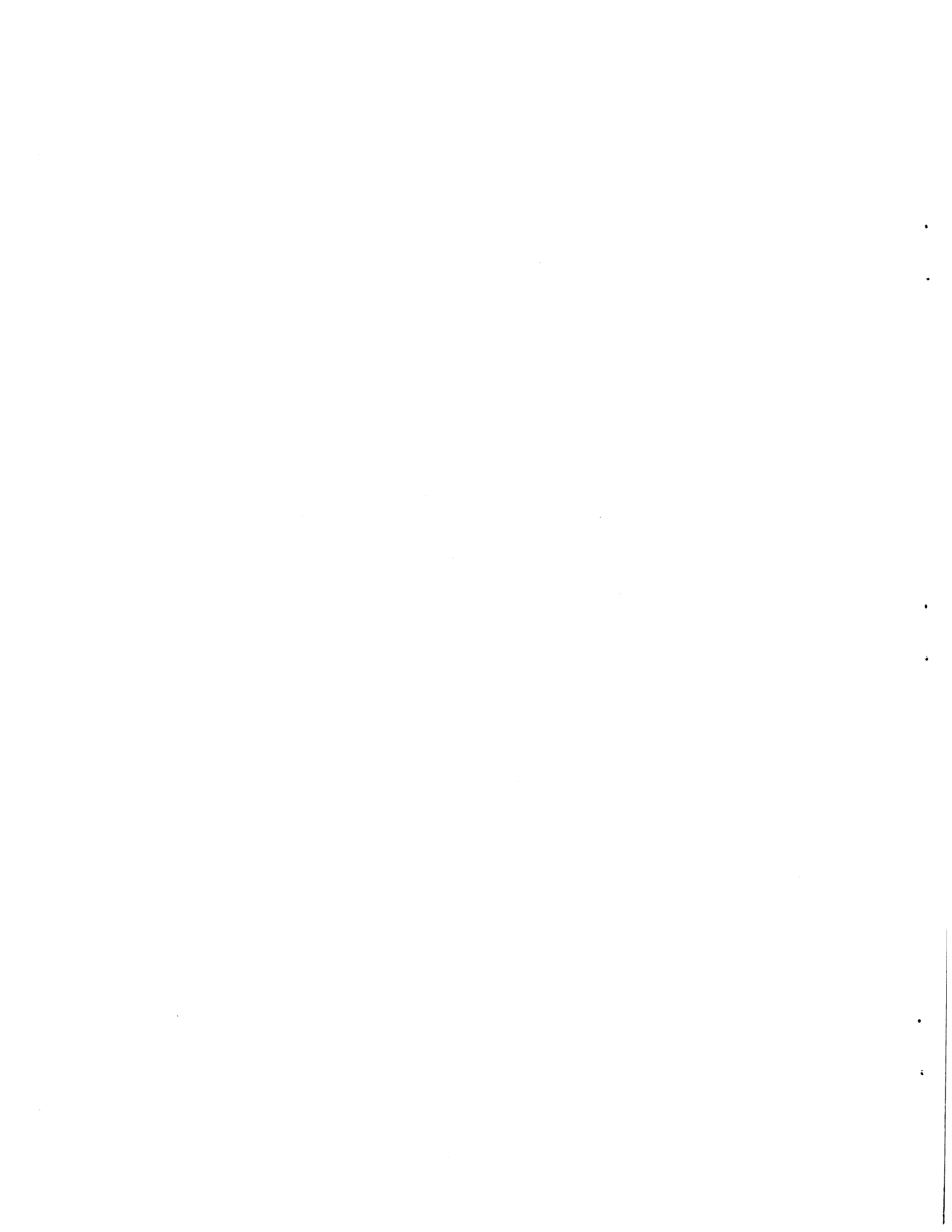
As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

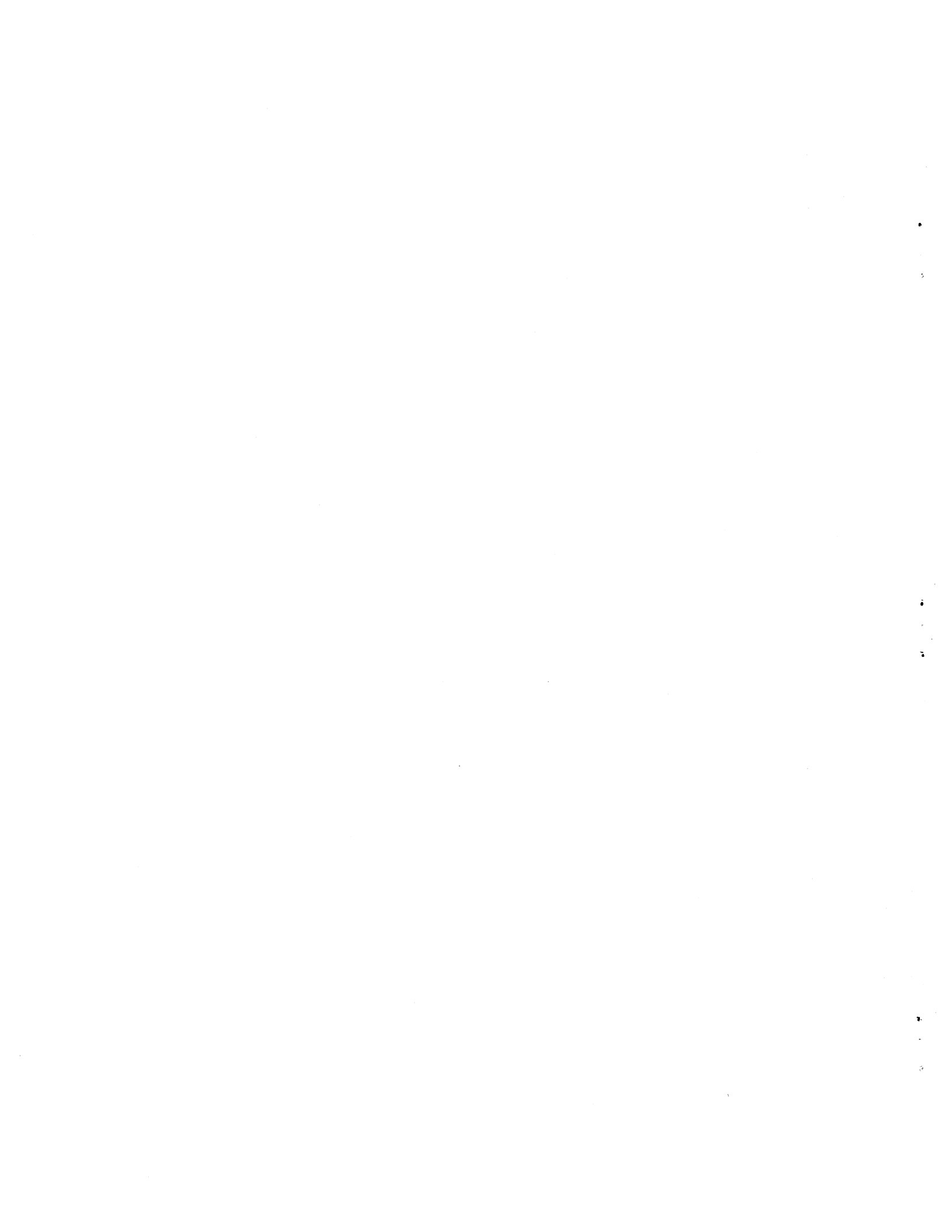
Addendum to ORNL-TM-203

An addition has been made to the IBM-7090 program MURGATROYD to produce a rough graph of the reactor power versus time. A logical tape 6 is required for storage of the power versus time results in addition to the standard input and output tapes. The plotting frequency (analogous to the printout frequency) is specified in columns 16-21 of the card containing the stop time and the number of ramp rate changes (see p 18, ORNL-TM-203). A sample of the graphical output is attached for the case given as an example on pages 19-25. If the plotting frequency specified in the input is zero or blank, no plot is produced; however, a logical tape 6 must be specified even if no plot is desired.

Corrigendum

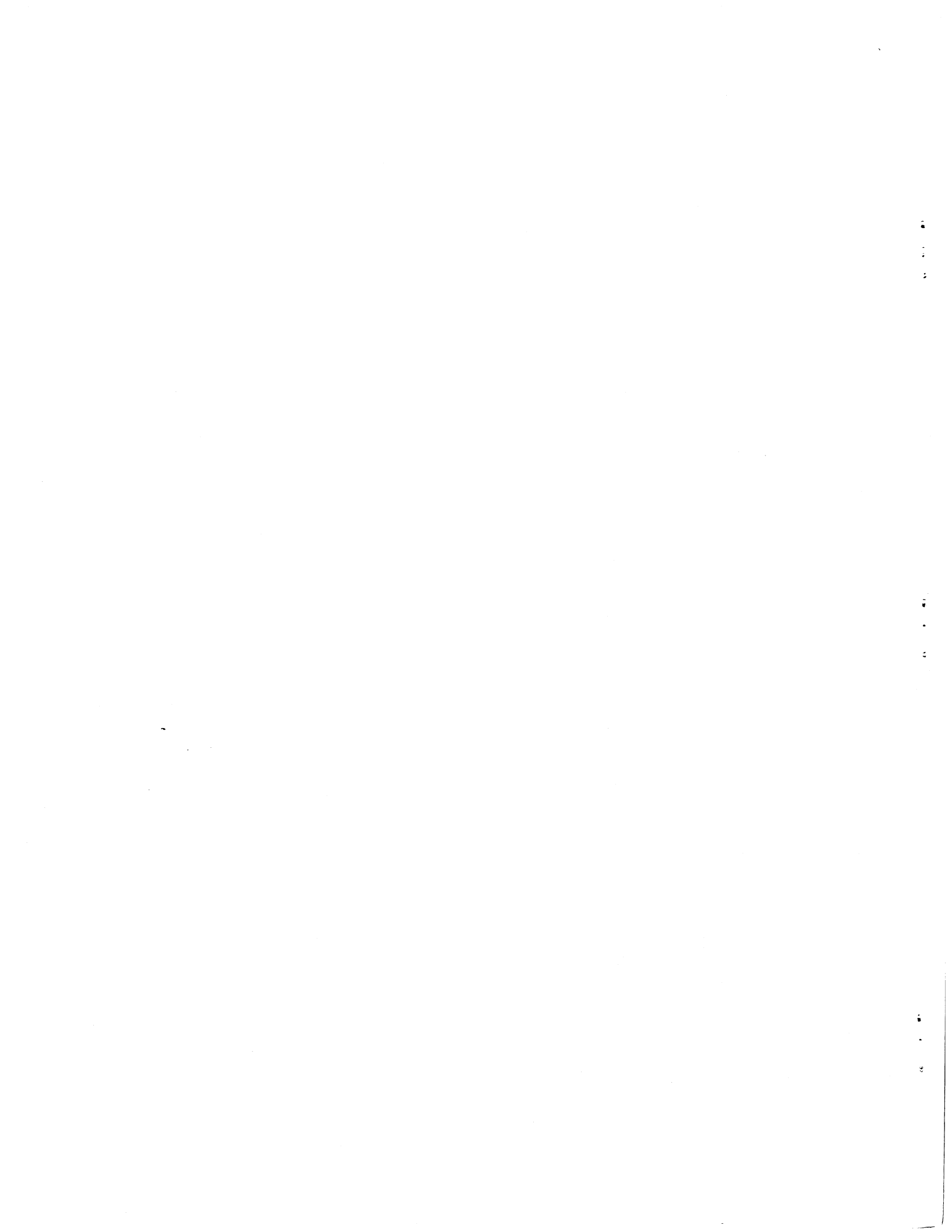
On page 15, in the last sentence, for "12AG" read "12A6".





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