MASTER

Subcontract NP-1

WANL-TME-1841

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Westinghouse Astronuclear Laboratory

SPECIAL REVIEW FINAL DETERMINATION	Reviewed	Class.	Date
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R-1 COMMON ANALOG MODEL

(Title Unclassified)

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R-1 Common Analog Model

The following sections define the R-1 Common Analog Model (R-1 CAM). The Table of Contents identifies the date and number of the latest revision for each section since the initial issue of this R-1 CAM on March 22, 1968. Approvals and acknowledgements of the revisions are at the end of the Table of Contents.

The R-1 test system will consist of the 1575 MW R-1 reactor and the Test Cell "C" feedsystem (single pump mode). A dynamics simulation of this test system has been developed to provide a common reference for NERVA R-1 dynamics analysis. Aerojet-General Corporation has provided the model equations and coefficients for the nozzle, including the thrust chamber thermocouple.

TABLE OF CONTENTS

	<u>Revision</u>	<u>Date</u>
I. MODEL SUMMARY		
A. Feedsystem		
1. Turbopump	0	March 22, 1968
2. Pump Bypass Valve	0	March 22, 1968
3. Heat Exchanger	0	March 22, 1968
4. Turbine and Turbine Inlet Valve	0	March 22, 1968
5. Feedline to Support System Connection	0	March 22, 1968
B. Reactor and Nozzle		
1. Feedline to Nozzle Torus	0	March 22, 1968
2. Nozzle Skirt	0	March 22, 1968
3. Nozzle Coolant Tubes	0	March 22, 1968
4. Reflector Inlet Plenum	0	March 22, 1968
5. Reflector and Peripheral Shield	0	March 22, 1968
6. Dome End Plenum	0	March 22, 1968
7. Shield and Support Plate	0	March 22, 1968
8. Core Inlet Plenum	0	March 22, 1968
9. Core and Core Periphery	0	March 22, 1968
10. Support System Inlet and Bypass	0	March 22, 1968
11. Support System	0	March 22, 1968
12. Reactivity	0	March 22, 1968
13. Kinetics	0	March 22, 1968
14. Thrust Chamber	0	March 22, 1968
C. Controls, Actuators, Transducers, Safety Circuits		
1. Drum Control	0	March 22, 1968
2. Turbine Inlet Valve Control	0	March 22, 1968
3. Heat Exchanger Valve Control	0	March 22, 1968
4. Pump Bypass Valve Control	0	March 22, 1968
D. Support Facility	—	—

TABLE OF CONTENTS (Cont'd.)

	<u>Revision</u>	<u>Date</u>
II. DERIVATIONS		
A. General	—	—
B. Specific	—	—
III. MODEL CHECKS		
A. Design		
1. Steady State	0	March 22, 1968
2. Frequency Response	0	March 22, 1968
3. Transient Response	—	—
B. Low Power		
1. Steady State	—	—
2. Frequency Response	—	—
3. Transient Response	—	—
IV. NOMENCLATURE	0	March 22, 1968

APPROVED BY

ACKNOWLEDGED BY

R. P. Rose

3/26/68

R. P. Rose, WANL

Date

D. Buden

7/10/68

D. Buden, AGC

I A-1 TURBOPUMP

- 1) $P_0 = C_{150}$
- 2) $XL_p = C_{153} Spd^2 - C_{154} W_1 Spd$
- 3) $DP_p = C_{155} Spd^2 - C_{156} W_1 Spd$
- 4) $P_1 = P_0 + DP_p$
- 5) $\frac{d}{dt} Spd = C_{157}(XL_t - XL_p)$
- 6) $\frac{d}{dt} W_1 = C_{158}\left(P_1 - P_2 - C_{159}|W_1|W_1\right)$

where:

C_{150}	=	81.89
C_{153}	=	3.450×10^{-5}
C_{154}	=	0.0010
C_{155}	=	3.280×10^{-6}
C_{156}	=	4.000×10^{-4}
C_{157}	=	3.396
C_{158}	=	77.61
C_{159}	=	0.005222

I A-2 PUMP BYPASS VALVE

1) $A_{109} = f(X_{109})$ (See Table I A-2-1)

2) $W_{109} = C_{160} A_{109} |P_2 - 13.5|^{.5} \left[\frac{(P_2 - 13.5)}{|P_2 - 13.5|} \right]$

where:

$C_{160} = 1.401$

I A-2 PUMP BYPASS VALVE (continued)

TABLE I A-2-1

A_{109} vs X_{109}

<u>$X_{109}(\%)$</u>	<u>$A_{109}(\text{in.}^2)$</u>
0.0	0.0
10.0	0.0
15.0	0.2394
20.0	0.5582
25.0	0.8996
30.0	1.386
35.0	1.943
40.0	2.797
72.0	10.21
100.0	12.6

I A-3 HEAT EXCHANGER

- 1) $\frac{d}{dt} W_{he1} = C_{161} (P_2 - P_{he1} - C_{162} |W_{he1}| W_{he1})$
- 2) $\frac{d}{dt} P_{he1} = C_{163} (W_{he1} - W_{he2})$
- 3) $A_{21} = C_{164} X_{21}$
- 4) $W_{he2} = C_{165} A_{21} |P_{he1} - P_{he2}|^{.5} \left[\frac{(P_{he1} - P_{he2})}{|P_{he1} - P_{he2}|} \right]$
- 5) $\frac{d}{dt} R_{he2} = C_{166} (W_{he2} - W_{he3})$
- 6) $P_{he2} = C_{167} R_{he2}$

where:

C_{161}	=	7.384
C_{162}	=	0.002250
C_{163}	=	166.9
C_{164}	=	0.02500
C_{165}	=	2.802
C_{166}	=	5.265×10^{-6}
C_{167}	=	5.711×10^6

I A-3 HEAT EXCHANGER (continued)

$$7) \frac{d}{dt} W_{he3} = C_{168} \left(P_{he2} - P_{he3} - \frac{C_{169} |W_{he3}| W_{he3}}{R_{he3}} \right)$$

$$8) \frac{d}{dt} R_{he3} = C_{170} (W_{he3} - W_{he4})$$

$$9) P_{he3} = C_{171} R_{he3}$$

where:

$$C_{168} = 3.244$$

$$C_{169} = 4.470 \times 10^{-5}$$

$$C_{170} = 2.045 \times 10^{-5}$$

$$C_{171} = 5.704 \times 10^6$$

I A-4 TURBINE AND TURBINE INLET VALVE

1) $A_{60} = f(X_{60})$ (See Table I A-4-1)

2) $P_{si} = f\left(\frac{P_{he4}}{P_{he3}}\right)$ (See Table I A-4-2)

3) $W_{he4} = C_{172} A_{60} P_{he3} P_{si}$

4) $P_{he4} = C_{173} W_{he4}$

5) $XL_t = P_{he4} (C_{151} - C_{152} Spd)$

where:

$C_{172} = 0.005643$

$C_{173} = 48.80$

$C_{151} = 66.30$

$C_{152} = 9.820 \times 10^{-4}$

I A-4 TURBINE AND TURBINE INLET VALVE (continued)

TABLE I A-4-1

A_{60} vs X_{60}

<u>X_{60} (%)</u>	<u>A_{60} (in.²)</u>
0.0	0.0
10.0	1.35
20.0	2.65
30.0	3.85
40.0	5.1
50.0	6.1
60.0	7.0
70.0	7.75
80.0	8.3
90.0	8.7
100.0	9.02

I A-4 TURBINE AND TURBINE INLET VALVE (continued)

TABLE I A-4-2

Psi vs $\left(\frac{P_{he4}}{P_{he3}}\right)$

$\left(\frac{P_{he4}}{P_{he3}}\right)$	Psi
0.0	1.0
0.528	1.0
0.7	0.92
0.8	0.81
0.9	0.60
0.95	0.45
0.99	0.13
1.00	0.0
1.03	-0.2

I A-5 FEEDLINE TO SUPPORT SYSTEM CONNECTION

$$1) \quad \frac{d}{dt} P_2 = C_{174}(W_1 - W_2 - W_{109} - W_{hel})$$

$$2) \quad \frac{d}{dt} W_2 = C_{175} \left(P_2 - P_3 - C_{176} |W_2| W_2 \right)$$

$$3) \quad \frac{d}{dt} P_3 = C_{177}(W_2 - W_3)$$

$$4) \quad \frac{d}{dt} W_3 = C_{178} \left(P_3 - P_4 - C_{179} |W_3| W_3 \right)$$

$$5) \quad \frac{d}{dt} P_4 = C_{180}(W_3 - W_4)$$

$$6) \quad W_4 = W_5 + W_{ss1} + W_{ssb}$$

where:

$$C_{174} = 1165.$$

$$C_{175} = 37.77$$

$$C_{176} = 0.001280$$

$$C_{177} = 124.6$$

$$C_{178} = 31.02$$

$$C_{179} = 0.002395$$

$$C_{180} = 188.1$$

I B-1 FEEDLINE TO NOZZLE TORUS

1) P_4 = Input from Test Cell "C" (See Section I A-5)

2) T_4 = Independent variable

3) T_5 = T_4

4) $\frac{d}{dt} W_5$ = $C_{63}(P_4 - P_5 - C_{64}W_5|W_5|)$

5) $\frac{d}{dt} P_5$ = $\left(\frac{C_{131} + C_{132}P_5}{C_{133}}\right)(W_5 - W_6 - W_{6x} - W_{18})$

where:

C_{63} = 161.9

C_{64} = 0.01145

C_{131} = 2000.

C_{132} = 1.560

C_{133} = 5.516

I B-2 NOZZLE SKIRT

$$1) \quad \frac{d}{dt} H_x = .067 \left(.068 |W_{15}|^{.8} (T_{15} - \phi_x) - .200 |W_{6x}|^{.8} (\phi_x - T_{6x}) \right)$$

$$2) \quad \phi_x = 8.7 H_x + 540$$

$$3) \quad \frac{d}{dt} T_{6x} = .0678 \left(.200 |W_{6x}|^{.8} (\phi_x - T_{6x}) - 3.86 W_{6x} (T_{6x} - T_5) \right)$$

$$4) \quad \frac{d}{dt} W_{6x} = 78.42 \left(P_5 - P_7 - .6961 W_{6x} |W_{6x}| \right)$$

I B-3 NOZZLE COOLANT TUBES

$$1) \quad \frac{d}{dt} H_n = .1688 \left(.162 |W_{15}|^{.8} (T_{15} - \phi_n) - .785 |W_6|^{.8} (\phi_n - T_6) \right)$$

$$2) \quad \phi_n = 8.1 H_n + 540$$

$$3) \quad \frac{d}{dt} T_6 = .5272 \left(.785 |W_6|^{.8} (\phi_n - T_6) - 3.86 W_6 (T_6 - T_5) \right)$$

$$4) \quad \frac{d}{dt} W_6 = 111.55 \left(P_5 - P_7 - .2018 W_6 |W_6| \right)$$

$$5) \quad \frac{d}{dt} W_{18} = 1.213 \left(P_5 - P_7 - 66.75 W_{18} |W_{18}| \right)$$

I B-4 REFLECTOR INLET PLENUM

$$1) \quad \frac{d}{dt} R_7 = C_1 (W_6 + W_{6x} + W_{18} - W_r)$$

$$2) \quad \frac{d}{dt} T_7 = C_2 (W_6 T_6 + W_{6x} T_{6x} + W_{18} T_5 - W_r T_7)$$

$$3) \quad P_7 = T_7 f_1(R_7) - f_2(R_7) \quad \begin{array}{l} \text{(See Tables I B-4-1} \\ \text{and I B-4-2)} \end{array}$$

$$4) \quad E_7 = C_3 T_7 - C_4 P_7 - C_5$$

where:

$$C_1 = 0.1741$$

$$C_2 = 0.6005$$

$$C_3 = 3.670$$

$$C_4 = 0.06514$$

$$C_5 = 162.0$$

I B-4 REFLECTOR INLET PLENUM (continued)

TABLE I B-4-1

$f_1(R_7)$ vs R_7

<u>$R_7(\text{lb/ft.}^3)$</u>	<u>$f_1(R_7)$ (psia/°R)</u>
0.0000	0.000
0.2516	1.426
0.6290	3.881
0.8806	5.733
1.132	7.787
1.635	12.53
2.020	16.62
2.520	23.20
3.019	31.87
3.271	37.15
3.744	49.82

I B-4 REFLECTOR INLET PLENUM (continued)

TABLE I B-4-2

$f_2(R_7)$ vs R_7

<u>R_7 (lb/ft.³)</u>	<u>$f_2(R_7)$ (psia)</u>
0.0000	0.0
0.2516	15.63
0.5032	60.06
1.040	224.2
1.384	410.7
1.824	674.7
2.390	1089.0
2.768	1420.0
3.500	2160.0
3.744	2371.0

I B-5 REFLECTOR AND PERIPHERAL SHIELD

$$1) \quad T_r = C_6 E_r + C_7 \left(\frac{P_7 + P_9}{2} \right) + C_8$$

$$2) \quad \begin{aligned} HD_r &= C_9 + C_{10} T_r & T_r < 250^\circ R \\ &= 0.300 & T_r > 250^\circ R \end{aligned}$$

$$3) \quad \phi_r = f(H_r) \quad (\text{See Table I B-5-1})$$

$$4) \quad \frac{d}{dt} W_r = C_{11} \left(P_7 - P_9 - \frac{C_{12} W_r |W_r|}{R_{10}} \right)$$

$$5) \quad \frac{d}{dt} E_r = C_{13} \left(2W_r (E_7 - E_r) + C_{14} HD_r |W_r|^{.8} (\phi_r - T_r) \right)$$

where:

$$\begin{aligned} C_6 &= 0.2725 \\ C_7 &= 0.01775 \\ C_8 &= 44.14 \\ C_9 &= 0.1960 \\ C_{10} &= 4.160 \times 10^{-4} \\ C_{11} &= 499.5 \\ C_{12} &= 0.008503 \\ C_{13} &= 0.6189 \\ C_{14} &= 36.97 \end{aligned}$$

I B-5 REFLECTOR AND PERIPHERAL SHIELD (continued)

$$6) \quad \frac{d}{dt} H_r = C_{15} \left(C_{14}^{HD} |W_r|^{.8} (T_r - \phi_r) + C_{16} S_{NQ} \right)$$

$$7) \quad T_9 = C_{17} E_9 + C_{18} P_9 + C_{19}$$

$$8) \quad P_9 = P_{10}$$

$$9) \quad E_9 = 2E_r - E_7$$

where:

$$C_{14} = 36.97$$

$$C_{15} = 7.405 \times 10^{-4}$$

$$C_{16} = 268.2$$

$$C_{17} = 0.2651$$

$$C_{18} = 0.03218$$

$$C_{19} = 45.00$$

I B-5 REFLECTOR AND PERIPHERAL SHIELD (continued)

TABLE I B-5-1

ϕ_r vs H_r

H_r (BTU/lb.)	ϕ_r ($^{\circ}$ R)
0	0
5	185
10	235
15	275
20	310
25	335
30	360
35	385
40	405
45	425
50	445
55	465
60	480
100	605

I B-6 DOME END PLENUM

- 1) $\frac{d}{dt} R_{10} = C_{23}(W_r + W_{ss} + W_{ssb} - W_s)$
- 2) $\frac{d}{dt} E_{10} = C_{24}(W_r E_9 + W_{ss} E_{22} + W_{ssb} E_{ssb} - W_s E_{10})$
- 3) $P_{10} = 5.32 R_{10} T_{10}$
- 4) $T_{10} = C_{20} E_{10} + C_{21} P_{10} + C_{22}$

where:

C_{20}	=	0.2651
C_{21}	=	0.03218
C_{22}	=	45.00
C_{23}	=	0.04998
C_{24}	=	0.1118

I B-7 SHIELD AND SUPPORT PLATE

$$1) \quad T_s = C_{25}E_s + C_{26} \left(\frac{P_{10} + P_{12}}{2} \right) + C_{27}$$

$$2) \quad \begin{aligned} HD_s &= C_{28} + C_{29}T_s & T_s < 250^\circ R \\ &= 0.300 & T_s > 250^\circ R \end{aligned}$$

$$3) \quad \phi_s = f(H_s) \quad (\text{See Table I B-7-1})$$

$$4) \quad \frac{d}{dt} W_s = C_{30} \left(P_{10} - P_{12} - \frac{C_{31}W_s |W_s|}{R_{12}} \right)$$

where:

$$\begin{aligned} C_{25} &= 0.2651 \\ C_{26} &= 0.03218 \\ C_{27} &= 45.00 \\ C_{28} &= 0.1960 \\ C_{29} &= 4.16 \times 10^{-4} \\ C_{30} &= 2832. \\ C_{31} &= 7.417 \times 10^{-4} \end{aligned}$$

I B-7 SHIELD AND SUPPORT PLATE (continued)

$$5) \frac{d}{dt} E_s = C_{32} \left(2W_s (E_{10} - E_s) + C_{33}^{HD_s} |W_s|^{.8} (\phi_s - T_s) \right)$$

$$6) \frac{d}{dt} H_s = C_{34} \left(C_{33}^{HD_s} |W_s|^{.8} (T_s - \phi_s) + C_{35} S_{NO} \right)$$

where:

$$C_{32} = 2.095$$

$$C_{33} = 20.24$$

$$C_{34} = 6.198 \times 10^{-4}$$

$$C_{35} = 38.55$$

I B-7 SHIELD AND SUPPORT PLATE (continued)

TABLE I B-7-1

ϕ_s vs H_s

<u>H_s (BTU/lb.)</u>	<u>ϕ_s ($^{\circ}$R)</u>
0	0
4	120
8	160
12	200
16	230
20	255
24	280
28	305
32	325
36	345
40	365
44	385
48	405
100	665

I B-8 CORE INLET PLENUM

$$1) \quad \frac{d}{dt} R_{12} = C_{39}(W_s - W_c - W_{cp})$$

$$2) \quad T_{12} = C_{36}E_{12} + C_{37}P_{12} + C_{38}$$

$$3) \quad P_{12} = 5.32T_{12}R_{12}$$

$$4) \quad E_{12} = 2E_s - E_{10}$$

where:

$$C_{36} = 0.2651$$

$$C_{37} = 0.03218$$

$$C_{38} = 45.00$$

$$C_{39} = 0.2530$$

I B-9 CORE AND CORE PERIPHERY

- 1) $T_{c1} = C_{40}E_{c1} + C_{41}$
- 2) $T_{c2} = C_{40}E_{c2} + C_{41}$
- 3) $T_{c3} = f(E_{c3})$ (See Table I B-9-1)
- 4) $HD_{c1} = C_{42} + C_{43}T_{c1}$
- 5) $HD_{c2} = C_{42} + C_{43}T_{c2}$
- 6) $HD_{c3} = C_{42} + C_{43}T_{c3}$
- 7) $\phi_{c1} = f(H_{c1})$ (See Table I B-9-2)
- 8) $\phi_{c2} = f(H_{c2})$ (See Table I B-9-2)
- 9) $\phi_{c3} = f(H_{c3})$ (See Table I B-9-2)
- 10) $E_{c1e} = 2E_{c1} - E_{12}$
- 11) $E_{c2e} = 2E_{c2} - E_{c1e}$
- 12) $E_{c3e} = 2E_{c3} - E_{c2e}$
- 13) $T_{c3e} = f(E_{c3e})$ (See Table I B-9-1)
- 14) $\phi_c = .125(3\phi_{c1} + 2\phi_{c2} + 3\phi_{c3})$

where:

$$\begin{aligned}
 C_{40} &= 0.2791 \\
 C_{41} &= 56.00 \\
 C_{42} &= 0.2750 \\
 C_{43} &= 4.75 \times 10^{-5}
 \end{aligned}$$

I B-9 CORE AND CORE PERIPHERY (continued)

$$\begin{aligned} 15) \quad \frac{d}{dt} E_{c1} &= C_{44} \left(2W_c (E_{12} - E_{c1}) + C_{47}^{HD} c1 |W_c|^{.8} (\phi_{c1} - T_{c1}) \right) \\ 16) \quad \frac{d}{dt} E_{c2} &= C_{45} \left(2W_c (E_{c1e} - E_{c2}) + C_{47}^{HD} c2 |W_c|^{.8} (\phi_{c2} - T_{c2}) \right) \\ 17) \quad \frac{d}{dt} E_{c3} &= C_{46} \left(2W_c (E_{c2e} - E_{c3}) + C_{47}^{HD} c3 |W_c|^{.8} (\phi_{c3} - T_{c3}) \right) \\ 18) \quad \frac{d}{dt} H_{c1} &= C_{51} \left(C_{47}^{HD} c1 |W_c|^{.8} (T_{c1} - \phi_{c1}) + C_{48} S \right) \\ 19) \quad \frac{d}{dt} H_{c2} &= C_{51} \left(C_{47}^{HD} c2 |W_c|^{.8} (T_{c2} - \phi_{c2}) + C_{49} S \right) \\ 20) \quad \frac{d}{dt} H_{c3} &= C_{51} \left(C_{47}^{HD} c3 |W_c|^{.8} (T_{c3} - \phi_{c3}) + C_{50} S \right) \\ 21) \quad R_c &= C_{52} R_{12} + C_{53} R_{15} \end{aligned}$$

where:

$$\begin{aligned} C_{44} &= 0.9854 \\ C_{45} &= 1.971 \\ C_{46} &= 3.942 \\ C_{47} &= 61.11 \\ C_{48} &= 4020. \\ C_{49} &= 6361. \\ C_{50} &= 3955. \\ C_{51} &= 0.001025 \\ C_{52} &= 0.1590 \\ C_{53} &= 0.8410 \end{aligned}$$

I B-9 CORE AND CORE PERIPHERY (continued)

$$22) \quad \frac{d}{dt} W_c = C_{54} \left[P_{12} - P_{14} - W_c |W_c| \left(\frac{C_{55}}{R_{12}} + \frac{C_{56}}{R_{15}} \right) \right]$$

$$23) \quad W_{cp} = C_{57} W_c$$

$$24) \quad T_{13a} = T_{12} + C_{58} (\phi_c - T_{12})$$

$$25) \quad P_{14} = P_{15}$$

where:

$$C_{54} = 1879.$$

$$C_{55} = 3.479 \times 10^{-3}$$

$$C_{56} = 2.521 \times 10^{-4}$$

$$C_{57} = 0.01714$$

$$C_{58} = 0.2897$$

I B-9 CORE AND CORE PERIPHERY (continued)

TABLE I B-9-1

T_{cn} vs E_{cn} $n = 3, 3e$

<u>E_{cn} (BTU/lb.)</u>	<u>T_{cn} ($^{\circ}$R)</u>
0	0
1659	500
3411	1000
5158	1500
6938	2000
8790	2500
10720	3000
12730	3500
14810	4000
17025	4500
19435	5000
21850	5500

I B-9 CORE AND CORE PERIPHERY (continued)

TABLE I B-9-2

ϕ_{cn} vs H_{cn} $n = 1, 2, 3$

<u>H_{cn} (BTU/lb.)</u>	<u>ϕ_{cn} ($^{\circ}$R)</u>
0	0
200	1110
400	1630
600	2085
800	2530
1000	2950
1200	3350
1400	3760
1600	4170
1800	4580
2000	4990
2200	5400
2400	5810

I B-10 SUPPORT SYSTEM INLET AND BYPASS

$$1) \quad W_{ssi} = C_{65} F_{ssv} |P_4 - P_{20}|^{.5} \left[\frac{(P_4 - P_{20})}{|P_4 - P_{20}|} \right]$$

$$2) \quad \theta_{ssv} = \text{Independent variable}$$

$$3) \quad F_{ssv} = \frac{\theta_{ssv}}{90}$$

$$4) \quad \frac{d}{dt} P_{20} = C_{66} (W_{ssi} - W_{ss})$$

$$5) \quad W_{ssb} = C_{110} F_{ssb} |P_4 - P_{10}|^{.5} \left[\frac{(P_4 - P_{10})}{|P_4 - P_{10}|} \right]$$

$$6) \quad F_{ssb} = f(\theta_{ssv})$$

(See Table I B-10-1)

$$7) \quad E_{ssb} = C_{111} T_4 + C_{112} P_{10} - C_{113}$$

where:

$$C_{65} = 23.75$$

$$C_{66} = 727.9$$

$$C_{110} = 1.933$$

$$C_{111} = 3.405$$

$$C_{112} = 0.01342$$

$$C_{113} = 239.5$$

I B-10 SUPPORT SYSTEM INLET AND BYPASS (continued)

TABLE I B-10-1

F_{ssb} vs θ_{ssv}

θ_{ssv} (Deg.)	F_{ssb}
0.0	0.8029
0.1962	0.7725
1.035	0.6608
2.298	0.5272
3.235	0.4478
3.969	0.3949
4.825	0.3422
6.456	0.2631
8.835	0.1841
11.30	0.1315
14.97	0.08413
19.42	0.05258
27.12	0.02629
67.02	0.0

I B-11 SUPPORT SYSTEM

- 1) $T_{20} = T_4$
- 2) $T_{ss1} = T_{20} + C_{75}(\phi_{t1j} - T_{ss1})$
- 3) $T_{ss1e} = 2T_{ss1} - T_{20}$
- 4) $T_{ss2} = T_{ss1e} + C_{76}(\phi_{t2j} - T_{ss2})$
- 5) $T_{ss2e} = 0.5 (3T_{ss2} - T_{ss1e})$
- 6) $T_{ss3} = T_{ss2e} + C_{77}(\phi_{t2\phi} - T_{ss3}) + C_{78}(\phi_{t3j} - T_{ss3})$
- 7) $T_{ss3e} = 0.5 (3T_{ss3} - T_{ss2e})$
- 8) $T_{ss4} = T_{ss3e} + C_{79}(\phi_{t1\phi} - T_{ss4})$
- 9) $T_{ss4e} = 2T_{ss4} - T_{ss3e}$
- 10) $T_{22} = T_{ss4e}$
- 11) $\phi_{t1j} = \phi_{t1} + C_{80}|W_{ss}|(T_{ss1} - \phi_{t1j})$

where:

C_{75}	=	0.3036
C_{76}	=	0.7071
C_{77}	=	1.583
C_{78}	=	1.867
C_{79}	=	0.9059
C_{80}	=	0.005608

I B-11 SUPPORT SYSTEM (continued)

$$12) \quad \phi_{t1\phi} = \phi_{t1} + C_{81}|W_{ss}|(T_{ss4} - \phi_{t1\phi})$$

$$13) \quad \phi_{t2j} = \phi_{t2} + C_{82}|W_{ss}|(T_{ss2} - \phi_{t2j})$$

$$14) \quad \phi_{t2\phi} = \phi_{t2} + C_{83}|W_{ss}|(T_{ss3} - \phi_{t2\phi})$$

$$15) \quad \phi_{t3j} = \phi_{t3} + C_{84}|W_{ss}|(T_{ss3} - \phi_{t3j})$$

$$16) \quad \phi_{pj} = C_{85}\phi_p + (1 - C_{85})\phi_{t3}$$

$$17) \quad \phi_{sgj} = C_{86}\phi_{sg} + (1 - C_{86})\phi_p$$

$$18) \quad \frac{d}{dt} \phi_{t1} = C_{87}(\phi_{t1\phi} - \phi_{t1}) - C_{88}(\phi_{t1} - \phi_{t1j}) + C_{89}S_{NO}$$

where:

$$C_{81} = 0.01653$$

$$C_{82} = 0.006161$$

$$C_{83} = 0.01731$$

$$C_{84} = 0.03120$$

$$C_{85} = 0.02767$$

$$C_{86} = 0.9597$$

$$C_{87} = 143.0$$

$$C_{88} = 137.4$$

$$C_{89} = 0.0$$

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I B-11 SUPPORT SYSTEM (continued)

$$19) \frac{d}{dt} \phi_{t2} = C_{90}(\phi_{t2\phi} - \phi_{t2}) - C_{91}(\phi_{t2} - \phi_{t2f}) + C_{92}S_{NO}$$

$$20) \frac{d}{dt} \phi_{t3} = C_{93}(\phi_{pj} - \phi_{t3}) - C_{94}(\phi_{t3} - \phi_{t3f}) + C_{95}S_{NO}$$

$$21) \frac{d}{dt} \phi_p = C_{96}(\phi_{sgf} - \phi_p) - C_{97}(\phi_p - \phi_{pj}) + C_{98}S_{NO}$$

$$22) \frac{d}{dt} \phi_{sg} = C_{99}(\phi_{c2} - \phi_{sg}) - C_{100}(\phi_{sg} - \phi_{sgf}) + C_{101}S_{NO}$$

where:

C_{90}	=	144.7
C_{91}	=	139.0
C_{92}	=	3.414
C_{93}	=	33.94
C_{94}	=	31.82
C_{95}	=	1.992
C_{96}	=	0.2537
C_{97}	=	0.2054
C_{98}	=	0.5486
C_{99}	=	5.935
C_{100}	=	4.761
C_{101}	=	1.328

I B-11 SUPPORT SYSTEM (continued)

$$23) \quad P_{ss2} = P_{20} - C_{102}(P_{20} - P_{10})$$

$$24) \quad P_{ss3} = P_{20} - C_{103}(P_{20} - P_{10})$$

$$25) \quad P_{sse} = P_{20} - C_{104}(P_{20} - P_{10})$$

$$26) \quad R_{ss2} = \frac{P_{ss2}}{5.32T_{ss2}}$$

$$27) \quad R_{ss3} = \frac{P_{ss3}}{5.32T_{ss3}}$$

$$28) \quad R_{sse} = \frac{P_{sse}}{5.32T_{22}}$$

$$29) \quad R_{ss} = C_{105}R_{ss2} + (1 - C_{105})R_{ss3}$$

$$30) \quad \frac{d}{dt} W_{ss} = C_{106} \left(P_{20} - P_{10} - \frac{C_{107}W_{ss}|W_{ss}|}{R_{sse}} \right)$$

$$31) \quad E_{22} = C_{109}T_{22} - C_{108}$$

where:

$$C_{102} = 0.01300$$

$$C_{103} = 0.1520$$

$$C_{104} = 0.4780$$

$$C_{105} = 0.7031$$

$$C_{106} = 81.68$$

$$C_{107} = 0.2488$$

$$C_{108} = 195.0$$

$$C_{109} = 3.531$$

I B-12 REACTIVITY

$$1) \quad Dk_f = -C_{114}\phi_c + C_{115}R_c + C_{116}R_{ss} + C_{117}$$

$$2) \quad Dk_d = C_{118}\sin^2 \left(\frac{\Theta D_M}{2M} \right) - C_{119}$$

$$3) \quad Dk_t = Dk_f + Dk_d$$

where:

$$C_{114} = 7.950 \times 10^{-4}$$

$$C_{115} = 21.30$$

$$C_{116} = 5.060$$

$$C_{117} = 0.4200$$

$$C_{118} = 9.000$$

$$C_{119} = 6.322$$

I B-13 KINETICS

$$1) \quad S = S_N + O_1 + O_2 + O_3)$$

$$2) \quad S_{NQ} = 0.6547 S_N + 6.409 (O_1 + O_2 + O_3)$$

$$3) \quad \frac{d}{dt} S_N = \frac{0.0071(Dk_t - 1)}{25. \times 10^{-6}} S_N + 0.0127 CI_1 + 0.0317 CI_2 \\ + 0.115 CI_3 + 0.311 CI_4 + 1.40 CI_5 + 3.87 CI_6$$

$$4) \quad \frac{d}{dt} CI_1 = 10.8 S_N - 0.0127 CI_1$$

$$5) \quad \frac{d}{dt} CI_2 = 60.5 S_N - 0.0317 CI_2$$

$$6) \quad \frac{d}{dt} CI_3 = 53.4 S_N - 0.115 CI_3$$

$$7) \quad \frac{d}{dt} CI_4 = 115.6 S_N - 0.311 CI_4$$

$$8) \quad \frac{d}{dt} CI_5 = 36.35 S_N - 1.40 CI_5$$

$$9) \quad \frac{d}{dt} CI_6 = 7.35 S_N - 3.87 CI_6$$

$$10) \quad \frac{d}{dt} O_1 = 0.000117 S_N - 0.00322 O_1$$

$$11) \quad \frac{d}{dt} O_2 = 0.000757 S_N - 0.05525 O_2$$

$$12) \quad \frac{d}{dt} O_3 = 0.003734 S_N - 0.2707 O_3$$

I B-14 THRUST CHAMBER

$$1) \quad T_{15} = C_{59}T_{c3e} + C_{60}T_{13a}$$

$$2) \quad W_{15} = \left[\frac{C_{61}P_{15}}{T_{15}^{.5}} \right]$$

$$3) \quad P_{15} = 5.32R_{15}T_{15}$$

$$4) \quad \frac{d}{dt} R_{15} = C_{62}(W_c + W_{cp} - W_{15})$$

where:

$$\begin{aligned} C_{59} &= 0.9831 \\ C_{60} &= 0.02426 \\ C_{61} &= 12.99 \\ C_{62} &= 0.05547 \end{aligned}$$

I C-1 DRUM CONTROL

1) T_{15D} = Independent variable

2) $\frac{d}{dt} T_{15M} = \frac{W_{15}^{.5}}{2.85} (T_{15} - T_{15M})$

3) $T_{15E} = T_{15D} - T_{15M}$

4) $\frac{\theta_D^D}{\theta_D^D} = \frac{1}{1 + .16s + .00645s^2}$

5) $\frac{\theta_D^D}{T_{15E}} = \frac{.01 (1 + s)}{s}$

I C-2 TURBINE INLET VALVE CONTROL

1) W_{2D} = Independent variable

2) W_{2E} = $W_{2D} - W_2$

3) $\frac{Spd_D}{W_{2E}}$ = $\frac{185.}{s}$

4) Spd_E = $Spd_D - Spd$

5) $\frac{x_{60}}{Spd_E}$ = $\frac{.025(1 + \frac{s}{7.7})}{s}$

I C-3 HEAT EXCHANGER VALVE CONTROL

1) DP_D = Independent variable

2) DP_M = $P_{he1} - P_{he2}$

3) DP_E = $DP_D - DP_M$

4) $\frac{X_{21}}{DP_E}$ = $\frac{-.059(1 + \frac{s}{.615})}{s(1 + \frac{s}{11.})}$

I C-4 PUMP BYPASS VALVE CONTROL

$$1) \quad SS_E = -0.7875(W_1 - 0.00425 \text{ Spd})$$

$$2) \quad \frac{X_{109}}{SS_E} = \frac{(1 + \frac{s}{16.4})}{s(1 + \frac{s}{100})}$$

III A-1 DESIGN STEADY STATE

Reactor:

T_{15} 4500.
 P_{15} 459.7
 θD_M 90.01

CI_1	80030.	E_{ssb}	167.2	P_{10}	641.5
CI_2	179600.	E_{22}	1384.	P_{12}	626.8
CI_3	43700.	F_{ssb}	0.3949	P_{14}	459.7
CI_4	34980.	F_{ssv}	0.04410	P_{15}	459.7
CI_5	2443.	HD_r	0.2936	P_{20}	822.4
CI_6	178.7	HD_s	0.3000	P_{ss2}	820.1
DK_d	-1.882	HD_{c1}	0.3196	P_{ss3}	794.9
DK_f	1.822	HD_{c2}	0.3983	P_{sse}	735.9
DK_t	0.000	HD_{c3}	0.4671	Q_1	3.419
E_7	427.8	H_x	219.3	Q_2	1.289
E_r	655.3	H_n	113.8	Q_3	1.298
E_9	882.8	H_r	23.89	R_7	0.7701
E_{10}	821.3	H_s	28.28	R_{10}	0.4255
E_s	843.0	H_{c1}	356.6	R_{12}	0.4002
E_{12}	864.6	H_{c2}	1189.	R_{15}	0.01920
E_{c1}	3164.	H_{c3}	1728.	R_c	0.07978
E_{cle}	5464.	P_4	1028.	R_{ss2}	0.4791
E_{c2}	9103.	P_5	987.7	R_{ss3}	0.2874
E_{c2e}	12740.	P_7	711.0	R_{sse}	0.3093
E_{c3}	15000.	P_9	641.5	R_{ss}	0.4222
E_{c3e}	17270.				

III A-1 DESIGN STEADY STATE (continued)

S	100.1	T ₂₀	72.72	φ _x	2448.
S _N	94.10	T _{ss1}	148.6	φ _n	1462.
S _{NQ}	100.1	T _{ss1e}	224.4	φ _r	329.4
T ₄	72.72	T _{ss2}	321.7	φ _s	306.4
T ₅	72.72	T _{ss2e}	370.4	φ _{c1}	1515.
T _{6x}	138.5	T _{ss3}	519.9	φ _{c2}	3328.
T ₆	197.6	T _{ss3e}	594.7	φ _{c3}	4432.
T ₇	173.3	T _{ss4}	520.9	φ _c	3062.
T _r	234.7	T _{ss4e}	447.2	φ _{t1j}	398.3
T ₉	299.7	T ₂₂	447.2	φ _{t1}	419.3
T ₁₀	283.4	W ₅	59.00	φ _{t1o}	439.5
T _s	288.9	W ₆	37.03	φ _{t2j}	459.4
T ₁₂	294.4	W _{6x}	19.94	φ _{t2}	472.1
T _{c1}	939.1	W ₁₈	2.036	φ _{t2o}	481.9
T _{c2}	2597.	W _r	59.00	φ _{t3j}	632.2
T _{c3}	4044.	W _s	89.00	φ _{t3}	684.8
T _{c3e}	4550.	W _c	87.50	φ _{pj}	728.2
T _{13a}	1096.	W _{cp}	1.500	φ _p	2254.
T ₁₅	4500.	W ₁₅	89.00	φ _{sqj}	3273.
T _{15D}	4500.	W _{ssi}	15.00	φ _{sq}	3316.
T _{15M}	4500.	W _{ss}	15.00	θ _D	90.01
T _{15E}	0.000	W _{ssb}	15.00	θ _M	90.01
				θ _{ssv}	3.969

III A-1 DESIGN STEADY STATE (continued)

Test Cell "C"		X ₆₀	13.64
		X ₁₀₉	14.61
		X ₂₁	16.88
A ₂₁	0.4219	Spd	25620.
A ₆₀	1.823	Spd _D	25620.
A ₁₀₉	0.2209	Spd _E	0.000
DP _D	70.00	SS _E	0.000
DP _E	0.000	W ₁	108.9
DP _M	70.00	W ₂	89.00
DP _P	1037.	W ₃	89.00
P ₀	81.89	W ₄	89.00
P ₁	1119.	W _{he1}	9.890
P ₂	1057.	W _{he2}	9.890
P ₃	1047.	W _{he3}	9.890
P ₄	1028.	W _{he4}	9.890
P _{he1}	1057.	W ₁₀₉	9.997
P _{he2}	986.9	W _{2D}	89.00
P _{he3}	961.6	W _{2E}	0.000
P _{he4}	482.7	XL _p	19860.
Ps1	1.000	XL _t	19860.
R _{he2}	1.728 x 10 ⁻⁴	X ₂₁	16.88
R _{he3}	1.686 x 10 ⁻⁴	X ₆₀	13.64
		X ₁₀₉	14.61

III A-2 DESIGN FREQUENCY RESPONSE

$$\Delta T_{15} / \Delta \theta_{ssv}$$

<u>Frequency</u> (Rad./Sec.)	<u>Gain</u> (Decibels)	<u>Phase</u> (Degrees)
1.000 E-02	48.620	-0.349
1.500 E-02	48.599	-0.776
2.500 E-02	48.548	-1.242
4.000 E-02	48.500	-1.575
6.300 E-02	48.485	-1.934
1.000 E-01	48.537	-2.596
1.500 E-01	48.691	-3.794
2.500 E-01	49.162	-7.600
4.000 E-01	49.905	-17.063
6.300 E-01	50.338	-37.616
1.000 E+00	48.506	-71.232
1.500 E+00	43.969	-97.192
2.500 E+00	36.934	-112.880
4.000 E+00	30.670	-117.582
6.300 E+00	25.134	-117.642
1.000 E+01	20.152	-118.322
1.500 E+01	15.906	-122.211
2.500 E+01	10.195	-131.375
4.000 E+01	4.263	-143.119
6.300 E+01	-2.387	-156.372
1.000 E+02	-10.547	-169.895

III A-2 DESIGN FREQUENCY RESPONSE

$$\Delta P_{15} / \Delta \theta D_M$$

<u>Frequency</u> (Rad./Sec.)	<u>Gain</u> (Decibels)	<u>Phase</u> (Degrees)
1.000 E-02	3.387	0.993
1.500 E-02	3.386	0.866
2.500 E-02	3.361	1.122
4.000 E-02	3.357	1.917
6.300 E-02	3.423	3.223
1.000 E-01	3.636	5.027
1.500 E-01	4.058	6.697
2.500 E-01	5.130	6.945
4.000 E-01	6.652	0.623
6.300 E-01	7.835	-17.487
1.000 E+00	6.633	-47.390
1.500 E+00	2.707	-66.612
2.500 E+00	-2.286	-68.242
4.000 E+00	-4.707	-67.954
6.300 E+00	-6.919	-78.254
1.000 E+01	-10.369	-94.712
1.500 E+01	-14.591	-109.885
2.500 E+01	-21.470	-125.250
4.000 E+01	-29.167	-129.972
6.300 E+01	-36.838	-115.425
1.000 E+02	-40.420	-86.749

III A-2 DESIGN FREQUENCY RESPONSE

$$\Delta T_{15} / \Delta \Theta_D M$$

<u>Frequency</u> (Rad./Sec.)	<u>Gain</u> (Decibels)	<u>Phase</u> (Degrees)
1.000 E-02	35.590	-0.027
1.500 E-02	35.570	-0.292
2.500 E-02	35.522	-0.439
4.000 E-02	35.482	-0.298
6.300 E-02	35.484	0.055
1.000 E-01	35.578	0.488
1.500 E-01	35.809	0.641
2.500 E-01	36.465	-0.950
4.000 E-01	37.476	-7.987
6.300 E-01	38.231	-25.632
1.000 E+00	36.841	-55.019
1.500 E+00	32.949	-75.962
2.500 E+00	27.348	-85.139
4.000 E+00	22.923	-87.306
6.300 E+00	18.913	-89.138
1.000 E+01	14.866	-90.936
1.500 E+01	11.339	-92.624
2.500 E+01	6.912	-95.605
4.000 E+01	2.804	-99.888
6.300 E+01	-1.265	-106.178
1.000 E+02	-5.619	-115.707

III A-2 DESIGN FREQUENCY RESPONSE

$$\Delta W_4 / \Delta X_{60}$$

<u>Frequency</u> (Rad./Sec.)	<u>Frequency</u> (Rad./Sec.)	<u>Gain</u> (Decibels)	<u>Phase</u> (Degrees)
1.000 E-02	1.000 E-02	13.821	-1.293
1.500 E-02	1.500 E-02	13.817	-1.939
2.500 E-02	2.500 E-02	13.806	-3.228
4.000 E-02	4.000 E-02	13.777	-5.151
6.300 E-02	6.300 E-02	13.708	-8.059
1.000 E-01	1.000 E-01	13.538	-12.584
1.500 E-01	1.500 E-01	13.208	-18.277
2.500 E-01	2.500 E-01	12.309	-27.814
4.000 E-01	4.000 E-01	10.746	-37.520
6.300 E-01	6.300 E-01	8.561	-45.029
1.000 E+00	1.000 E+00	6.058	-48.889
1.500 E+00	1.500 E+00	4.068	-49.945
2.500 E+00	2.500 E+00	2.138	-52.523
4.000 E+00	4.000 E+00	0.634	-61.089
6.300 E+00	6.300 E+00	-1.324	-77.593
1.000 E+01	1.000 E+01	-4.744	-100.962
1.500 E+01	1.500 E+01	-9.307	-121.604
2.500 E+01	2.500 E+01	-16.312	-139.771
4.000 E+01	4.000 E+01	-18.755	-149.202
6.300 E+01	6.300 E+01	-24.496	-187.376
7.000 E+01	7.000 E+01	-25.020	-194.660
8.000 E+01	8.000 E+01	-24.738	-208.154
9.000 E+01	9.000 E+01	-23.259	-232.548
1.000 E+02	1.000 E+02	-23.050	-281.446

III A-2 DESIGN FREQUENCY RESPONSE

$$\Delta P_4 / \Delta X_{60}$$

<u>Frequency</u> (Rad./Sec.)	<u>Gain</u> (Decibels)	<u>Phase</u> (Degrees)
1.000 E-02	41.100	-1.293
1.500 E-02	41.096	-1.939
2.500 E-02	41.084	-3.228
4.000 E-02	41.056	-5.151
6.300 E-02	40.987	-8.059
1.000 E-01	40.817	-12.584
1.500 E-01	40.486	-18.277
2.500 E-01	39.588	-27.814
4.000 E-01	38.025	-37.520
6.300 E-01	35.840	-45.029
1.000 E+00	33.337	-48.889
1.500 E+00	31.347	-49.945
2.500 E+00	29.417	-52.523
4.000 E+00	27.913	-61.089
6.300 E+00	25.955	-77.593
1.000 E+01	22.535	-100.962
1.500 E+01	17.972	-121.604
2.500 E+01	10.967	-139.771
4.000 E+01	8.524	-149.202
6.300 E+01	2.783	-187.376
7.000 E+01	2.259	-194.660
8.000 E+01	2.541	-208.154
9.000 E+01	4.020	-232.548
1.000 E+02	4.229	-281.446

IV. NOMENCLATURE

Variables

A	=	Effective valve area, in. ²
CI_j	=	Precursor concentration in j^{th} group
C_i	=	i^{th} fixed constant
Dk_d	=	Reactivity feedback of drums, \$
Dk_f	=	Reactivity feedback of reactor, \$
Dk_t	=	Total reactivity feedback, \$
DP	=	Pressure difference, psid
E	=	Enthalpy of parahydrogen, BTU/lb.
F	=	Function of valve area
H	=	Enthalpy of solid material, BTU/lb.
HD	=	Temperature dependent portion of heat transfer coefficient
P	=	Pressure, psia
Ψ	=	ψ function of pressure ratio
O_i	=	i^{th} term of decay heat power, %
R	=	Density, lb./ft. ³
s	=	Laplace operator
S	=	Thermal power in fueled sections, %
S_N	=	Nuclear power, %
S_{NQ}	=	Thermal power in unfueled section, %
Spd	=	Pump speed, rpm
SS_E	=	Specific speed error to controller
t	=	Time, sec.
T	=	Fluid temperature, °R

IV. NOMENCLATURE (continued)

Variables (continued)

W	=	Mass flow rate, lb/sec.
X	=	Valve position, %
XL	=	Torque, in-lb.
ϕ	=	Material temperature, °R
θ_D	=	Drum position, Deg.
θ_{ssv}	=	Support system control valve position, Deg.

Station Designations

0	=	Pump inlet
1	=	Pump discharge
2	=	Feedline at heat exchanger connection
3	=	Feedline at L_{11} valve
4	=	Feedline at support system connection
5	=	Nozzle torus
6	=	Nozzle coolant tube exit
6x	=	Skirt coolant tube exit
7	=	Reflector inlet plenum
9	=	Peripheral shield exit plenum
10	=	Dome end plenum
12	=	Core inlet plenum
13a	=	Core periphery exit
14	=	Core exit plenum
15	=	Nozzle chamber
18	=	Bolt coolant

IV. NOMENCLATURE (continued)

Station Designations (continued)

- 20 = Support system control valve discharge
- 22 = Support system discharge

Qualifying Subscripts

- c = Reactor core, average
- ci = Reactor core, ith section
- cp = Reactor core periphery
- D = Demand
- e = Exit
- E = Error
- hei = Heat exchanger, ith section
- j = Radial inside
- M = Measured
- n = Nozzle
- p = Pyrographite; Pump
- r = Reflector
- s = Shield
- sg = Structural graphite
- ss = Support system, average
- ssb = Support system, bypass
- ssi = Support system, inlet
- ssj = Support system, jth section
- t = Turbine
- ti = Stainless steel, ith section

IV. NOMENCLATURE (continued)

Qualifying Subscripts (continued)

x	=	Nozzle skirt
ϕ	=	Radial outside
21	=	Heat exchanger valve
60	=	Turbine inlet valve
109	=	Pump bypass valve

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Page 5 of 6
First Issue
March 22, 1968

SCHEMATIC DIAGRAM OF R-1 NUCLEAR SUBSYSTEM

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SCHEMATIC DIAGRAM OF SUPPORT SYSTEM

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