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Westinghouse Astronuclear Laboratory

DETAILED ANALOG MODELS STATUS REPORT
(Title Unclassified)

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DETAILED ANALOG MODELS STATUS REPORT

September 17, 1965

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SUMMARY

This report presents a detailed description of various analog computer models of the NERVA system developed during CY '65 for systems and control analysis work at WANL. These models were developed prior to the agreements between WANL and REON to use a Common Analog Model for all official predictions of test performance. However, the models described in this report have been of considerable value in helping to assess the validity of several proposed versions of the Common Analog Model and will continue to be used for validation of proposed nuclear subsystem models.

Included in this report are detailed descriptions of the basic NERVA-I reactor and nozzle model, EST and TCA feedsystem models, one-console NERVA-I and NERVA-II models, and PCV-41 and PCV-18 emergency flow shutdown models. Also included is a description of the nuclear subsystem portion of the Common Analog Model II for the EST engine system.

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This report presents detailed descriptions of the various analog computer models of the NERVA system which have been developed at WANL during CY '65 for NRX and engine system and control analysis. Each of the models discussed is operative at present. The report should be used in conjunction with WANL-TME-1220⁽¹⁾, which gives a complete verbal description of the models.

The report contains detailed descriptions of the following models:

1. The basic model of the NERVA-I test article. This model contains the nozzle tubes, reflector, shield, tie rod, and reactor core and can be used with all auxiliary feedsystems.
2. The EST feedsystem model. This model can be used for bootstrap and power range operation.
3. The NRX Feedsystem model⁽²⁾.
4. One-console models for NERVA-I and -II. These are simplified versions of the basic engine system model and are intended for profile and preliminary control studies.
5. PCV-41 emergency shutdown simulation⁽³⁾.
6. PCV-18 emergency shutdown system.
7. EST Common Analog Model II (WANL input).

The material is presented in the order indicated above. Due to the fact that the report is a summary of a number of different models, a complete set of constants and nomenclature is presented for each model discussed. Therefore, it should only be necessary to refer to one particular section to obtain complete details of a specific model.

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II. BASIC MODEL OF THE NERVA-I TEST ARTICLE

The basic computer model consists of a simulation of the nozzle tubes, reflector, shield, tie rod, core, and nozzle chamber. The model can be used either with the EST or NRX-TCA feedsystem models (to be described later) to form a complete analytical tool for NRX or engine studies. The model can be employed for studies both at low and high power, from approximately 0.5% to 100% power and from 3 lb/sec to design weight flow. The model will be most accurate in the normal operating range and should only be used for qualitative answers near the bottom of the operating range of power and flow. The basic model has been used with both liquid and gaseous hydrogen as the propellant and for preliminary bootstrap studies. It assumes that the liquid-gas interface occurs in the nozzle coolant tubes and that, from the reflector inlet plenum on, the propellant is gaseous. Figure 1 shows a block diagram of the basic model.

A. Nozzle Coolant Tubes

The nozzle coolant tube simulation considers a one lump axial representation (see figure below) and attempts to describe single and two-phase heat transfer dynamics. (See Table I for nomenclature).

FIGURE 1

BLOCK DIAGRAM OF BASIC ANALOG MODEL

TABLE I

NOZZLE TUBE NOMENCLATURE

Variables

E	Enthalpy of fluid	BTU/lb
f_{bo}	Boiling heat flux	BTU/(sec-in ²)
HD	Property dependent part of heat transfer coefficient	
P	Fluid pressure	psia
t	Time	sec
T	Fluid temperature	°R
W	Weight flow rate	lb/sec
XTP	Fraction of time two-phase flows past a given point	
ρ	Fluid density	lb/in ³
ϕ	Material temperature	°R
λ	Heat of vaporization	BTU/lb
B_o	Boiling number	

Reactor Station
Designations*

4	Inlet to nozzle
5	Reflector inlet plenum
8	Reactor chamber

* 0.5 Designates Midsections

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TABLE I (CONT'D)

Subscripts

N	Nozzle hot side
NC	Nozzle cold side
NCF	Nozzle coolant film
NCV	Nozzle coolant vapor

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The model may be overly complicated for the rest of the analog basic model, but until parameter studies can be made to determine the relative importance of certain features, the tube simulation to be described will be used. The model is discussed in detail in Reference 4 and will be briefly presented here.

The differential equation used for simulating heat transfer from the hot to the cold side of one nozzle tube is as follows:

$$3.72 \frac{d H_{NC}}{dt} = 0.0212 HD_N \times W_8^{0.8} \left(\frac{T_8}{T_f} \right)^{0.8} (0.8 T_8 - \phi_{4.5}) - 0.162 HD_{NC} \times W_{4.5}^{0.8} [(1 - XTP) \left(\frac{\phi_{4.5}}{T_{NCV}} \right)^{-0.55} (\phi_{4.5} - T_{NCV}) - XTP \left(\frac{\phi_{4.5}}{T_{NCF}} \right)^{-0.55} (\phi_{4.5} - T_{NCF})] - 52.6 XTP f_{bo} \quad (1)$$

where $\phi_{4.5} = f(H_{NC})$ is shown in Figure 2; HD_N in Figure 3; HD_{NC} in Figure 4; and f_{bo} is found as a function of temperature and as a linear extrapolation between 180 and 20 psia pressure data in Figure 5. The function XTP is given in Figure 6 and is a function of the reciprocal of the boiling number

$$B_o = \frac{18.6 f_{bo}}{W\lambda} \quad (2)$$

where λ , the heat of vaporization is given in Figure 7. In equation (1),

$$T_f = \frac{\phi_{4.5} - 0.8T_8}{2} \quad (3)$$

$$T_{NCF} = \frac{50 + \phi_{4.5}}{2} \quad (4)$$

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FIGURE 6
XTP VERSUS BORLING NUMBER

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From an energy balance, the enthalpy of the vapor at the midsection of the nozzle tubes is

$$E_{4.5} = 0.081 \text{ HD}_{\text{NC}} \frac{W_{4.5}^{0.8} \phi_{4.5}^{-0.55}}{W_{4.5} \left(\frac{\phi_{4.5}}{T_{\text{NCV}}} \right)} (\phi_{4.5} - T_{\text{NCV}}) - 70 \quad (5)$$

The total fluid enthalpy is obtained from dividing the total heat transferred to the cold side (last two terms in equation (1)) by the total flow rate.

The enthalpy stored in the reflector inlet plenum is computed by

$$\frac{dE_{5.5}}{dt} = 3.42 (E_5 - E_{5.5}) \quad (6)$$

Fluid temperatures are obtained from the following representation of the temperature-enthalpy diagram

$$T = 300 - f_1 (P) (910 - E) - f_2 (P) (80 - E) \quad (7)$$

where the enthalpy in the second term on the right is limited to values greater than or equal to 80 BTU/lb and the third term is limited to values less than or equal to 80 BTU/lb. For a temperature greater than or equal to 300°R, the following equation for temperature is used.

$$T = 0.26 E + 65 \quad (8)$$

The values of $f_1 (P)$ and $f_2 (P)$ are shown in Figures 8 and 9 respectively. A graph of the temperature-enthalpy diagram defined by the above equations is shown in Figure 10.

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FIGURE 9

$f_2(P)$ VERSUS PRESSURE IN ENTHALPY CALCULATION

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The perfect gas equation of state for hydrogen is used to obtain pressures as a function of density and temperature:

$$P = 9200 \rho T \quad (9)$$

The density is obtained from integration of the net flow into the nozzle and reflector plenums:

$$\frac{d}{dt} \rho_5 = 0.125 \times 10^{-4} (W_4 - W_5) \quad (10)$$

The nozzle tube pressure drops appear in the following differential equation for the momentum:

$$\begin{aligned} - \frac{dW_{4.5}}{dt} = & 23.9 (P_4 - P_5) + [(0.179 \times 10^{-3}) W_{4.5}^2] \\ & \times \left[\frac{1.075}{\rho_4 + \rho_5} + \frac{1.65}{\rho_5} + \frac{1.65}{\rho_4} \right] \end{aligned} \quad (11)$$

B. Reflector

The current reflector model is a simplification over what has previously been used.*⁽⁵⁾ The model assumes that all the major flow passages, such as the inner and outer reflector annuli or the beryllium holes can be satisfactorily represented by an "average" flow passage containing the same total heat transfer and cross-sectional area. The analog reflector is schematically shown below.

* Table II contains the nomenclature and Table III, the constant values for the reflector, shield, tie rod, and reactor core.

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TABLE I

NOMENCLATURE FOR REFLECTOR, SHIELD, CORE, AND TIE ROD

Constants

A	Cross-sectional flow area	in ²
C, k	Constant (with numerical subscript) obtained empirically or by curve fitting	
C _p	Specific heat at constant pressure	BTU/lb _m (°R)
g	Gravitational acceleration	in/sec ²
k	Thermal conductivity (may also be variable)	BTU/sec(in.)(°R)
L	Length	in.
R	Gas constant for hydrogen	in/°R
V	Volume	in ³
α	Heat transfer surface area	in ²

Variables

E	Enthalpy of fluid	BTU/lb _m
$H = \int_0^\phi C_p d\phi$	Enthalpy of component	BTU/lb _m
Q	Heat power generated or transferred	BTU/sec-%
P	Fluid pressure	psia
t	Time	sec
T	Fluid temperature	°R

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TABLE II (CONT'D)

Variables

W	Weight flow rate	lb _m /sec
ρ	Fluid density	lb _m /in ³
φ	Temperature of material	°R

Station Designations

5	Reflector inlet plenum
6	Core shield inlet plenum or reflector shield exit
7	Core inlet plenum
8	Thrust chamber or core exit plenum and entrance to hot-bleed port

Component and Flow Channel Identification

c	Fueled graphite channels in the core
pg	Pyrolytic graphite sleeve in tie rod channel
s	Core shield
sg	Structural graphite support element
ss	Stainless steel liner in tie rod channel
tr	Tie rod

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TABLE II (CONT'D)

Qualifying Sub-subscripts

e	Exit
g	Gas
H	Hot side
i	Inlet
j	Surface at inside radius of component
o	Surface at outside radius of component
r	In the radial direction
x	In the axial direction

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TABLE III

CONSTANT VALUES FOR REFLECTOR, SHIELD, CORE, AND TIE ROD

Reflector

a	$=$	321	in^3/lb
A_r	$=$	85.55	in^2
b	$=$	6.39×10^8	in^4/lb
C_r	$=$	1.675×10^{-5}	$1/\text{in}^3$
g	$=$	386.4	in/sec^2
k_6	$=$	7.254×10^{-5}	$\text{BTU}/\text{lb-}^\circ\text{R-in}^2$
k_r	$=$	241.8	$\text{BTU}/\%- \text{sec}$
L_r	$=$	53.5	in.
M_r	$=$	4014	lb.
V_6	$=$	31,096	in^3
α_r	$=$	87,661	in^2

Shield

A_s	$=$	68.6	in^2
C_s	$=$	2.66×10^{-3}	$1/\text{in}^3$
K_s	$=$	19.95	$\text{BTU}/\%- \text{sec}$
k_s	$=$	4.143×10^{-5}	$\text{BTU}/\text{lb-}^\circ\text{R-in}^2$
L_s	$=$	32.5	in.
M_s	$=$	2813	lb.

$$\left. \frac{W_{ciT}}{\rho_{ci} V_6} \right|_{\text{design}} = 7.507 \quad 1/\text{sec.}$$

$$\alpha_s = 17,860 \quad \text{in}^2$$

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Core

A_c	=	7.233×10^{-3}	in^2
B_1	=	2.125×10^5	$1/\text{lb}$
B_2	=	9.658×10^5	$1/\text{lb}$
B_3	=	17.71×10^5	$1/\text{lb}$
$C_{c.1}$	=	14.45	$1/\text{in}^3$
$C_{c.2}$	=	18.13	$1/\text{in}^3$
$C_{c.3}$	=	11.55	$1/\text{in}^3$
D_1	=	2.289×10^5	$1/\text{lb}$
D_2	=	13.87×10^5	$1/\text{lb}$
D_3	=	27.03×10^5	$1/\text{lb}$
F_1	=	16.97×10^6	$^\circ\text{R}/\text{lb}$
F_2	=	205.7×10^6	$^\circ\text{R}/\text{lb}$
F_3	=	589.3×10^6	$^\circ\text{R}/\text{lb}$
$K_{c.1}$	=	0.3629	$\text{BTU}/\%-\text{sec}$
$K_{c.2}$	=	0.4005	$\text{BTU}/\%-\text{sec}$
$K_{c.3}$	=	0.2125	$\text{BTU}/\%-\text{sec}$
$k_{c.1}$	=	1.4066	$\text{BTU}/\text{lb}-^\circ\text{R}-\text{in}^2$
$k_{c.2}$	=	1.9765	$\text{BTU}/\text{lb}-^\circ\text{R}-\text{in}^2$
$k_{c.3}$	=	2.101	$\text{BTU}/\text{lb}-^\circ\text{R}-\text{in}^2$
L_c	=	53.5	in
$M_{c.n}$	=	0.0759	lb
V_c	=	3.87	in^3
$\alpha_{c.n}$	=	16.13	in^2

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Kinetics

$$\begin{aligned}k_1 &= 4.0 \times 10^4 \quad 1/\text{sec} \\k_2 &= 0.70 \\k_{3_1} &= 122.13 \quad 1/\text{sec} \\k_{3_2} &= 240.14 \quad 1/\text{sec} \\k_{3_3} &= 74.43 \quad 1/\text{sec} \\k_4 &= 0.0702 \\k_5 &= 0.040 \\k_6 &= 1.560 \times 10^{-3} \\k_7 &= 273.0 \quad \text{in}^3/\text{lb} \\k_8 &= 7.28 \times 10^{-6} \quad 1/^\circ\text{R} \\k_9 &= 6.254 \times 10^{-3} \quad \text{in}^3/\text{lb-}^\circ\text{R}\end{aligned}$$

Tie Rod

$$\begin{aligned}A_{tr} &= 0.0306 \quad \text{in}^2 \\C_{tr_1} &= 25.06 \quad 1/\text{in}^3 \\L_{tr} &= 53.5 \quad \text{in} \\C_{tr_2} &= 5.297 \quad 1/\text{in}^3 \\k_{sg_1} &= 0.3827 \\M_{sg} &= 1.385 \quad \text{lb} \\k_{sg} &= 1.435 \quad \text{BTU/sec-}^\circ\text{R} \\K_{sg} &= 0.699 \quad \text{BTU/\% -sec} \\M_{pg} &= 0.195 \quad \text{lb} \\k_{pg_1} &= 0.00261 \quad \text{BUT/sec-}^\circ\text{R}\end{aligned}$$

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Tie Rod

$$k_{pg_2} = 0.0282 \text{ BTU/sec-}^{\circ}\text{R}$$

$$K_{pg} = 0.085 \text{ BTU/\%-sec}$$

$$k_{pg} = 0.1685$$

$$C_{tr_o} = 3.03 \text{ sec/lb}$$

$$C_{tr_o} = 8.25 \text{ BTU/lb-}^{\circ}\text{R}$$

$$C_{tr_j} = 38.53 \text{ sec/lb}$$

$$C'_{tr_j} = 4.84 \text{ BTU/lb-}^{\circ}\text{R}$$

$$k_{tr} = 0.01222 \text{ BTU/sec-}^{\circ}\text{R-in}^3$$

$$C_{p_{tr}} = 0.12 \text{ BTU/lb-}^{\circ}\text{R}$$

$$\rho_{tr} = 0.272 \text{ lb/in}^3$$

$$K_{tr} = 0.0109 \text{ BTU/\%-sec-in}^3$$

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The flow through the reflector is assumed to be instantaneous; that is, the flow rate in is always equal to the reflector outlet flow rate.

$$W_5 = W_r = W_6 \quad (12)$$

The rate of change of exit weight flow is computed by subtracting the friction and exit losses from the total pressure drop

$$\frac{d}{dt} W_6 = \frac{A_r g}{L_r} (P_5 - P_6) - C_r \frac{W_6^2}{\rho_6} \quad (13)$$

The dome plenum pressure is computed by the Van der Waals equation of state

$$P_6 = \frac{R \rho_6 T_6}{1 - a \rho_6} - b \rho_6^2 \quad (14)$$

The density is computed by using the equation of continuity in the dome plenum,

$$(V_6) \frac{d}{dt} \rho_6 = W_6 - W_{ci_T} - W_{cB} - W_{tr_T} \quad (15)$$

where it is assumed that all the compressibility effects of the reflector, reflector exit plenum, dome and core inlet plenum can be "lumped" into one overall delay. In the steady state, the reflector exit flow must equal the sum of the core inlet, tie rod, and diluent bleed flows in order that mass is conserved.

An average enthalpy of the reflector solid is determined by subtracting the heat convected to the passing gas from the nuclear power generated

$$M_r \frac{d}{dt} H_r = k_6 \alpha_r W_6 (T_r - \phi_r) + k_r n \quad (16)$$

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The temperature of the solid is then computed from the enthalpy by a graphical solution of the equation

$$H_r = \int_0^{\phi_r} C_p d\phi_r \quad (17)$$

$\phi_r = f(H_r)$ as determined in this way is shown in Figure 11. The change in the enthalpy of the fluid is equal to the amount of heat lost by the solid

$$E_6 - E_5 = -\alpha_r k_6 (T_r - \phi_r) \quad (18)$$

For the reflector, it is assumed that the specific heat of the gas is constant at 3.7 BTU/lb-°R and that the axial temperature distribution in the reflector is linear

$$T_r = \frac{T_5 + T_6}{2} \quad (19)$$

C. Shield

For the analog computer model, the pressure drop across the shield and inlet orifice to the reactor core is lumped into one equation. The rate of change of core inlet flow is computed from the equation:

$$\frac{d}{dt} W_{ci_T} = \frac{A_s g}{L_s} (P_6 - P_{ci}) - C_s \frac{W_{ci_T}^2}{\rho_{ci}} \quad (20)$$

The heat transfer effects in the shield are lumped into one axial section as shown schematically below.

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FIGURE 11

INITIALITY - TEMPERATURE CURVE FOR REFLECTOR SOLID

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The change in the enthalpy of the shield is computed by subtracting the heat lost to the gas from the nuclear power generated.

$$M_s \frac{d}{dt} H_s = k_s \alpha_s W_{ci} (T_s - \phi_s) + K_s n \quad (21)$$

The solid temperature is determined from the enthalpy by the curve in Figure 12.

The enthalpy increase of the gas is equal to the amount of heat picked up from the solid

$$E_7 - E_6 = k_s \alpha_s (T_s - \phi_s) \quad (22)$$

For the shield simulation, it is assumed that the specific heat of the gas is constant and that the axial temperature distribution is linear.

$$T_s = \frac{T_6 + T_7}{2} \quad (23)$$

An energy balance is written for the fluid about the core inlet plenum to account for the heat capacity of the gas. This heat storage property for the reflector exit, dome and core inlet plenum is lumped between the shield and core inlet orifices.

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$$\left. \frac{d}{dt} E_{ci} = \frac{W_{ci} T}{\rho_{ci} V_6} \right|_{\text{design}} (E_7 - E_{ci}) \quad (24)$$

D. The Reactor Core

The basic analog computer reactor core model is based upon the assumption that all 30,600 fuel channels can be satisfactorily represented by an average channel with an associated mass. This average channel is further subdivided into three axial flow and heat transfer sections. This is shown in the figure below.

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Each of the n axial sections is set up in an identical manner. From each section, the inlet density is computed from the equation of continuity.

$$\left(\frac{V}{3}\right) \frac{d}{dt} \rho_{c.n_i} = W_{c.n_i} - W_{c.n_e} \quad (25)$$

The rate of change of exit weight flow for each section is given by a momentum balance

$$\frac{d}{dt} W_{c.n_e} = \frac{3A_c g}{L_c} (P_{c.n_i} - P_{c.n_e}) - C_{c.n} \frac{W_{c.n_e}}{\rho_{c.n_e}} \quad (26)$$

where the linear average

$$W_{c.n} = 1/2 (W_{c.n_i} + W_{c.n_e}) \quad (27)$$

is used. The ideal gas law is employed at each inlet and exit to each section to give the pressure

$$P_{c.n_i} = \rho_{c.n_i} R T_{c.n_i} \quad (28)$$

At the exit of the channel, it is assumed that $P_{c.3_e} = P_8$, where P_8 is the nozzle throat pressure. Here the density is calculated by the ideal gas law.

$$\rho_{c.3_e} = \frac{P_{c.3_e}}{R T_{c.3_e}} \quad (29)$$

The average fluid density is computed by

$$\rho_c = \frac{1}{8} (\rho_{ci} + 3\rho_{c.1_e} + 3\rho_{c.2_e} + \rho_{c.3_e}) \quad (30)$$

This equation is exact if the density versus axial distance down the channel is of cubic form or of lesser degree.

In each section the enthalpy change of the fueled graphite is equal to the amount of nuclear heat generated minus the heat convected away to the gas.

$$M_{c.n} \frac{d}{dt} H_{c.n} = \alpha_{c.n} k_{c.n} W_{c.n} (T_{c.n} - \phi_{c.n}) + K_{c.n} n \quad (31)$$

where

$$\phi_{c.n} = f(H_{c.n})$$

shown in Figure 13.

The average fuel temperature along each channel is given by

$$\phi_c = \frac{1}{8} (3\phi_{c.1} + 2\phi_{c.2} + 3\phi_{c.3}) \quad (32)$$

In the reactor core, the specific heat of the propellant is assumed constant. The rate of change of temperature is calculated by balancing the amount of heat picked up from the fuel and flow work with the heat lost by convection.

$$\begin{aligned} \frac{d}{dt} T_{c.n} = & B_n W_{c.n} (T_{c.n-1_e} - T_{c.n}) + D_n W_{c.n} (\phi_{c.n} - T_{c.n}) \\ & + F_n (W_{c.n-1_e} - W_{c.n_e}) \end{aligned} \quad (33)$$

The linear approximation of $\frac{\partial}{\partial X} T_{c.n} = \left(\frac{T_{c.n-1_e} - T_{c.n}}{L} \right)$ is not used for the last two sections. Here the higher order approximation

$$\frac{\partial}{\partial X} T_{c.n} = \frac{3}{2L} \times (2T_{c.n-1_e} - \frac{1}{2} T_{c.n-1} - \frac{3}{2} T_{c.n}) \text{ is used.}$$

The average core outlet temperature is obtained by using a weighted function of the second and third section fluid temperatures as given below.

$$T_{c.3_e} = 3T_{c.3} - 3T_{c.2_e} + T_{c.2} \quad (34)$$

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A computed axial temperature distribution using the higher order terms is shown in Figure 14. In this figure, the current analog distribution at design is compared with a 15 section digital computer steady state. (e)

The nuclear power is computed using three group "10" kinetics. The equations are:

$$\frac{d}{dt} \ln n = k_1 \delta k_T + k_2 \sum \lambda_i \frac{C_i}{n} \quad (35)$$

$$\frac{d}{dt} \left(\frac{C_i}{n} \right) = k_{3_i} - \frac{\lambda_i C_i}{n} - \frac{C_i}{n} \frac{d}{dt} \ln n \quad (36)$$

where C_i is the relative precursor density of delayed group i ; n is power in per cent.

$$\delta k_T = \delta k_D + \delta k_f \quad (37)$$

$$\delta k_D = k_4 \sin^2 \frac{\theta_D}{2} - k_5 \quad (38)$$

$$\delta k_f = k_6 + k_7 \rho_c - k_8 \phi_c - k_9 \phi_c^0 c \quad (39)$$

E. The Support Element

The analog computer basic model of the NERVA reactor includes the simulation of the essential features of the support element. The goal is to give an adequate description of the tie rod exit gas temperature in order that the specified tie rod limits are not exceeded. The dynamics of this exit temperature can only be adequately described by including a fairly complete radial representation of the transient heat conduction which occurs. Due to this fairly rigorous radial treatment, only one axial section down the core channel could be used mainly due to analog equipment limitations.

FIGURE 14
COMPARISON BETWEEN ANALOG AND DIGITAL COMPUTER
REACTOR AXIAL TEMPERATURE DISTRIBUTIONS AT DESIGN

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A radial schematic is shown below. The mathematical model to be presented is based upon this geometrical configuration.

Fueled graphite

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The tie rod weight flow equation assumes no compressibility effects so that

$$W_{tr_i} = W_{tr} = W_{tr_e} = \frac{1}{289} W_{tr_T} \quad (40)$$

where sub T indicates total flow.

The rate of change of tie rod flow is obtained by subtracting the inlet loss and friction loss from the pressure drop.

$$\frac{d}{dt} W_{tr} = \frac{A_{tr} g}{L_{tr}} (P_6 - P_8) - C_{tr_1} \frac{W_{tr}^2}{\rho_6} - C_{tr_2} \frac{W_{tr}^2}{\rho_{tr_e}} \quad (41)$$

The ideal gas law is used to compute exit tie rod density

$$\rho_{tr_e} = \frac{P_8}{R T_{tr_e}} \quad (42)$$

For the hydrogen gap between the fuel and structural graphite, it was assumed that the principal heat transfer resistance was conduction and that the h_2 in the gap was stationary. The general cylinder (one dimension) equation with constant thermal conductivity is used as a basis for all the tie rod conduction models⁽⁷⁾.

$$\rho \frac{\partial}{\partial t} H = \left[\left(\frac{1}{r} \frac{\partial}{\partial r} \phi + \frac{\partial^2}{\partial r^2} \phi \right) k + Q \right] \quad (43)$$

Using the standard approximation⁽⁸⁾, this equation reduces to

$$\rho \frac{d}{dt} H_n = k \left(\frac{1}{r_n \Delta r} (\phi_{n+1} - \phi_{n-1}) \right) + \frac{k}{\Delta r^2} (\phi_{n+1} - 2\phi_n + \phi_{n-1}) \quad (44)$$

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For the first hydrogen gap, the second term on the right of equation (44) is large compared with the others due largely to the thinness of the gap and equation (44) reduces to

$$0 = \frac{k}{\Delta r^2} (\phi_{sg_0} - 2T_H' + \phi_{c.2})$$

or

$$T_H' = \frac{\phi_{sg_0} + \phi_{c.2}}{2} \quad (45)$$

At the outside surface of the structural graphite, the heat lost by the structural graphite must be equal to the heat gained by the hydrogen

$$k_{sg} \frac{\partial}{\partial r} \phi_{sg_0} = k_{H_2} \frac{\partial}{\partial r} T_H \quad (46)$$

and using simple approximations to the first derivative⁽⁸⁾ and solving for ϕ_{sg_0}

$$\phi_{sg_0} = k_{sg_1} \phi_{sg} + (1 - k_{sg_1}) T_H \quad (47)$$

At the center of the structural graphite, the heat accumulated is computed by equation (44) with the assumption that $\phi_{pg_0} = \phi_{sg}$

$$M_{sg} \frac{d}{dt} H_{sg} = k_{sg} (\phi_{sg_0} - \phi_{sg}) + K_{sg} n \quad (48)$$

$$\phi_{sg} = f(H_{sg}); \text{ Figure 15.}$$

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In the pyro graphite, equation (44) is used again as

$$M_{pg} \frac{d}{dt} H_{pg} = k_{pg1} (\phi_{sg} - \phi_{pgj}) + k_{pg2} (\phi_{sg} - 2\phi_{pgj} + \phi_{pgj}) + K_{pg} n \quad (49)$$

where

$$\phi_{pg} = f(H_{pg}); \quad \text{Figure 16.}$$

At the inside surface of the pyro graphite, the heat conducted from the pyro graphite is equal to the amount of heat picked up by the h_2 gap.

$$k_{pg} \frac{\partial}{\partial r} \phi_{pg} = k_{H_2} \frac{\partial}{\partial r} T_H$$

or

$$\phi_{pgj} = k_{pg} \phi_{pg} + (1 - k_{pg}) T_H \quad (50)$$

The same simplification can be made in the second h_2 gap as for the first and

$$T_H = \frac{\phi_{pgj} + \phi_{ss_o}}{2} \quad (51)$$

Due to the extreme thinness of the stainless steel liner and the good thermal conductivity,

$$\phi_{ss} = \frac{\phi_{ss_o} + \phi_{ssj}}{2} \quad (52)$$

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At the inside surface of the liner, the amount of heat convected to the passing fluid must equal the amount conducted away

$$k_{ss} \frac{\partial}{\partial r} \phi_{ss} = h (T_{tr} - \phi_{ss})$$

where h is the overall heat transfer coefficient = $C_{tr_o} W_{tr}$. Then

$$\phi_{ss_j} = \phi_{ss} + C_{tr_o} W_{tr} (T_{tr} - \phi_{ss_j}) \quad (53)$$

For the passing fluid, the heat gained from the tie rod and the stainless steel liner must equal the change in enthalpy.

$$E_{tr_e} = E_{tr_i} - C_{tr_j} (T_{tr} - \phi_{tr_o}) - C_{tr_o} (T_{tr} - \phi_{ss_j}) \quad (54)$$

For the tie rod simulation, C_p = constant, and it was assumed

$$T_{tr} = \frac{T_6 + T_{tr_e}}{2} \quad (55)$$

At the outside surface of the tie rod itself

$$k_{tr} \frac{\partial}{\partial r} \phi_{tr} = C'_{tr_j} W_{tr} (\phi_{tr_o} - T_{tr})$$

or linearizing

$$\phi_{tr_o} = \phi_{tr} + C_{tr_j} W_{tr} (T_{tr} - \phi_{tr_o}) \quad (56)$$

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In equation 44,

$$C_{p_{tr}} \rho_{tr} \frac{d}{dt} \phi_{tr} = k_{tr} (\phi_{tr_o} - \phi_{tr}) + K_{tr} n \quad (57)$$

A typical radial temperature distribution is shown in Figure 17, showing the importance of a fairly detailed radial heat transfer model.

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III. EST FEEDSYSTEM

The EST feedsystem is comprised of the pump, turbine, turbine power control valve, hot and diluent bleed lines, and associated piping. The analog computer model consists of a simulation of these basic components. The basic performance characteristics such as turbopump head rise and efficiency are obtained from AGC and incorporated into the feedsystem model. A schematic of the system is shown below with the corresponding station points designated.

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The model presented here has been used with the basic analog model to predict the performance of the NRX/EST system during both bootstrap and normal power operation. It should be emphasized that although the equations which represent the feedsystem are consistent, the accuracy of the entire simulation depends strongly on the correctness of the pump and turbine characteristics.

Pump Inlet Line

For the pump inlet line, it is assumed that all the pressure drop is taken across the propellant shutoff valve (PSOV),*

$$P_2 = P_1 - \frac{W_p^2}{2A_1^2 g \rho_L} \quad (1)$$

where P_1 is the dewar pressure and ρ_L is the propellant density. It is assumed that no temperature change occurs in this line and that the propellant is liquid.

$$T_2 = T_1 = \text{CONSTANT} \quad (2)$$

Pump

The change in enthalpy across the pump is obtained theoretically by the following relation

$$h_4 = E_3 = E_2 + \frac{1}{\rho_L J} \frac{1}{\eta_p} (P_3 - P_2) \quad (2a)$$

where η_p is the pump efficiency and J is the mechanical equivalent of heat. For standard pump operation

* Nomenclature is given in Table IV

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TABLE IV

EST FEEDSYSTEM NOMENCLATURE

Constants

A	Cross-sectional flow area	in ²
C _p	Specific heat at constant pressure	BTU/lb _m (°R)
g	Gravitational acceleration	sec ²
R	Gas constant for hydrogen	in/°R
V	Volume	in ³
γ	Specific heat ratio	

Variables

E	Enthalpy of fluid	BTU/lb _m
M	Torque	ft/lb
N	Rotor speed	RPM
P	Fluid pressure	psia
t	Time	sec
T	Fluid temperature	°R
W	Weight flow rate	lb _m /sec
ρ	Fluid density	lb _m /in ³
	Efficiency	%
θ	TPCV valve angle	degrees

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TABLE IV (CONT'D)

Station Designations

1	TSOV inlet
2	Pump suction line inlet or TSOV exit pump inlet
3	Pump discharge line inlet or pump exit
4	Inlet to either nozzle skirt or nozzle coolant tube inlet manifold
6	Core shield inlet plenum or reflector shield exit
8	Thrust chamber or core exit plenum and entrance to hot-bleed port
15	Turbine nozzle inlet
16	Inlet to turbine exhaust line

Qualifying Sub-Subscripts

b	Pertains to bulk properties
c	Cold side
e	Exit
p	Pump
t	Turbine
a	Ambient pressure
v	Valve

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$$m_p = f_1 \left(\frac{W}{N} \right); \text{ CONSTANT } \left(\frac{\text{Suction Pressure}}{N^2} \right) \quad (2b)$$

and

$$\frac{P_3 - P_2}{N^2} = f_2 \left(\frac{W}{N} \right); \text{ CONSTANT } \left(\frac{\text{Suction Pressure}}{N^2} \right) \quad (2c)$$

where N is the rotor speed.

The torque is equal to the change in enthalpy times the weight flow divided by the rotor speed

$$M_p = \frac{30J (E_3 - E_2) W_p}{\pi N} \quad (2d)$$

where the rate of change of speed is obtained by subtracting the turbine and pump torques

$$\frac{d}{dt} N = \frac{30}{\pi I} (M_t - M_p) \quad (3)$$

The current analog computer model of the EST pump uses a quadratic fit to equation (2c) supplied by AGC of the form

$$\frac{P_3 - P_2}{N^2} = C_1 + C_2 \left(\frac{W}{N} \right) + C_3 \left(\frac{W}{N} \right)^2 \quad (4)$$

Substituting equation (2a) into (2d), one obtains

$$\frac{M_p}{N^2} = \frac{1}{\rho} \frac{W_p}{N} \left(\frac{30}{\pi \rho} \right) \left(\frac{P_3 - P_2}{N^2} \right) \quad (4a)$$

The analog computer simulation uses another quadratic in $\left(\frac{W}{N} \right)$ as given by AGC.

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$$\frac{M_p}{N^2} = C_4 + C_5 \left(\frac{W_p}{N}\right) + C_6 \left(\frac{W_p}{N}\right)^2 \quad (5)$$

It should be noted that in equation (4a), if the pump efficiency is a linear function of W_p/N , then M_p/N^2 is a constant time $\Delta P/N^2$ (equation (4)). If the efficiency is a quadratic in W_p/N , then

$$M_p = k W_p N.$$

Pump Discharge Line

The pressure drop across the pump discharge valve is computed by

$$P_4 = P_3 - \frac{W_p^2}{2A_2^2 g \rho_L} \quad (6)$$

It is assumed that the temperature remains constant in the line

$$T_4 = T_3 \quad (7)$$

The flow rate was assumed to be instantaneous

$$W_p = W_{nc} \quad (8)$$

where W_{nc} is the nozzle coolant weight flow.

Turbine

Turbine Torque

Assuming isentropic flow through the turbine, specific heat at constant pressure is constant, and specific heat ratio is constant, the torque can be expressed as

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$$M_t = \frac{C_p t W_t T_{15}}{N} \left[1 - \left(\frac{P_{16}}{P_{15}} \right)^{\frac{\gamma-1}{\gamma}} \right] \frac{30J}{\pi} \quad (8a)$$

A torque parameter $T_r = \frac{M_t}{W_t \sqrt{T_{15}}}$ can be defined as

$$T_r = \frac{M_t}{W_t \sqrt{T_{15}}} = \frac{C_p t \left[1 - \left(\frac{P_{16}}{P_{15}} \right)^{\frac{\gamma-1}{\gamma}} \right]}{\frac{N}{\sqrt{T_{15}}}} \frac{30J}{\pi} \quad (8b)$$

It was assumed that T_r can be satisfactorily represented by a linear function of $N/\sqrt{T}$ for constant pressure ratios. This is only rigorous when efficiency is a quadratic function of $N/\sqrt{T}$. Figure 18 shows this to be approximately true.

A plot of the torque parameter versus $N/\sqrt{T}$ for constant pressure ratios across the turbine is shown in Figure 19. When $N/\sqrt{T_{15}} = 0$ (zero speed), the torque parameter, T_r , can be expressed as a linear function of pressure ratio as shown in Figure 20. The torque is obtained as

$$M_t = 10.12 W_t \sqrt{T_{15}} - 11 W_t \sqrt{T_{15}} \left(\frac{P_{16}}{P_{15}} \right) - 4.05 \times 10^{-3} W_t N \quad (9)$$

When P_{16} is atmospheric, torque is obtained in the same manner as

$$M_t = 12 W_t \sqrt{T_{15}} - 14 W_t \sqrt{T_{15}} \left(\frac{P_{16}}{P_{15}} \right) - 7.7 \times 10^{-3} W_t N \quad (9a)$$

Bleed Flow

Diluent Bleed

$$W_{cb} = A_{v3} [C_{7p6} (P_6 - P_8)]^{1/2} \quad (10)$$

where A_{v3} is the effective area of the orifice in the diluent bleed line.

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Hot Bleed

$$W_{HB} = W_t - W_{db} \quad (11)$$

Turbine

Turbine flow is given by the nozzle equation based on a pressure ratio function obtained from AGC across the turbine. (See Figure 20A for a function)

$$W_t = \frac{P_{15}}{\sqrt{T_{15}}} \propto \left(\frac{P_{16}}{P_{15}} \right) \quad (12)$$

Turbine inlet temperature is calculated by an energy balance

$$\frac{d}{dt} T_{15} = \frac{W_t}{\rho_t V_{15}} \bigg|_{\text{design}} \left[\frac{W_{hb}}{W_t} (T_8 - T_6) + T_c - T_{15} \right] \quad (13)$$

The inlet pressure is expressed as a function of the turbine power control valve angle and chamber pressure shown in Figure 21 as received from AGC.

$$P_{15} = P_8 f_1(\theta_v) \quad (14)$$

Turbine exit flow is obtained from the orifice equation:* (See Figure 21A for ψ function)

$$W_{16} = \frac{C_{816} P_{16}}{\sqrt{T_{16}}} \left[\psi \left(\frac{P_a}{P_{16}} \right) \right] \quad (15)$$

The turbine exit temperature is obtained from an energy balance

$$T_{16} = T_{15} - \frac{12N M_t \pi}{30J W_t C_{pt}} \quad (16)$$

* Equations (15), (16), (17) assume there is an orifice or nozzle downstream of the turbine. If no turbine nozzle exists, then $P_{16} = 12.7 = \text{CONSTANT}$.

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The turbine exit pressure is obtained from the continuity equation:

$$\frac{d}{dt} P_{16} = \frac{R T_{16}}{V_{16}} [W_t - W_{16}] \quad (17)$$

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IV. NRX FEEDSYSTEM

The NRX feedsystm analog model consists of the following elements:
(see Figure 22).

- (1) Pump suction line
- (2) Pump
- (3) Pump discharge line including the bypass valve, ACV-6
- (4) Turbine inlet gas line
- (5) Turbine inlet gas control valve, PCV-50
- (6) Turbine speed control loop
- (7) Reactor flow control loop
- (8) Pump minimum specific speed control loop

The model is used for studies under normal operating conditions and can be operated with flows down to approximately 10 lbs/sec. The model presented in this report is **essentially** the same as that reported in WANL-TME-1124. Minor changes to this model have been made, such as, including only two sections in the pump discharge line instead of four, etc. The model presented here is the feedsystm representation which was used in the NRX-A2 and NRX-A3 studies.

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FIGURE 22

SCHEMATIC DIAGRAM OF THE NRX FEEDSYSTEM

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NRX FEEDSYSTEM

Pump Inlet Line*

$$1. \frac{d W_d}{dt} = \frac{A_s g}{\ell_{il}} (P_d - P_{pil}) - \left(\frac{A_s g}{\ell_{il}} R_1 \right) W_d^2$$

$$2. \frac{d P_{pil}}{dt} = \frac{144 \beta}{A_s \ell_{il} \rho} (W_d - W_{pil})$$

$$3. \frac{d W_{pil}}{dt} = \frac{A_s g}{\ell_{i2}} (P_{pil} - P_{pi2}) - \left(\frac{A_s g}{\ell_{i2}} R_1 \right) W_{pil}^2$$

$$4. \frac{d P_{pi2}}{dt} = \left(\frac{144 \beta}{A_s \ell_{i2} \rho} \right) (W_{pil} - W_p)$$

Pump

$$5. \frac{\Delta P_p}{N^2} = f_1 \left(\frac{W_p}{N} \right) \quad \text{Table VI}$$

$$6. \frac{L_p}{N^2} = f_1 \left(\frac{W_p}{N} \right) \quad \text{Table VII}$$

$$7. P_{pe1} = P_{pi2} + \Delta P_p$$

* Nomenclature and constants are given in Table V

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TABLE V

NOMENCLATURE AND CONSTANTS FOR THE NRX FEEDSYSTEM

List of Variables

W_{pi1}	=	average hydrogen flow in the upstream half of the pump inlet liquid line (lb/sec)
P_{pi1}	=	pressure of the hydrogen liquid in the pump inlet line 60 feet upstream of the pump (psi)
W_{pi2}	=	average hydrogen flow in the downstream half of the pump inlet liquid line (lb/sec)
P_{pi2}	=	pressure of the hydrogen liquid at the pump inlet (psi)
W_p	=	liquid hydrogen flow in the pump (lb/sec)
ΔP_p	=	the pressure rise generated by the pump (psi)
N	=	pump speed RPM)
L_p	=	pump torque (lb-in)
P_{pe1}	=	pressure of the liquid hydrogen at the pump exit (psi)
W_{bp}	=	liquid hydrogen flow through bypass valve ACV-6 (lb/sec)
A_{bp}	=	area of the liquid hydrogen bypass valve (in)
P_m	=	pressure of the liquid hydrogen in the mixing chamber (psi)
W_d	=	average liquid hydrogen flow in the pump discharge line between the pump exit and the ACV-6 line
P_4	=	pressure at the nozzle cooling jacket inlet (psi)
X_{50}	=	stem position of the turbine inlet control valve PCV-50 (in)

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List of Variables (Cont'd)

X_{50d}	=	stem position demand of the turbine inlet control valve actuator PCV-50 (in)
A_{50}	=	area of the turbine inlet control valve PCV-50 (in)
W_{ta}	=	flow of gaseous hydrogen through the turbine inlet nozzle (lb/sec)
P_{ti}	=	hydrogen pressure at the turbine inlet nozzle (psi)
W_{ti}	=	flow of gaseous hydrogen through the turbine inlet nozzle (lb/sec)
L_t	=	torque developed by the turbine (lb-in)
X_6	=	stem position of the bypass valve ACV-6 (%)
X_{6d}	=	stem position demand signal for the bypass valve actuator (%)
A_6	=	area of the bypass valve ACV-6 (in)
N_e	=	turbine speed controller error (RPM)
N_d	=	turbine speed control demand signal [RPM)
W_e	=	flow controller error (lb/sec)
W_{dem}	=	flow controller demand signal (lb/sec)
W_{pe}	=	specific speed controller error signal (lb/sec)
W_{d2}	=	average liquid hydrogen flow in the second section of the pump discharge line (lb/sec)
W_{d3}	=	average liquid hydrogen flow in the third section of the pump discharge line (lb/sec)
W_4	=	liquid hydrogen flow at the nozzle coolant tubes inlet line (lb/sec)
P_{d3}	=	average liquid hydrogen pressure in the second section of the pump discharge line (psi)
P_{d4}	=	average liquid hydrogen pressure in the third section of the pump discharge line (psi)

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List of Parameters

- A_s = cross sectional area of the pump section line (in^2)
- g = acceleration of gravity (ft/sec^2)
- l_{i2} = length of the second section of the pump inlet
- l_{i1} = length of the first section of the pump inlet line (ft)
- P_d = dewar pressure (psi)
- R_1 = flow impedance per section of the pump suction line ($\text{psi} \cdot (\text{lb}/\text{sec})^2$)
- β = liquid hydrogen bulk modulus, (psi)
- ρ = liquid hydrogen density (lb/sec^2)
- A_{tn} = throat area of the turbine nozzle (in^2)
- I = moment of inertia (turbine and pump), (in lb sec^2)
- K_1 = PCV-50 area to position coefficient (in^2/in)
- P_t = gaseous hydrogen tank pressure (psi)
- R = hydrogen gas constant ($\text{ft}^3/\text{in}^2 \text{ } ^\circ\text{R}$)
- V = volume of the turbine inlet gas line between valve PCV-50 and the turbine inlet nozzle (ft^3)
- T = hydrogen ambient gas temperature ($^\circ\text{R}$)
- R_2 = flow impedance of the pump discharge liquid line between the bypass valve and the mixing chamber ($\text{psi}/(\text{lb}/\text{sec})^2$)
- A_d = flow area of the pump discharge line (in^2)
- = inlet line length between the first section of the pump and the dewar (ft)
- C^* = gaseous hydrogen sonic velocity (ft/sec)

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List of Parameters (Cont'd)

- V_d = total volume of the pump discharge line including the mixing chamber (ft)
- l = length of the pump discharge line between the pump exit and the reactor nozzle inlet (ft)
- R_3 = flow impednace of the pump discharge line between the mixing chamber exit and the reactor inlet (psi/(lb/sec)²)
- K_2 = approximate reactor load constant (psi/lb/sec)
- K_n = minimum pump flow to pump speed ratio demand in the specific speed controller (lb/sec/RPM)
- P_{t1} = atmospheric pressure (psi)
- K_3 = bypass valve area to position ratio, (in²/%)
- R_4 = flow impedance per section of the pump discharge line, (four section simulation), psi/(lb/sec)²
- V_r = volume of one section of the pump discharge liquid line, (four section simulation), (ft³)
- l_r = length of one section of the pump discharge line (four section simulation), (ft)

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List of Parameter Values

A_s	=	50.25 in ²
g	=	32.2 ft/sec ²
ℓ_{il}	=	60 ft
P_d	=	72.75 psi
R_1	=	0.00116 psi/(lb-sec) ²
β	=	9000 psi
ρ	=	4.39 lb/ft ³
A_{tn}	=	2.41 in ²
C^*	=	5275 ft/sec
I	=	2.3 in lb sec (Mark IX Turbine and Mark IX Pump)
K	=	$\frac{3.45 \text{ in}}{1.5 \text{ in}}$
P_t	=	3500 psi
R	=	5.33 ft /in °R
T	=	530°R
V	=	0.147 ft ³
R_2	=	0.167 psi (lb/sec) ²
A_d	=	50.3 in
ℓ	=	76 ft
V_d	=	43 ft ³

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List of Parameter Values

l	=	114 ft
R_3	=	$0.01667 \text{ psi}/(\text{lb}/\text{sec})^2$
K_n	=	$3.1 \times 10^{-3} \frac{\text{lb}/\text{sec}}{\text{RPM}}$
P_t	=	14 psia
K_3	=	$2.429 \frac{\text{in}^2}{\text{in}}$
K_t	=	$1.72 \times 10^{-2} \frac{\text{lb-in}^2}{\text{lb-sec}}$
K_2	=	$8.10^{-8} \frac{\text{lb-in}^2}{\text{lb-RPM-sec}}$
A_{50}	=	3.45 in^2

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TABLE VI

MARK IX PUMP, $\Delta P/N^2 = f_1(W_p/N)$

$10^3 \frac{W_p}{N} \left(\frac{\#/\text{sec}}{\text{RPM}} \right)$	$\frac{1.5}{4} \times 10^5 \frac{W_p}{N} - 45.75$	$10^6 \frac{\Delta P}{N^2} \left(\frac{\text{psi}}{\text{RPM}^2} \right)$	$5 \times 10^7 \frac{\Delta P}{N^2}$
3.64	90.75	0.508	25.40
3.63	92.25	0.302	15.10
3.72	93.75	0.000	00.00
3.60	89.25	0.640	32.00
3.58	88.50	0.696	34.80
3.56	87.75	0.745	37.25
3.54	87.00	0.783	39.15
3.52	86.25	0.820	41.00
3.50	85.50	0.855	42.75
3.46	84.00	0.920	46.00
3.40	81.75	0.998	49.90
3.36	80.25	1.049	52.45
3.32	78.75	1.115	55.75
3.26	76.50	1.157	57.85
3.20	74.25	1.217	60.85
3.08	69.75	1.327	66.35
2.96	65.25	1.432	71.60
2.60	51.75	1.728	86.40
2.35	42.38	1.520	76.00
1.22	0.00	1.440	72.00

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TABLE VII

MARK IX PUMP $L_p/N^2 = f_2 (W_p/N)$

$10^3 \frac{W_p}{N} \left(\frac{\text{lb/sec}}{\text{RPM}} \right)$	$\frac{1.5}{4} \times 10^5 \frac{W_p}{N} - 45.75$	$10^5 \frac{L_p}{N^2} \left(\frac{\text{in-lb}}{\text{RPM}^2} \right)$	$\frac{10^7}{2.3} \frac{L_p}{N^2}$
3.72	93.75	0.00	0.00
3.71	93.38	0.47	20.43
3.68	92.25	0.82	35.65
3.65	91.13	1.01	43.91
3.62	90.00	1.16	50.43
3.58	88.50	1.29	56.09
3.54	87.00	1.40	60.87
3.50	85.50	1.48	64.35
3.45	83.63	1.56	67.83
3.39	81.38	1.64	71.30
3.30	78.00	1.73	75.22
3.24	75.75	1.78	77.39
3.14	72.00	1.85	80.43
3.02	67.50	1.92	83.48
2.88	62.25	1.98	86.09
2.60	51.75	2.08	90.43
2.40	44.25	2.04	88.70
2.20	36.75	2.01	87.40
2.00	29.25	1.90	82.61
1.70	18.00	1.965	85.43
1.22	0.00	1.94	84.35

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$$8. \quad W_{bp}^2 = \frac{2g}{144} A_{bp}^2 (P_{pe1} - P_{ATM})$$

$$9. \quad W_p = W_{d2} + W_{bp}$$

Pump Discharge Line

$$10. \quad \frac{d W_{d2}}{dt} = \frac{2A_d g}{l} (P_{pe1} - P_{d3}) - \frac{2A_d g}{l_1} R_2 W_{d2}^2$$

$$11. \quad \frac{d P_{d3}}{dt} = \frac{(2)(144)\beta}{A_d l \rho} (W_{d2} - W_{d3})$$

$$12. \quad \frac{d W_{d3}}{dt} = \frac{2A_d g}{l} (P_{d3} - P_{d4}) - \frac{2A_d g}{l} R_3 W_{d3}^2$$

$$13. \quad \frac{d P_{d4}}{dt} = \frac{2\beta}{A_d l g} (W_{d3} - W_4)$$

Turbine Control Valve Actuator

$$14. \quad \frac{X_{50}}{X_{50d}} = \frac{1}{\left(\frac{s}{W_n}\right)^2 + \frac{2\zeta s}{W_n} + 1}$$

$$W_n = 94; \quad \zeta = 0.6$$

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Turbine Inlet Gas Line

$$15. A_{50} = K_1 X_{50} \quad K_1 = \frac{A_{50}}{X_{50}} = 2.3 \text{ in}$$

$$16. W_{ta} = \frac{A_{50} g P_T}{C^*}$$

$$17. \frac{d P_{Ti}}{dt} = \frac{RT}{V} (W_{ta} - W_{ti})$$

Mark IX Turbine

$$18. W_{ti} = (K_T - K_2 N) P_{Ti}$$

$$19. L_T = W_{ti} (4267 - 0.092N + 6.59 \times 10^{-7} N^2 - 1022 + 0.0744N - 1.79 \times 10^{-6} N^2)$$

$$20. \frac{dN}{dt} = \frac{30}{I\pi} (L_T - L_p)$$

Turbopump Specific Speed Controller

$$21. \frac{10^2 X_6 / 1.75}{10^2 X_{6d} / 1.75} = \frac{1}{(\tau s + 1) \left[\left(\frac{s}{W_N} \right)^2 - \frac{2\zeta}{W_N} s + 1 \right]}$$

$$\tau = \frac{1}{32}, W_N = 100, \zeta = 0.4$$

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$$\begin{aligned} 22. \quad A_6 &= 0 & X_6 < 0.175 \text{ in} \\ A_6 &= K_3 X_6 & 0.175 < X_6 < 1.204 \\ A_6 &= 2.5 & X_6 > 1.204 \end{aligned}$$

Turbine Speed Controller

$$23. \quad \frac{X_{50}^d}{N_\epsilon} = \frac{K \left(1 + \frac{S}{7.17}\right) \left(1 + \frac{S}{60.5}\right)}{S \left(1 + \frac{S}{133}\right)}$$

$$K = 0.5475 \times 10^{-3}$$

$$24. \quad N_\epsilon = N_d - N$$

Reactor Flow Controller

$$25. \quad \frac{N_d}{W_\epsilon} = \frac{K \left(1 + \frac{S}{20}\right)}{S \left(1 + \frac{S}{4}\right)} \quad K = 808$$

$$26. \quad W_\epsilon = W_{dem} - W_{d2}$$

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Turbopump Specific Speed Controller

$$27. \frac{10^2 \times \frac{6d}{1.75}}{W_{pe}} = \frac{K (1 + S/16.7)}{S (1 + S/102)} \quad K = 3.92$$

$$28. W_{pe} = K_n N - W_{pi2}$$

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V. ONL-CONSOLE MODELS

A. NERVA I

The equations used for the one-console model of the NERVA I system are presented in Section V-C. Represented by the model are the following components:

- (1) Nozzle coolant tubes
- (2) Reflector
- (3) Reactor Core
- (4) Tie Rod and
- (5) Nozzle Chamber

A block diagram indicating the location of these components in the flow system is shown in Figure 1.

The equations used for the representation of the system on one console are derived under the same general assumptions as the basic analog model described in Section II; therefore, the equations will merely be presented in listed form at the end of this particular section. The reduction in the amount of analog-computer equipment required to implement the system was accomplished by:

- (1) reducing the number of flow sections,
- (2) neglecting the flow work terms in the energy equations, for the reactor core, and
- (3) assuming tie rod flow to be directly proportional to core flow.

Dynamically the model should not be used for frequencies above one cycle per second. Statically the model gives reasonable results from the 100% design point down to approximately 10% power and flow.

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B. NERVA II

The equations used for the simulation of the NERVA II system on the analog computer are the same as those used for the NERVA I simulation, except for the tie tubes and the parameter values. The equations for the tie tube simulation and the constants used for the NERVA II model are presented in Section V-C. A flow schematic of the basic NERVA II system is shown in Figure 23.

The accuracy of the model is estimated to be approximately the same as that of the NERVA I one-console model; that is, dynamically accurate to about one cycle per second and statically good to approximately 10% power and flow.

C. Equations (See Table II for Nomenclature)

Nozzle Coolant Tubes:*

$$\frac{d}{dt} W_5 = \frac{A_{nc} g}{L_{nc}} (P_4 - P_5) - C_{nc} \frac{W_5^2}{\rho_5} \quad (1)$$

$$P_5 = \frac{\rho_5 R T_5}{1 - a \rho_5} - b \rho_5^2 \quad (2)$$

$$V_5 \frac{d}{dt} \rho_5 = W_5 - W_6 \quad (3)$$

$$M_{nc} C_{p_{nc}} \frac{d}{dt} \phi_{nc} = K_c \alpha_c W_5 (T_{nc} - \phi_{nc}) + K_H \alpha_H W_5 (T_8 - \phi_{nc}) \quad (4)$$

$$T_{nc} = \frac{2C_{p_g}}{2C_{p_g} + K_c \alpha_c} T_4 + \frac{K_c \alpha_c}{2C_{p_g} + K_c \alpha_c} \phi_{nc} \quad (5)$$

$$T_5 = 2T_{nc} - T_4 \quad (6)$$

*Parameter values are presented in Table VIII

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FIGURE 23

FLOW SCHEMATIC OF BASIC NERVA II SYSTEM

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TABLE VIII

PARAMETER VALUES FOR ONE-CONSOLE MODELS

<u>Parameter</u>		<u>NERVA I</u>	<u>NERVA II</u>
<u>Nozzle Coolant Tubes</u>			
A_{nc}	IN^2	15.4	32.38
L_{nc}	IN	64	92.8
C_{nc}	$1/IN^3$	1.307×10^{-3}	23.47×10^{-5}
V_5	IN^3	8070	5304
M_{nc}	lb	700	2100
Cp_{nc}	BTU/lb-°R	0.055	0.055
K_c	BTU/lb- IN^2 -°R	2.23×10^{-3}	1.079×10^{-3}
α_c	IN^2	9783	20,569
K_H	BTU/lb- IN^2 -°R	2.02×10^{-5}	8.124×10^{-6}
Cp_g	BTU/lb-°R	3.8	3.7
<u>Reflector</u>			
A_r	IN^2	85.55	273
L_r	IN	53.5	52
C_r	$1/IN^3$	1.657×10^{-3}	5.936×10^{-4}
V_r	IN^3	31,096	47,000
M_r	lb	4014	6664
Q_r	BTU/%-sec	196	688
K_r	BTU/lb- IN^2 -°R	6.67×10^{-5}	4.262×10^{-6}
α_r	IN^2	87,661	2.2×10^5
Cp_r	BTU/lb-°R	3.8	3.8

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PARAMETER VALUES (CONT'D)

<u>Parameter</u>		<u>NERVA I</u>	<u>NERVA II</u>
<u>Core</u>			
A_c	IN^2	7.23×10^{-3}	9.8×10^{-3}
L_c	IN	53.5	54
C_c	$1/IN^3$	21.73	12.36
M_c	lb	0.0759	0.0704
$Q_{c.1}$	$BTU/\%-sec$	0.3902	0.4564
$K_{c.1}$	$BTU/lb-IN^2-^{\circ}R$	2.191	0.5258
α_c	IN^2	16.13	19.0
$Q_{c.2}$	$BTU/\%-sec$	0.2700	0.4062
$K_{c.2}$	$BTU/lb-IN^2-^{\circ}R$	1.694	0.9968
Cp_c	$BTU/lb-^{\circ}R$	3.7	3.8
<u>Nozzle Chamber</u>			
V_c	IN^3	28,485	95,070
C_8	$^{\circ}R^{1/2}-IN^2/sec$	8.139	30.457
<u>Tie Rod (NERVA I)</u>			
K_{tr}		6.77	
α_{sg_o}	IN^2	167	
k_{sg}	$BTU/sec-^{\circ}R-IN$	1.53×10^{-3}	
M_{sg}	lb	1.385	

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PARAMETER VALUES (CONT'D)

<u>Parameter</u>	<u>NERVA I</u>	<u>NERVA II</u>
<u>Tie Rod (NERVA I)</u>		
Δ_{sg} IN	0.215	
$C_{p_{sg}}$ BTU/lb-°R	0.36	
Q_{sg} BTU/%-sec	0.515	
k_{pg} BTU/sec-°R-IN	8.1×10^{-6}	
$C_{p_{pg}}$ BTU/lb-°R	0.5	
ρ_{pg} lb/IN ³	0.0793	
Δ_{pg} IN	0.0565	
$\bar{r}_{pg}$ IN	0.1522	
Q_{pg} BTU/%-sec	0.085	
M_{pg} lb	0.194	
k_H BTU/sec-°R-IN	4.6×10^{-6}	
Δ_h IN	6.5×10^{-3}	
k_{ss} BTU/sec-°R-IN	2.31×10^{-4}	
Δ_{ss} IN	5×10^{-4}	
K_{tr_o} BTU/°R-lb-IN	0.2175	
K_{tr_j} BTU/°R-lb-IN	0.2592	
α_{ss_j} IN ²	38.4	
α_{tr_o} IN ²	18.65	

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PARAMETER VALUES (CONT'D)

<u>Parameter</u>	<u>NERVA I</u>	<u>NERVA II</u>
<u>Tie Rod (NERVA I)</u>		
C_{p_g} BTU/lb-°R	3.7	
k_{tr} BTU/sec-°R-IN	1.85×10^{-4}	
Δ_{tr} IN	0.055	
$C_{p_{tr}}$ BTU/lb-°R	0.12	
ρ_{tr} lb/IN ³	0.272	
Q_{tr} BTU/%-sec	0.0561	
<u>Tie Tube (NERVA II)</u>		
A_{tt} IN ²		0.0397
L_{tt} IN		106
C_{tt} 1/IN ³		1.419
K_{60}		0.84
α_{sg_o} IN ²		128.5
k_{sg} BTU/sec-IN-°R		1.3×10^{-4}
M_{sg} lb		1.165
Δ_{sg} IN		0.1635
$C_{p_{sg}}$ BTU/lb-°R		0.30
Q_{sg} BTU/%-sec		0.4738
k_{pg} BTU/sec-IN-°R		1.5×10^{-5}

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PARAMETER VALUES (CONT'D)

<u>Parameter</u>	<u>NERVA I</u>	<u>NERVA II</u>
<u>Tie Tube (NERVA II)</u>		
$C_{p_{pg}}$ BTU/lb-°R		0.18
ρ_{pg} lb/IN ³		0.102
Δ_{pg} IN		0.05
$\bar{r}_{pg}$ IN		0.1975
Q_{pg} BTU/%-sec		0.1148
M_{pg} lb		0.3354
k_{ss} BTU/sec-IN-°R		1.4×10^{-4}
Δ_{ss_2} IN		5×10^{-3}
$K_{ss_{2j}}$ BTU/IN ² -°R-lb		0.126
$K_{ss_{10}}$ BTU/IN ² -°R-lb		0.150
Δ_{ss_1} IN		0.015
$C_{p_{ss}}$ BTU/lb-°R		0.11
ρ_{ss} lb/IN ³		0.272
$\bar{r}_{ss_1}$ IN		0.0905
Q_{ss_1} BTU/%-sec		0.0434
M_{ss_1} lb		0.1230
$\alpha_{ss_{10}}$ IN ²		32.63
$\alpha_{ss_{2j}}$ IN ²		55.78

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PARAMETER VALUES (CONT'D)

<u>Parameter</u>	<u>NERVA I</u>	<u>NERVA II</u>
<u>Tie Tube (NERVA II)</u>		
C_{p_g} BTU/lb-°R		3.7
$K_{ss_{lj}}$ BTU/IN ² -°R-lb		0.1268
$\alpha_{ss_{lj}}$ IN ²		27.64

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Reflector:

$$\frac{d}{dt} W_6 = \frac{A_r g}{L_r} (P_5 - P_6) - C_r \frac{W_r^2}{\rho_6} \quad (7)$$

$$P_6 = \rho_6 R T_6 \quad (8)$$

$$V_r \frac{d}{dt} \rho_6 = W_r - W_{c_T} - W_{tr_T} \quad (\text{NERVA I}) \quad (9a)$$

$$V_r \frac{d}{dt} \rho_6 = W_r + W_{tt_T} - W_{c_T} \quad (\text{NERVA II}) \quad (9b)$$

$$M_r \frac{d}{dt} H_r = K_r \alpha_r W_5 (T_r - \phi_r) + Q_r n \quad (10)$$

$$\phi_r = f(H_r); \text{ Figure 11} \quad (11)$$

$$T_r = T_5 + \frac{K_r \alpha_r}{2 C p_r} (\phi_r - T_r) \quad (12)$$

$$T_{r_e} = 2 T_r - T_5 \quad (13)$$

$$P_7 = P_6 \quad (14)$$

$$T_{c_i} = T_{tr_i} = T_{r_e} \quad (\text{NERVA I}) \quad (15a)$$

$$T_{c_i} = \frac{W_r}{W_c} T_{r_e} + \frac{W_{tt}}{W_c} T_{tt_e} \quad (\text{NERVA II}) \quad (15b)$$

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Core:

$$\frac{d}{dt} W_c = \frac{A_c g}{L_c} (P_7 - P_8) - C_c \frac{W_c^2}{\rho_8} \quad (16)$$

$$M_c \frac{d}{dt} H_{c.1} = K_{c.1} \alpha_c W_c (T_{c.1} - \phi_{c.1}) + Q_{c.1} n \quad (17)$$

$$\phi_{c.1} = f(H_{c.1}); \quad \text{Figure 13} \quad (18)$$

$$M_c \frac{d}{dt} H_{c.2} = K_{c.2} \alpha_c W_c (T_{c.2} - \phi_{c.2}) + Q_{c.2} n \quad (19)$$

$$\phi_{c.2} = f(H_{c.2}); \quad \text{Figure 13} \quad (20)$$

$$T_{c.1} = T_{c_i} + \frac{K_{c.1} \alpha_c}{4 C p_c} (\phi_{c.1} - T_{c.1}) \quad (21)$$

$$T_{c.1_e} = 2 T_{c.1} - T_{c_i} \quad (22)$$

$$T_{c.2} = \frac{1}{3} (4 T_{c.1_e} - T_{c.1}) + \frac{K_{c.2} \alpha_c}{4 C p_c} (\phi_{c.2} - T_{c.2}) \quad (23)$$

$$T_{c.2_e} = 3 T_{c.2} - 3 T_{c.1_e} + T_{c.1} \quad (24)$$

$$\phi_c = \frac{1}{2} (\phi_{c.1} + \phi_{c.2}) \quad (25)$$

$$\rho_c = \frac{1}{7.28} (\rho_6 + 6.28 \rho_8) \quad (26)$$

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Nozzle Chamber:

$$V_c \frac{d}{dt} \rho_8 = W_{c_T} + W_{tr_T} - W_8 \quad (\text{NERVA I}) \quad (27a)$$

$$V_c \frac{d}{dt} \rho_8 = W_{c_T} - W_8 \quad (\text{NERVA II}) \quad (27b)$$

$$W_8 = C_8 \frac{P_8}{\sqrt{T_8}} \quad (28)$$

$$T_8 = 0.94 T_{c.2_e} + 0.06 T_{tr_e} \quad (\text{NERVA I}) \quad (29a)$$

$$T_8 = T_{c.2_e} \quad (\text{NERVA II}) \quad (29b)$$

$$P_8 = \rho_8 R T_8 \quad (30)$$

Tie Rod (NERVA I):

$$W_{tr} = K_{tr} W_c \quad (31)$$

$$\frac{d}{dt} \phi_{sg} = \frac{2\alpha_{sg} k_{sg}}{M_{sg} \Delta_{sg} C_{p_{sg}}} (\phi_c - \phi_{sg}) + \frac{Q_{sg}}{M_{sg} C_{p_{sg}}} n \quad (32)$$

$$\begin{aligned} \frac{d}{dt} \phi_{pg} = & \frac{k_{pg}}{C_{p_{pg}} \rho_{pg}} \left[\frac{1}{\Delta_{pg} r_{pg}} (\phi_{sg} - \phi_{pg_j}) + \frac{l}{\Delta_{pg}^2} (\phi_{sg} - 2\phi_{pg} + \phi_{pg_j}) \right] \\ & + \frac{Q_{pg}}{M_{pg} C_{p_{pg}}} n \end{aligned} \quad (33)$$

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$$\phi_{pg_j} = \frac{k_{pg} \Delta_h}{k_{pg} \Delta_h + k_H \Delta_{pg}} \phi_{pg} + \frac{k_H \Delta_{pg}}{k_{pg} \Delta_h + k_H \Delta_{pg}} T_H \quad (34)$$

$$T_H = \frac{1}{2} (\phi_{pg_j} + \phi_{ss_o}) \quad (35)$$

$$\phi_{ss_o} = \frac{k_{ss} \Delta_h}{k_{ss} \Delta_h + k_H \Delta_{ss}} \phi_{ss} + \frac{k_H \Delta_{ss}}{k_{ss} \Delta_h + k_H \Delta_{ss}} T_H \quad (36)$$

$$\phi_{ss} = \frac{1}{2} (\phi_{ss_j} + \phi_{ss_o}) \quad (37)$$

$$\phi_{ss_j} = \phi_{ss} + \frac{K_{tr_o} \Delta_{ss}}{2k_{ss}} W_{tr} (T_{tr} - \phi_{ss_j}) \quad (38)$$

$$T_{tr} = \phi_{tr_o} + \frac{K_{tr_o} \alpha_{ss_j}}{K_{tr_j} \alpha_{tr_o}} (\phi_{ss_j} - T_{tr}) + \frac{2Cp_g}{K_{tr_j} \alpha_{tr_o}} (T_{tr_i} - T_{tr}) \quad (39)$$

$$T_{tr_e} = 2 T_{tr} - T_{tr_i} \quad (40)$$

$$\phi_{tr_o} = \phi_{tr} + \frac{\Delta_{tr} K_{tr_j}}{2k_{tr}} W_{tr} (T_{tr} - \phi_{tr_o}) \quad (41)$$

$$\frac{d}{dt} \phi_{tr} = \frac{2k_{tr}}{Cp_{tr} \rho_{tr} \Delta_{tr}^2} (\phi_{tr_o} - \phi_{tr}) + \frac{Q_{tr}}{M_{tr} Cp_{tr}} n \quad (42)$$

Tie Tubes (NERVA II) (Nomenclature is given in Table IX):

$$\frac{d}{dt} W_{tt} = \frac{A_{tt} g}{L_{tt}} (P_{tt_i} - P_6) - C_{tt} \frac{W_{tt}^2}{\rho_6} \quad (43)$$

$$P_{tt_i} = K_{60} P_4 \quad (44)$$

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TABLE IX

NOMENCLATURE FOR TIE TUBES

Constants

A	Cross-sectional flow area	in^2
C, K	Constant (with subscript) obtained empirically or by curve fitting	
C _p	Specific heat at constant pressure	BTU/lb-°R
k	Thermal conductivity	BTU/sec-in-°R
L	Length	in
M	Mass	lb
$\bar{r}$	Average radius	in
α	Heat transfer surface area	in^2
Δ	Radial distance	in
ρ	Solid density (with letter subscript)	lb/in^3

Variables

P	Fluid pressure	psia
Q	Heat Power Generated	BTU/%-sec
t	Time	sec
T	Fluid Temperature	°R
W	Weight flow rate	lb/sec
ρ	Fluid density (with numerical subscript)	lb/in^3
ϕ	Material temperature	°R

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TABLE IX (CONT'D)

Station Designations

4	Tie tube and nozzle coolant tube inlet
6	Core inlet

Component and Flow Channel Identification

c	Fueled graphite channel in core
pg	Pyrolytic graphite sleeve in tie tube
ss ₁	Inner stainless steel liner
ss ₂	Outer stainless steel liner
sg	Structural graphite support element
tt	Tie tube

Qualifying Sub-subscripts

b	Mid-point in tie tube flow channel
e	Exit
i	Inlet
j	Surface at inside radius of component
o	Surface at outside radius of component

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$$\frac{d}{dt} \phi_{sg} = \frac{2\alpha_{sg_o} k_{sg}}{M_{sg} \Delta_{sg} C_{p_{sg}}} (\phi_c - \phi_{sg}) + \frac{Q_{sg}}{M_{sg} C_{p_{sg}}} n \quad (45)$$

$$\begin{aligned} \frac{d}{dt} \phi_{pg} = & \frac{k_{pg}}{C_{p_{pg}} \rho_{pg}} \left[\frac{1}{\Delta_{pg} \bar{r}_{pg}} (\phi_{sg} - \phi_{pg_j}) + \frac{4}{\Delta_{pg}^2} (\phi_{sg} - 2\phi_{pg} + \phi_{pg_j}) \right] \\ & + \frac{Q_{pg}}{M_{pg} C_{p_{pg}}} n \end{aligned} \quad (46)$$

$$\phi_{ss_2} = \frac{1}{2} (\phi_{pg_j} + \phi_{ss_{2j}}) \quad (47)$$

$$\phi_{ss_{20}} = \phi_{pg_j} = \frac{k_p \Delta_{ss_2}}{k_{pg} \Delta_{ss_2} + k_{ss} \Delta_{pg}} \phi_{pg} + \frac{k_{ss} \Delta_{pg}}{k_{pg} \Delta_{ss_2} + k_{ss} \Delta_{pg}} \phi_{ss_2} \quad (48)$$

$$\phi_{ss_{2j}} = \phi_{ss_2} + \frac{K_{ss_{2j}} \Delta_{ss_2}}{2k_{ss}} W_{tt} (T_{tt_2} - \phi_{ss_{2j}}) \quad (49)$$

$$\phi_{ss_{10}} = \phi_{ss_1} + \frac{K_{ss_{10}} \Delta_{ss_1}}{2k_{ss}} W_{tt} (T_{tt_2} - \phi_{ss_{10}}) \quad (50)$$

$$\begin{aligned} \frac{d}{dt} \phi_{ss_1} = & \frac{k_{ss}}{C_{p_{ss}} \rho_{ss}} \left[\frac{1}{\Delta_{ss_1} \bar{r}_{ss_1}} (\phi_{ss_{10}} - \phi_{ss_{1j}}) + \frac{4}{\Delta_{ss_1}^2} (\phi_{ss_{10}} - 2\phi_{ss_1} + \phi_{ss_{1j}}) \right] \\ & + \frac{Q_{ss_1}}{M_{ss_1} C_{p_{ss}}} n \end{aligned} \quad (51)$$

$$T_{tt_e} = 2T_{tt_2} - T_{tt_b} \quad (52)$$

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$$T_{tt_2} = T_{tt_b} + \frac{K_{ss_{10}} \alpha_{ss_{10}}}{2C_{pg}} (\phi_{ss_{10}} - T_{tt_2}) + \frac{K_{ss_{2j}} \alpha_{ss_{2j}}}{2C_{pg}} (\phi_{ss_{2j}} - T_{tt_2}) \quad (53)$$

$$T_{tt_b} = 2T_{tt_1} - T_{tt_i} \quad (54)$$

$$T_{tt_1} = T_{tt_i} + \frac{K_{ss_{1j}} \alpha_{ss_{1j}}}{2C_{pg}} (\phi_{ss_{1j}} - T_{tt_1}) \quad (55)$$

$$\phi_{ss_{1j}} = \phi_{ss_1} + \frac{K_{ss_{1j}} \Delta_{ss_1}}{2k_{ss}} W_{tt} (T_{tt_1} - \phi_{ss_{1j}}) \quad (56)$$

$$T_{tt_i} = T_h \quad (57)$$

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VI. PCV-41 EMERGENCY SHUTDOWN SYSTEM

Feedline Equations for Flow Shutdown Simulation

The feedline and PCV-41 actuator are shown in Figure 24. The equations used in the simulation are divided into three groups: (1) the PCV-41 actuator dynamics; (2) the variable volume gas slug which purges liquid from the feedline to the reactor; and (3) the variable volume liquid slug which must be displaced to the reactor before the ambient gas.

The PCV-41 dynamics are represented by*

$$\frac{X_M}{X_D} = \frac{1}{[(S/94)^2 + 2(0.6)S/94 + 1]} \quad (1)$$

The equations used to simulate the physical system from PCV-41 to the reactor nozzle inlet will be given in their respective physical order.

The flow area of PCV-41 as a function of stem position is given by

$$A_{41} = 0.0962 X_M \quad (2)$$

PCV-41 is assumed to be sonic at all operating conditions and is represented by

$$W_{41} = A_{41} K_1 P_4 \quad (3)$$

The P_{41} pressure is obtained from storage of gas between PCV-41 and FE-10.

$$\frac{d P_{41}}{dt} = \frac{RT_0}{V} (W_{41} - W_1) \quad (4)$$

The FE-10 flow venturi is simulated for both the sonic and subsonic flow regime by

$$W_1 = K_2 P_{41} \psi (P_1/P_{41}) \quad (5)$$

where the function, $\psi (P_1/P_{41})$ is shown in Figure 25.

* The Nomenclature and Constants are given in Table X.

FIGURE 24

SCHEMATIC OF NRX/EST PCV-41 AND PCV-18 EMERGENCY SHUTDOWN SYSTEMS

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TABLE X

NOMENCLATURE AND CONSTANTS FOR PCV-41 EMERGENCY SHUTDOWN MODEL

Constants

A_G	Average flow area of gas line pipe (NRX/EST)	31.8 in ²
A_L	Average flow area of liquid line pipe (NRX)	28.83 in ²
	Average flow area of liquid pipe (EST)	17.95 in ²
g	Acceleration of gravity	386.2 in/sec
K	Ratio of specific heats	1.4
K_1	Constant for sonic flow through PCV-41 with 2000 psia back pressure	0.00605/sec
K_2	Constant for sonic flow through FE-10	0.0183 in ² /sec
K_3	Linearized flow resistance of gas line	5 sec/in ²
K_4	Linearized flow resistance of liquid line	0.0835 sec/in ²
K_5	Constant approximating isentropic gas flow process	1.16
K_6	Constant for gas flow through nozzle tubes	1.28 sec/in ² - / $\sqrt{\theta R}$
K_7	Constant for gas flow through flow venturi	1.62 sec/in ² - / $\sqrt{\theta R}$
R	Gas constant for hydrogen	9200 in/ $^{\circ}R$
T_O	Temperature of gaseous hydrogen at P-041	525 $^{\circ}R$
ρ_L	Density of liquid hydrogen	0.00256 lb/in ³

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TABLE X (CONT'D)

Variables

A_{41}	Valve area of PCV-41 (full open)	9.62 in^2
P	System pressure	psia
t	Time	sec
T	Temperature	$^{\circ}\text{R}$
V	Volume of gas line from downstream side of PCV-41 to FE-10	3596 in^3
V_G	Initial volume of gas from FE-10 to liquid line (includes small lines)	$10400 \text{ in}^3 \text{ NRX}$
V_L	Initial volume of liquid from downstream side of ACV-3 to the reactor nozzle inlet (NRX) From engine pump outlet to reactor nozzle inlet (EST)	$19300 \text{ in}^3 \text{ NRX}$ $3895 \text{ in}^3 \text{ NRX}$
W	Mass flow rate	lb/sec
X	PCV-41 stem position	%
ρ_g	Gas density	lb/in^3

Subscripts

1	Downstream side of FE-10
2	Gas liquid interface and finally reactor inlet
4	Nozzle torus
5	Reflector inlet plenum
41	Downstream side of PCV-41

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TABLE X (CONT'D)

Subscripts

ri	Reactor nozzle inlet
t	Throat of FE-10 or flow venturi
o	Designate constant condition
M	Measured
F1	Upstream side of flow venturi
F2	Downstream side of flow venturi
D	Demanded
E	Error
U	Upstream of PCV-41
G	Gas
L	Liquid

Superscripts

-	Average
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It was assumed that the venturi recovery factor is 80% and is mathematically represented by

$$0.8 (P_{h1} - P_t) = (P_1 - P_t) \quad (6)$$

for

$$0 \leq (P_t/P_{h1}) \leq 1$$

Choked flow occurs for a venturi throat until the upstream pressure ratio of 0.528 or a downstream to upstream ratio of 0.905 under the 30% recovery factor condition is reached.

In the gas and liquid slugs acceleration, friction pressure losses and fluid storage are accounted for in respective lumped parameter equations.

A differential momentum balance for the variable gas volume is represented by

$$\frac{dW_G}{dt} = \xi \frac{A_G^2}{V_G} (P_1 - P_2) - \frac{\xi A_G^2 K_3}{V_G} \quad (7)$$

In the preceding equation, W_G is the average gas flow rate and is related to the inlet and outlet by

$$W_G = (W_1 + W_{2G}) \quad (8)$$

Mass accumulation of gas in the control volume is accounted for by integrating the net flow into the gas volume:

$$\frac{dP_G}{dt} = \frac{K_5 RT_o}{V_G} (W_1 - W_{G2}) \quad (9)$$

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In the above equation, gas density was related to average gas pressure by an average isentropic process

$$P_G \rho_G^{-K} = \text{CONST} \quad (10)$$

therefore

$$dP_G = K_5 R T_o dp_g \quad (11)$$

where a K_5 of 1.16 was used for an ambient gas temperature, T_o , of 525°R and a pressure drop of from 900 to 200 psia.

The average pressure P_G is related to inlet and outlet pressures by

$$P_G = (P_1 + P_2)/2 \quad (12)$$

The liquid gas interface exists while the gas pushes liquid to the reactor. At the end of the liquid, the liquid flow rate is artificially decayed to zero on a 0.1 second time constant for NRX and 0.01 second time constant for EST type flow shutdowns simulating the gradual transition from gas to liquid at the reactor nozzle. Prior to expelling all the liquid, the component velocities of gas and liquid at the interface are assumed to be equal and therefore

$$W_{2G} = W_{2L} \rho_G / \rho_L \quad (13)$$

In a manner similar to that in which the gas slug was simulated mathematically, a differential momentum balance for the liquid slug is given by

$$\frac{dW_L}{dt} = \frac{g A_L^2}{V_L} (P_2 - P_{ri}) - \frac{g A_L^2 K_4}{V_L} W_L^2 \quad (14)$$

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Storage is accounted for by integrating the net flow of liquid into the control volume assuming isentropic flow

$$\frac{dP_L}{dt} = \frac{\beta}{\rho_L V_L} (W_{2L} - W_{ri}) \quad (15)$$

As with the gas system, the relationship for average pressure and flow parameters is represented by

Flow

$$W_L = (W_{2L} + W_{ri})/2 \quad (16)$$

Pressure

$$P_L = (P_2 + P_{ri})/2 \quad (17)$$

The volume of liquid entering the reactor is obtained from integrating the liquid volumetric flow

$$\frac{dV_L}{dt} = - \frac{W_{ri}}{\rho_L} \quad (18)$$

where

$$V_L(0) = 19300 \text{ in}^3 \text{ NRX or } 3895 \text{ in}^3 \text{ EST} \quad (19)$$

The variable gas volume is then given by

$$V_G = 25840 - V_L \text{ NRX or EST} \quad (20)$$

where

$$0 < V_L < 19300 \text{ in}^3 \text{ NRX or } 0 < V_L < 3895 \text{ in}^3 \text{ EST.}$$

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The reactor model is used to simulate nozzle torus pressure as a function of flow for liquid flow. On switching to ambient gas, the following choked flow relationship is used for reactor nozzle tube pressure drop in the reactor model in place of the liquid flow nozzle tube pressure drop.

$$P_{L_4} = K_5 W / \overline{T_{L_4}} / \psi (P_5/P_{L_4}) \quad (21)$$

where

$$\psi (P_5/P_{L_4}) \text{ is shown in Figure 26} \quad (21)$$

The inlet temperature, T_{L_4} , is raised exponentially from liquid to ambient gas temperature on a 0.1 and 1 second time constant, respectively, for EST and NRX simulations. (This occurs after liquid to the reactor is exhausted).

The liquid flow venturi in the engine pump discharge line is simulated for gaseous hydrogen flow after the gas-liquid interface has past, i.e., just prior to exhausting the last 1210 in³ of liquid to the reactor which is equivalent to the line volume from the flow venturi to the reactor nozzle torus).

$$P_{F1} = K_7 W_{2G} / \overline{T_{F1}} / \psi (P_{F2}/P_{F1}) \quad (22)$$

where $\psi (P_{F2}/P_{F1})$ is the same as that shown in Figure 24 (assumed 80% recovery factor).

The temperature, T_{F1} , is simulated in the same manner as T_{L_4} . The pressure drop across the venturi, $P_{F1} - P_{F2}$, is added to the line losses of equation (6) when gas passes through it.

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FIGURE 26

$\psi(P_5/P_4)$ VERSUS PRESSURE RATIO (P_5/P_4)

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VII. PCV-18 EMERGENCY SHUTDOWN SYSTEM

The feedline and PCV-18 valve used in the emergency dome flow shutdown system are shown in Figure 24. The following equations describe the gas flow dynamics from the tank farm to the reactor dome.

The tank farm pressure is assumed constant*

$$P_T = 3200 \text{ psia} \quad (1)$$

A differential momentum balance for the gas volume between the tank farm and PCV-18 is represented by

$$\frac{dW_1}{dt} = \frac{gA_o}{L_o} (P_T - P_{18}) - \frac{gK_1RTA_o}{L_o} \frac{W_1^2}{P_{18}} \quad (2)$$

The pressure upstream of PCV-18 is established based on the accumulation of mass between the tank farm and the valve:

$$\frac{dP_{18}}{dt} = \frac{RT}{V_o} (W_1 - W_{18}) \quad (3)$$

Flow through the PCV-18 valve is represented by the following relationship

$$W_{18} = \frac{.14}{\sqrt{T}} A_{18} P_{18} \Psi(P_1/P_{18})$$

where the function, $\Psi(P_1/P_{18})$, is shown in Figure 27.

The pressure downstream of PCV-18 is calculated taking into account mass accumulation in the first half of the volume between PCV-18 and the reactor dome.

* Nomenclature and constants are given in Table XI.

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TABLE XI

NOMENCLATURE AND CONSTANTS FOR PCV-18 MODEL

Constants

K_1	Constant for pressure drop calculation	$1.33 \times 10^{-4} \text{ sec}^2/\text{in}^5$
K_2	Constant for pressure drop calculation	$0.177 \times 10^{-4} \text{ sec}^2/\text{in}^5$
V_0	Gas volume between tank farm and PCV-18	$325,000 \text{ in}^3$
V_1	Gas volume between PCV-18 and reactor dome	$23,591 \text{ in}^3$
R	Gas constant for hydrogen	$9200 \text{ in}/^\circ\text{R}$
g	Acceleration of gravity	$386 \text{ in}/\text{sec}^2$
P_T	Tank farm pressure	3200 psia
A_0	Gas line flow area between tank farms and PCV-18 (I.D. 5.189)	37.6 in^2
T_0	Ambient gas temperature	540°R
A_2	Total flow area of check valves in dome port	8.58 in^2
A_1	Average flow area between PCV-18 and dome check valves	24.6 in^2
L_0	Length between tank farm and PCV-18	8640 in.
L_1	Length between PCV-18 and reactor dome	952 in.

Variables

A_{18}	PCV-18 flow area (full open)	9.65 in^2
W	Gas flow	$\text{lb}/\text{sec.}$
P	System pressure	(psia)

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TABLE XI (CONT'D)

Subscripts

1	Downstream side of PCV-18
2	Upstream side of check valves in dome ports
18	Upstream side of PCV-18

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FIGURE 27

$\psi(P_1/P_{18})$ VERSUS PRESSURE RATIO (P_1/P_{18})

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$$\frac{dP_1}{dt} = \frac{2RT}{V_1} (W_{18} - W_2)$$

A differential momentum balance for the gas volume between PCV-18 and the reactor dome is represented by:

$$\frac{dW_2}{dt} = \frac{gA_1}{L_1} (P_1 - P_2) - \frac{gK_2RTA_1W_6^2}{L_1P_2}$$

The pressure upstream of the bleed ports in the reactor dome is calculated taking into account mass accumulation in the second half of the volume between PCV-18 and the reactor dome:

$$\frac{dP_2}{dt} = \frac{2RT}{V_1} (W_2 - W_6)$$

The bleed ports into the dome are simulated with the following GH_2 equation

$$W_6 = \frac{0.14}{\sqrt{T}} A_2 P_2 \Psi (P_6/P_2)$$

The above equations are coupled to the dome sector of the reactor analog model for emergency dome purge studies.

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VIII. CAM-II

A combined effort has been underway at AGC and WANL to establish a common analog model (CAM) for use in systems dynamic analysis. At the time of writing of this document, the second common analog model (CAM-II) has been agreed upon. WANL has responsibility for the reflector, shield, tie rod, and reactor core, while the other portions are the responsibility of AGC.

The CAM-II input of WANL is exactly as appears under Section II of this report with the exception of the nozzle tubes.

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