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From W. L. Howarth, F. D. Retallick, Reactor Analysis

TO: F. D. Retallick

Subject "Decay Heat Cooling Analysis of a Nuclear Rocket Engine" - Paper Presented at ARS/ANS/I[illegible]S Nuclear Propulsion Conference, August 17, 1962.

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1.0 INTRODUCTION

A specified requirement for the NERVA Nuclear Rocket Engine is for it to be restartable. Thus, the heat produced after power operation by delayed neutrons and decay of radioactive nuclei must be expended with a minimum penalty to the system performance.

The minimum penalty in performance is obtained when the cooling is performed within the allowable temperature limits of the many reactor components. When this is the case, the coolant is minimized since the maximum amount of heat is being removed by each pound of coolant. In addition, the specific impulse of the exhausted coolant is maximized which may be useful in increasing the velocity increment of the vehicle.

The NERVA reactor system, to be considered here, consists of a cooled exhaust nozzle, a pressure vessel, a shadow shield, a reflector containing the control devices, a lateral core supported from the top support plate by steel tie rods. The arrangement of these components and the reactor flow path are shown in Fig. 1.

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Figure 2 shows a typical curve of decay heat power for the NERVA reactor after having operated at full power for 20 minutes and for the instantaneous insertion of 4.5 dollars of shutdown reactivity. The heat in terms of percent of full power is found to vary from about 20.0 to 5.0×10^{-4} during the decay heat period, the latter figure being an estimate of the amount of heat which can be radiated to space from the engine exterior surfaces.

One method of decay heat cooling which can be envisioned, is to cool the reactor at as high a constant core exit temperature as possible and with just sufficient quantity of coolant to remove the heat being generated. In this scheme referred to as the continuous flow system, the cooling flow is directly proportional to decay power. Thus, the variation in power from 20.0 per cent to 5.0×10^{-4} percent also applies to the cooling flow.

Two difficulties arise with such a system. First it is difficult to imagine a flow metering device sufficient to provide the necessary wide range of control. Even though the absolute magnitude of cooling flow rates are low, they persist for long periods of time and small errors in absolute magnitude of the flow rate will result in excessive coolant loss and lowered specific impulse due to lower exit coolant temperatures. Secondly, analytical treatment of low flow rates in multi-passage heat exchangers such as the core, indicate that unpredictable flows and temperatures may exist in any one channel giving rise to excessive temperatures.

These problems of low flow rates have resulted in the consideration of another type of cooling system. In this system, referred to as the pulse system, the coolant is injected at reasonably high flow rates for short time durations. Cooling begins whenever a temperature limit in the reactor is reached and continues until a predetermined lower temperature is reached. At this lower temperature, cooling is stopped and the reactor system allowed to rise in temperature due to the decay heat, until an upper temperature limit in the reactor is again reached. The performance of such a system is dependent on the lower temperature to which the reactor system is cooled during the pulse. Increased differences between it and the upper temperature limit in the reactor result in larger amounts of coolant required and lower specific impulses of the coolant. Smaller temperature differences increases the system performance, but at the cost of system reliability because of the larger number of pulses. The selection of the temperature difference must be a compromise between performance and system reliability.

The following paragraphs will summarize the important flow considerations during cooldown, a brief description of the analytical method of handling the cooldown heat transfer calculations, and some results which have been obtained for the NERVA reactor system.

2.0 PARALLEL CHANNEL FLOW CHARACTERISTICS

The problem of flow stability in parallel channels at low flow rates must be recognized in considering any cooldown system. Figures 3 and 4 show a typical core channel characteristic obtained for various heat generation rates and flow rates in the range of interest during decay heat cooling with hydrogen. Fig. 3 is the flow-pressure loss characteristic of the channel; whereas, Figure 4 is the coolant temperature flow characteristic of the same channel. If the flow is decreased to the condition where it goes below Point A, shown as an example on Figure 3, then it is possible for some channels in a parallel channel system to be operating at Point B and others to be operating at Point A. Those operating at the conditions of Point B would be very hot and could overtemperature the steel tie rods in the core which would cause failure.

Since orificing is necessary in the many channels of the NERVA cores to provide high specific impulse, the characteristics shown vary, depending on the amount of orificing in the channel. This must be factored into the design and then the minimum allowable flow for any time during the decay heat cycle determined on the basis of those channels which would first get into trouble.

Presently, the use of a continuous flow system in the unstable region must be avoided since the distribution of flows and hot spots in the core cannot be calculated by theoretical analysis, and safe operation in this region cannot be determined except by model or full scale tests. A continuous flow system which would assure staying out of this unstable range would be inefficient on coolant usage, and for this reason investigation of a pulse system for NERVA has been performed.

3.0 DECAY HEAT COOLING ANALYTICAL MODEL

A finite difference heat transfer and flow equation solution has been used in a digital computer code for calculating reactor conditions during cooldown. In this code the following method of simulation is used. The flow from the propellant tank enters the nozzle at an area ratio of 4/1 and proceeds through the nozzle into the reflector region. Four parallel flow channels are considered in the reflector region:

1. The flow in the annulus between the pressure vessel and beryllium reflector.

2. The flow in the annulus between the beryllium reflector and the graphite reflector.
3. The flow in the cooling holes of the beryllium reflector.
4. The flow in the cooling holes in the lateral support.

The flows are iterated until the pressure drop across these flow passages are equal. The propellant then enters through the top support plate into the core and tie rod cooling channels and is discharged from these channels into the nozzle plenum. If the nozzle choked exit condition is not satisfied, the propellant flow is varied until it is satisfied.

The components are represented by either their actual geometry or an equivalent single tube which can be subdivided into 50 axial increments. In an axial increment of a component, the radial temperature and heat flux are assumed constant, but axial conduction and one or two phase convection are considered. Radial heat transfer by thermal radiation, conduction and convection between reactor components are considered. In the nozzle aluminum jacket it was necessary to consider radial conduction between it and the cooling tubes.

For pulse flow calculations the code uses an upper and lower temperature for control. The upper temperature is set by component temperature limits. When this limit is reached, the flow is turned on until the lower temperature is reached. The lower temperature is defined as the core average temperature corresponding to the upper temperature minus a constant core average temperature difference. Average core temperature was chosen because the core is the most efficient heat exchanger in the reactor. By limiting the temperature drop in the core, high core exit gas temperature can be achieved. Other component temperature differences may be used but its temperature relationship with respect to the core must be known and this relationship can only be obtained by first analyzing a specific engine design.

4.0 CONTINUOUS FLOW VERSUS PULSE FLOW DURING COOLDOWN

In the preceding discussion it has been pointed out that the flow instability region must be avoided to prevent possible overtemperaturing of the core. In the continuous flow cooldown system it is desirable to operate at the highest possible core exit gas temperature consistent with component temperature limitations. A reasonable core exit gas temperature for NERVA is 1950 °R, consistent with the use of steel in the core. On Figure 4, which was discussed previously, is plotted the flow stability line interpreted from Figure 3. If a system temperature exceeds this line in the range of flows shown, then the channel flow will be unstable. From Figure 4 it is shown that the continuous flow system operating line of 1950 °R coolant exit temperature intercepts the minimum stable flow line at 1.4 lb/sec. Further reduction in the flows are possible with a continuous flow system, but they must follow the minimum flow stability line. This, of course, results in excessive propellant usage and lowered specific impulse.

The effect of the flow stability limitations on the cooldown system can be illustrated by considering a typical cooldown problem.

For this problem the decay heat curve on Figure 2, which assumes 20 minutes of full NERVA power prior to shutdown, was used. The cooldown period consists of two parts. The first part is a programmed shutdown from rated flow with the turbo-pump operating. This part of the cooldown has not yet been fully established for the NERVA engine. The assumed cooldown schedule, shown on Figure 5, cools the core at a constant temperature rate of -42.8 ^{o}R/sec for 50 seconds. The reactor temperature at the end of this programmed shutdown was chosen so that the flow supplied at tank pressure is sufficient to prevent over-temperaturing of the steel sleeve which surrounds the tie rod.

The second part of the cooldown is accomplished with the coolant fed to the system by tank pressure. During this period it is possible to utilize either the continuous flow system, observing the stability limits, or the pulse flow system.

With the decay heat curve and a cooldown schedule in which the decay heat equals the heat removed by the coolant at 1950 ^{o}R, the flow for a continuous flow system from the start of the second cooldown to the limiting stable flow line was calculated as a function of cooldown time. These results are plotted on Figure 5. At 190 seconds after shutdown of the reactor, the minimum stable flow at 1950 ^{o}R was reached. For longer times the conditions of flow and temperature consistent with the flow stability line had to be used for calculating coolant requirements. Considering heat stored in the reactor, heat removed by the coolant, and decay heat generation, the coolant flow requirements were calculated and the results are plotted on Figure 5 along with the coolant temperature which it was necessary to observe. It was necessary to reduce this temperature from 1950 ^{o}R at the start of the stable flow limit to 750 ^{o}R at 2000 seconds after shutdown. Stable flow data were not available to determine the core exit gas temperature for longer times. To estimate the performance of the continuous flow system, it was assumed that the 750 °R temperature can be maintained throughout the remainder of the cooldown. If the flow stability line was extrapolated to lower flows, a decrease in gas temperature is apparent. Thus, the continuous flow system performance will be optimistic due to the assumed higher core exit gas temperature. The total coolant required by the continuous flow system for 10^6 seconds after reactor shutdown was 6560 pounds or 7.8 percent of the total propellant consumed during the full power run, with a total impulse of 2.44×10^6 lb-sec.

For comparison, the same decay heat cooling problem was calculated using a pulse flow system. After the termination of turbo-pump operation and with a tank pressure of 30 psia, it was found necessary to hold the tank shutoff valve wide open for another period of 50 seconds in order to cool the steel sleeve below its limiting temperature. After this (100 seconds after shutdown) it was possible to shut the flow off and begin pulse cooling.

In Table 1 are summarized the pulse times, the average pulse core exit flow conditions, the average pulse thrust and the coolant consumed. The flow was kept on during a pulse until the average core temperature had decreased 300 °R. The components which become temperature limited and initiated the pulses were the steel sleeve surrounding the core tie rods for the second and third pulses, the steel tie rods from the fourth to the thirty-eighth pulse and the aluminum orifices from the thirty-ninth to the forty-sixth pulse. The steel sleeve limit was set at 2000 °R, the tie rod at 1700 °R and the orifices at 1100 °R.

Axial temperature gradients in the core, the tie rod and the steel sleeve for the first, twenty-fifth, and forty-fifth pulses are presented in Figures 6, 7 and 8. On

Figure 9 is shown the axial temperature gradients in the other components of the engine for the forty-fifth pulse.

The axial temperature gradient in the core changes from a cosine type shape at the beginning of pulse cooling to a uniform shape towards the end of the decay cooldown. This trend can be observed by comparing the core axial temperature gradients at the start of a pulse on Figures 6 and 9 for the first and forty-sixth pulses. The factors which change the core temperature distribution are decay heat and axial conduction. At long times after shutdown the decay heat is small and longer off times are required in order to heat the reactor up to its limiting component temperature. During this long shutoff time the axial conduction becomes significant and the temperature distribution in the core tends to become uniform. Therefore, components adjacent to the core as well as components inside of the core will limit the pulse system temperature.

The components which are adjacent to the core are: The core lateral support, the core support plate, and the nozzle. Since the orificing material is aluminum, this component will become limiting towards the end of the decay cooling time period. The limiting temperature of aluminum is 1100 ^{o}R which is considerably less than the tie rod temperature limit of 1700 ^{o}R. When a lower component limiting temperature is reached, the core is cooled to a lower temperature than that of the preceding limiting components. This trend is illustrated on Table 1. At the thirty-ninth pulse the orifices are limiting and it was necessary to reduce the core exit gas temperature from 1679 ^{o}R to 1300 ^{o}R by the forty-fifth pulse. Thus, the pulse cycle performance is penalized.

For the pulse cycle studied here the propellant required for 10^6 seconds after shutdown was 4183 pounds or 5.0 percent of the full 20 minute power run requirements and the total impulse was 2.03×10^6 lb-sec.

5.0 CONCLUSIONS

The selection of either the pulse or continuous flow system depends on the nuclear rocket mission. In general, either system can be used for short restart times up to one hour because their performances are comparable. At longer restart times the continuous flow system performance is penalized by the flow stability limitation. As was illustrated in the sample problem for 10^6 seconds after shutdown the continuous flow system required an additional ton of hydrogen to cool the NERVA reactor. This penalizes the payload of the rocket. Therefore, at long restart times the pulse system is more efficient than the continuous flow system.

Additional data from basic heat transfer and full scale reactor tests are required to verify the flow instability area in the core channels.

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F. D. Retallick

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W. L. Howarth

TABLE 1

SUMMARY OF PULSE SYSTEM COOLDOWN CALCULATIONS

Pulse	Time after shutdown sec (flow is turned on)	Time off sec (before pulse)	Time on sec (length of pulse)	Average flow rate lb/sec	Propellant used per pulse lb	Average Propellant Exit temp. °R	Total Propellant usage lb	Average Thrust lb
Initial turbine cooldown (estimated)	0	0	50	10.4	520	3000	520	----
1	50	0	50	4.09	204.6	1923	725	2110
2	111.4	11.4	20	4.15	82.9	1937	808	2160
3	164.7	33.3	16	3.95	63.1	1980	871	2040
4	183.1	2.4	13	4.33	56.2	1897	927	2230
5	249.5	53.4	13	4.03	52.4	1888	980	2070
6	298.4	35.9	12	4.12	49.4	1874	1029	2100
7	345.9	35.4	12	4.20	50.3	1849	1079	2130
8	414.7	56.9	12	4.16	49.9	1836	1129	2100
9	487.8	61.0	11	4.15	45.7	1821	1175	2080
10	560.4	61.7	11	4.20	46.2	1801	1221	2100
11	645.3	73.9	11	4.20	46.3	1785	1267	2100
12	739.3	83.0	11	4.22	46 4	1769	1314	2100
13	853.7	103.5	11	4.18	46.0	1768	1360	2080
14	967.7	103.0	11	4.21	46.3	1762	1406	2080
15	1087.8	109.2	11	4.25	46.8	1744	1453	2100

Pulse	Time after shutdown sec (flow is turned on)	Time off sec (before pulse)	Time on sec (length of pulse)	Average flow rate lb/sec	Propellant used per pulse lb	Average Propellant Exit temp. °R	Total Propellant usage lb	Average Thrust lb
16	1232.6	133.8	11	4.25	46.7	1727	1500	2080
17	1414.5	170.9	11	4.18	46.0	1731	1546	2060
18	1588.0	162.4	11	4.20	46.2	1734	1592	2000
19	1741.5	142.6	10	4.27	42.7	1712	1635	2080
20	1963.2	211.7	11	4.23	46.5	1705	1681	2060
21	2224.6	250.3	11	4.18	46.0	1711	1727	2040
22	2455.3	219.7	11	4.21	46.3	1714	1773	2050
23	2693.1	226.8	11	4.22	46.4	1707	1820	2060
24	2959.7	255.6	11	4.23	46.6	1693	1866	2060
25	3288.5	317.8	11	4.18	46.0	1692	1912	2020
26	3602	302.5	11	4.20	46.2	1690	1959	2040
27	3957	343.8	11	4.18	46.0	1688	2005	2020
28	4348	380.6	11	4.17	45.8	1686	2050	2020
29	4770	410.2	11	4.16	45.8	1681	2096	2010
30	5262	481.5	12	4.15	49.8	1678	2146	2000
31	5883	609.1	12	4.09	49.0	1685	2195	1980
32	6453	557.7	12	4.09	49.1	1681	2244	1970
33	7206	741.3	12	4.03	52.4	1683	2296	1950

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Pulse	Time after shutdown sec (flow is turned on)	Time off sec (before pulse)	Time on sec (length of pulse)	Average flow rate lb/sec	Propellant used per pulse lb	Average Propellant Exit temp. °R	Total Propellant usage lb	Average Thrust lb
34	8064	844.4	13	4.00	52.0	1684	2349	1940
35	9005	928.1	13	3.98	51.7	1682	2400	1930
36	10118	1100.0	14	3.96	55.4	1678	2456	1910
37	11615	1484	15	3.87	58.1	1679	2514	1907
38	13423	1792	16	3.81	61.0	1679	2575	1905
39	15688	2249	17	3.78	63.9	1674	2639	1905
40	17795	2090	16	3.83	61.2	1637	2700	1905
41	20135	2324	16	3.90	62.4	1573	2762	1902
42	22793	2644	16	3.99	63.8	1503	2826	1902
43	25773	2962	17	4.11	69.9	1436	2896	1901
44	29378	3588	16	4.22	67.6	1361	2964	1900
45	33407	4013	16	4.32	69.1	1296	3033	1900
46	38066	4644	16	4.44	71.0	1233	3104	1900
47-61 Estimated	10^6				71.9	1200	4183	

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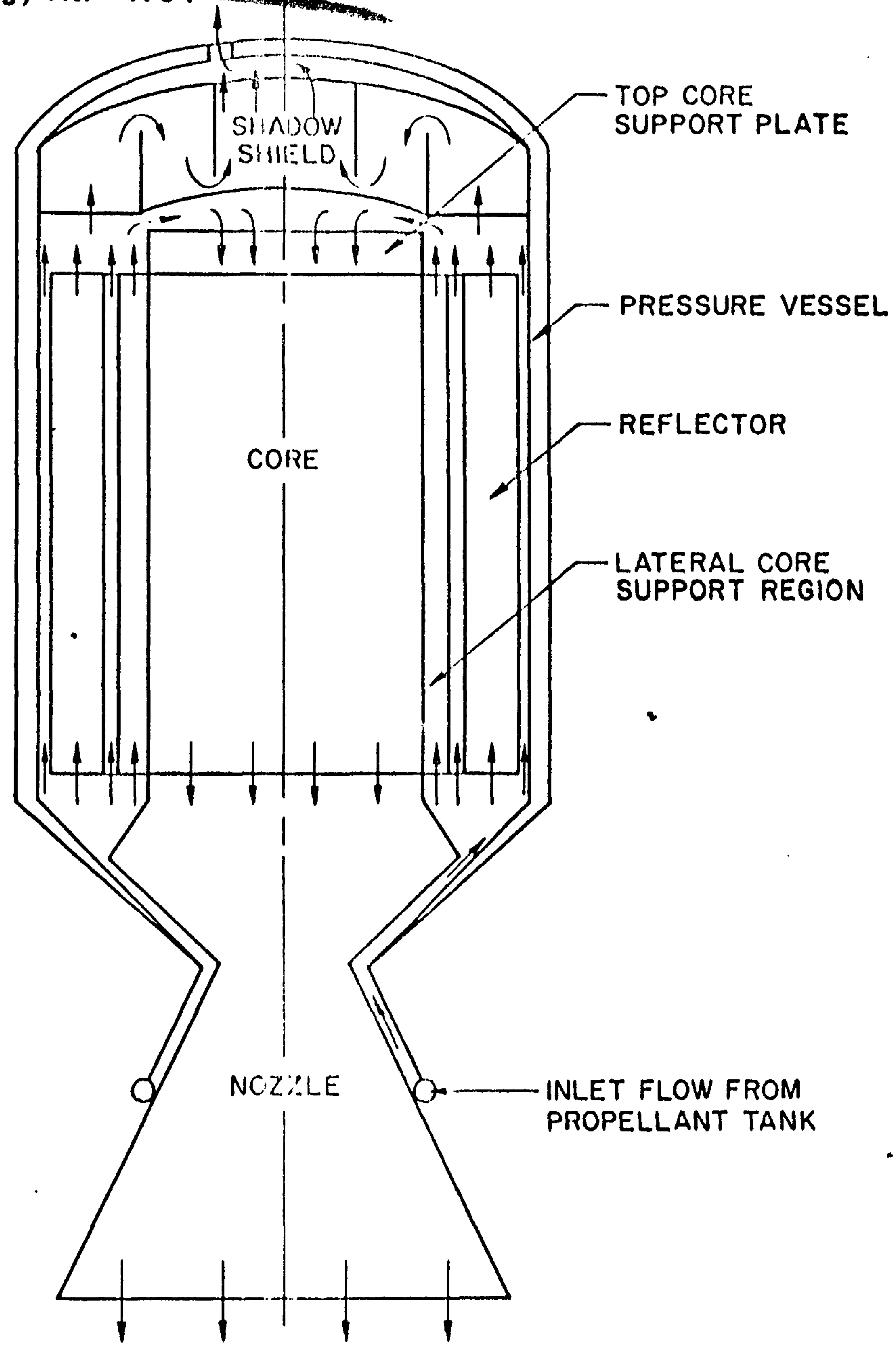

FIGURE I

NERVA REACTOR SCHEMATIC

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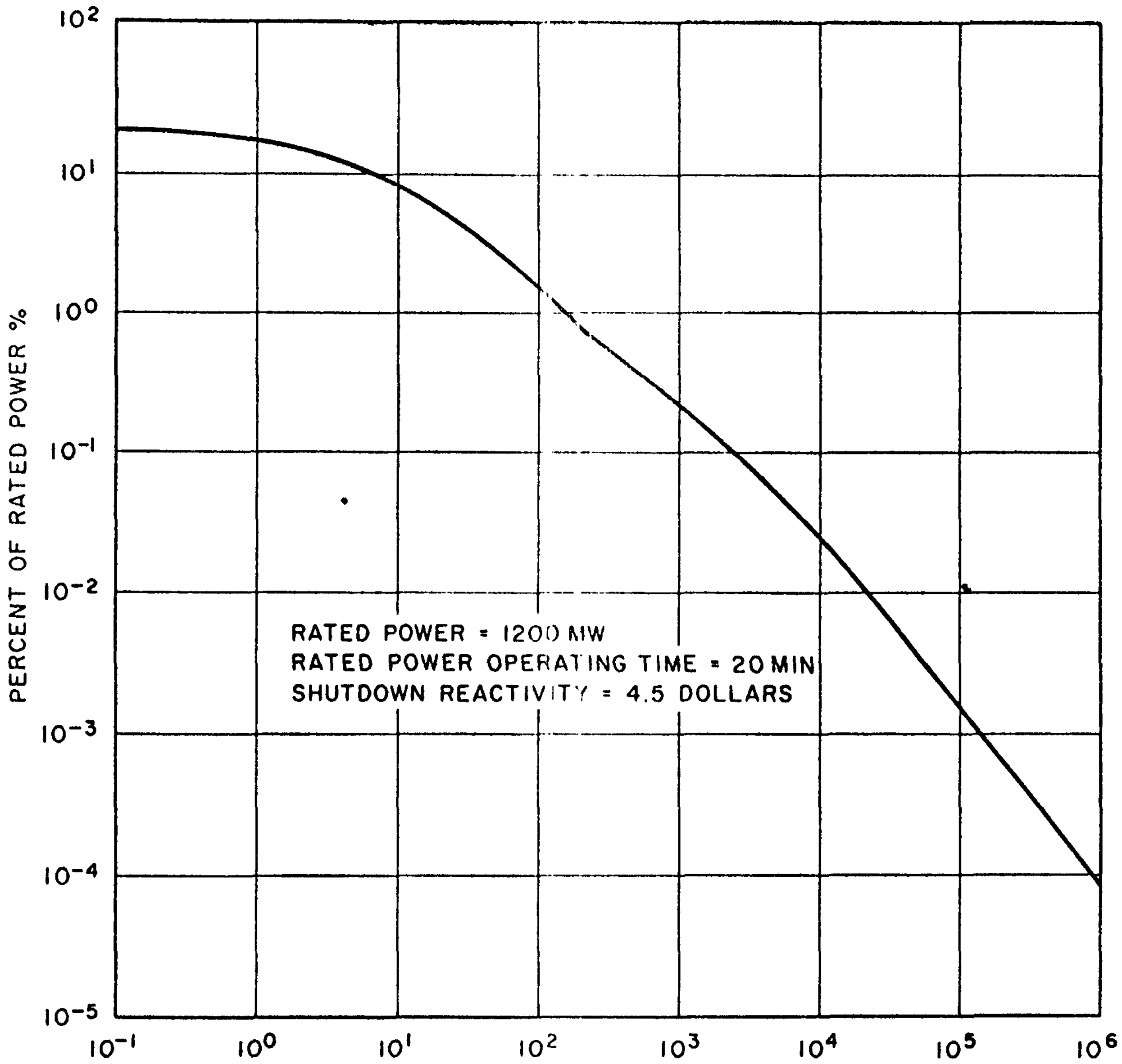

FIGURE 2

TOTAL DECAY HEAT

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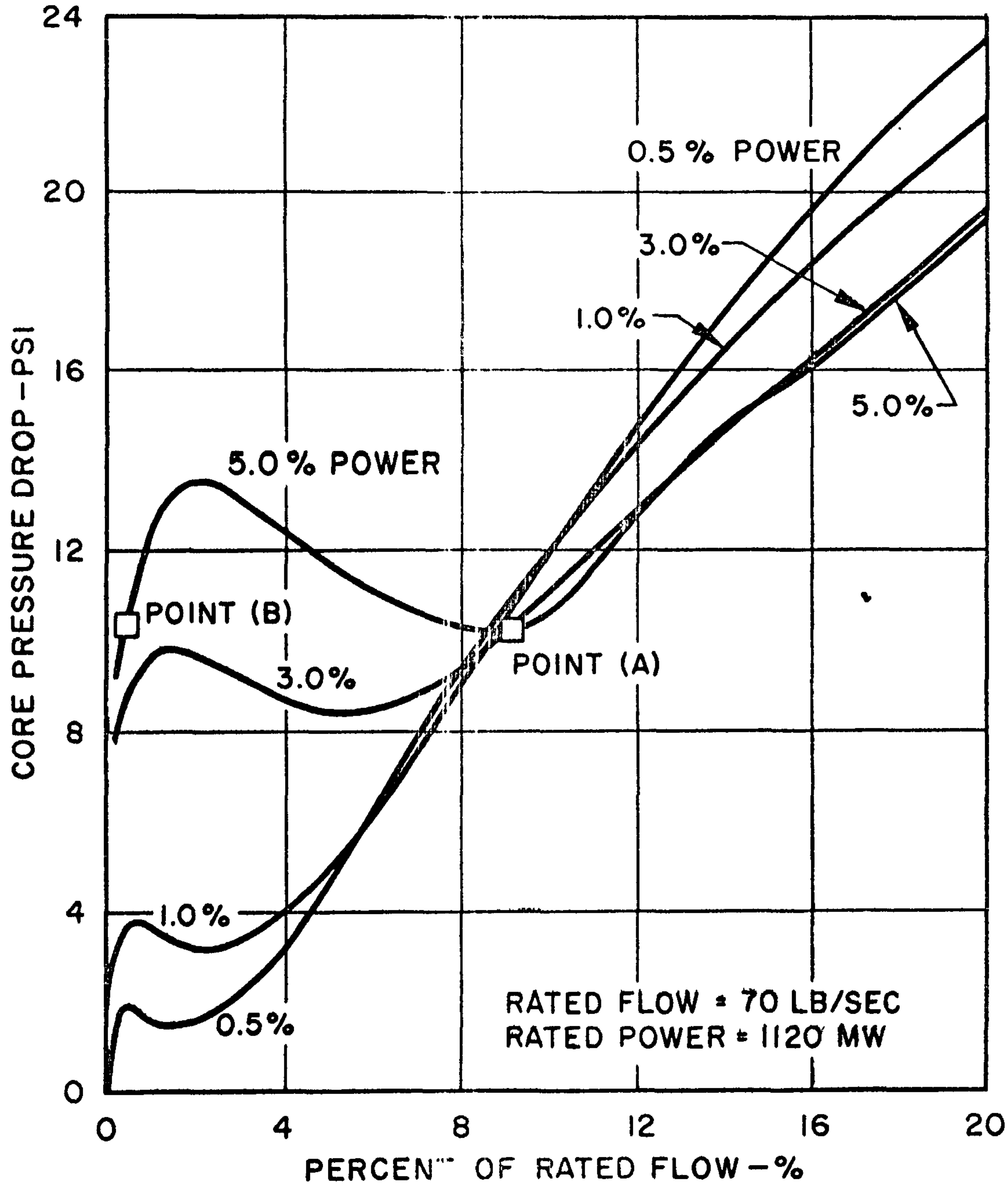

FIGURE 3

NERVA CORE CHANNEL CHARACTERISTICS – PART I

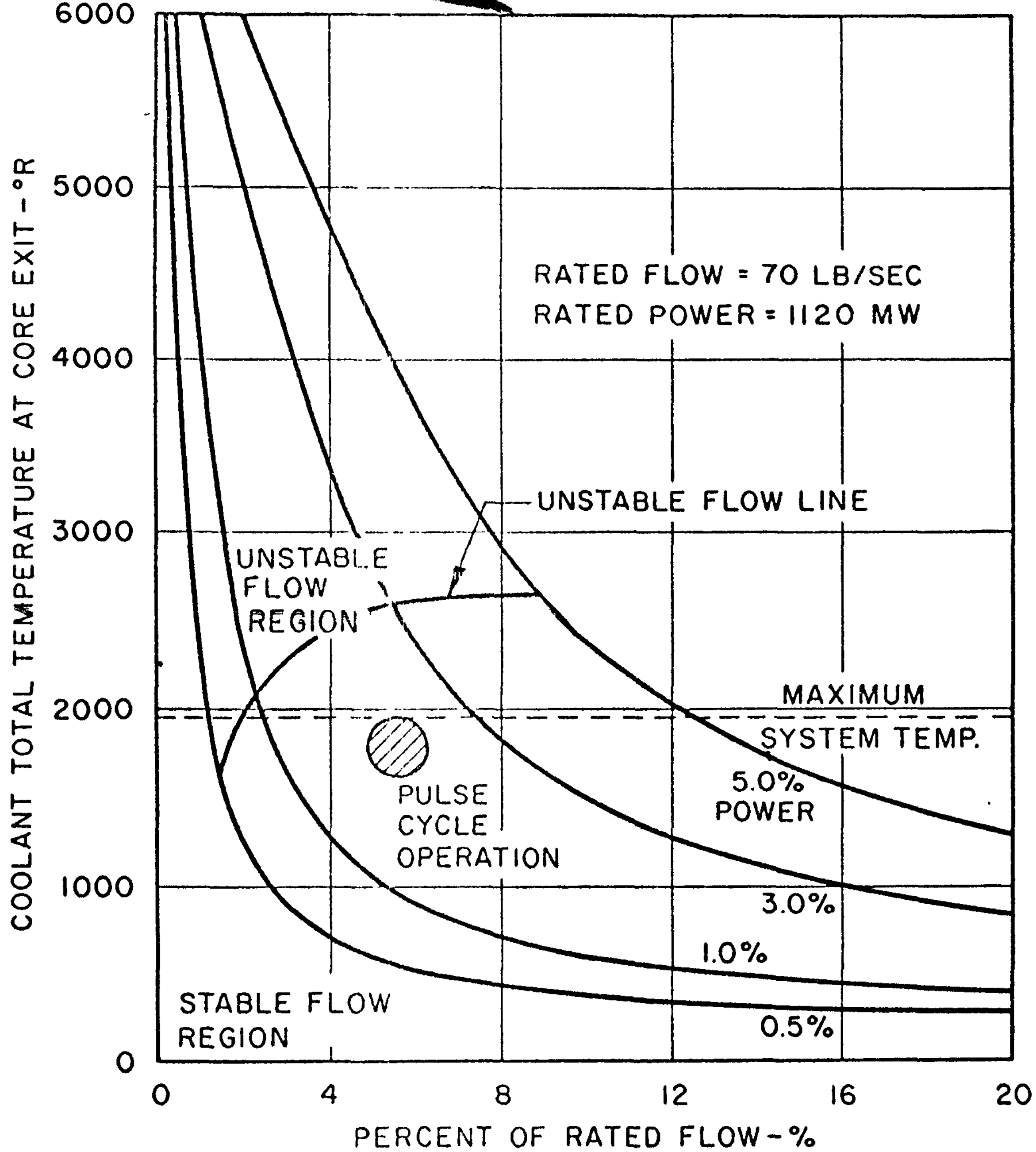

FIGURE 4

NERVA CORE CHANNEL CHARACTERISTICS - PART II

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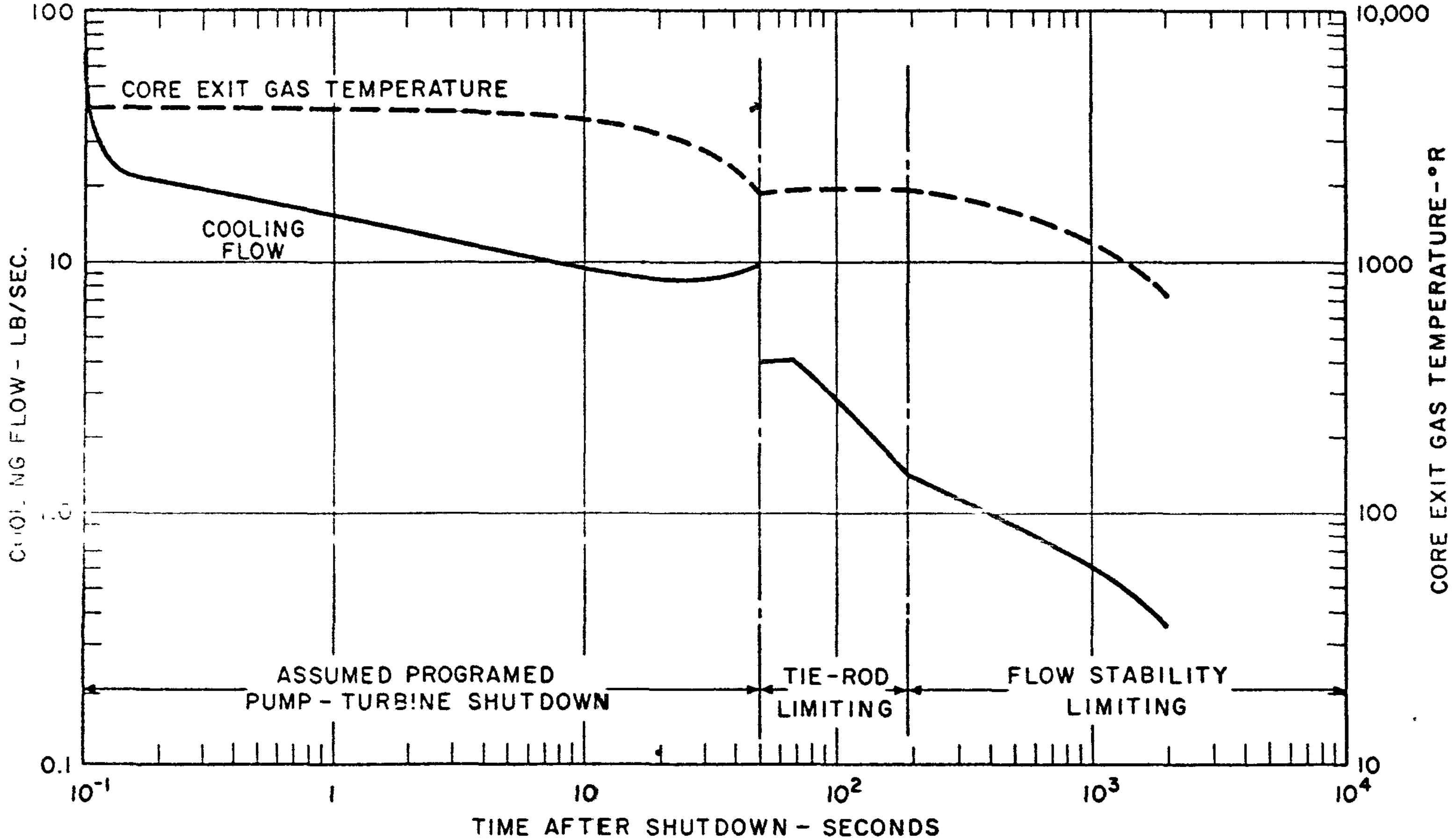

FIGURE 5 - NERVA CONTINUOUS FLOW SYSTEM COOLDOWN

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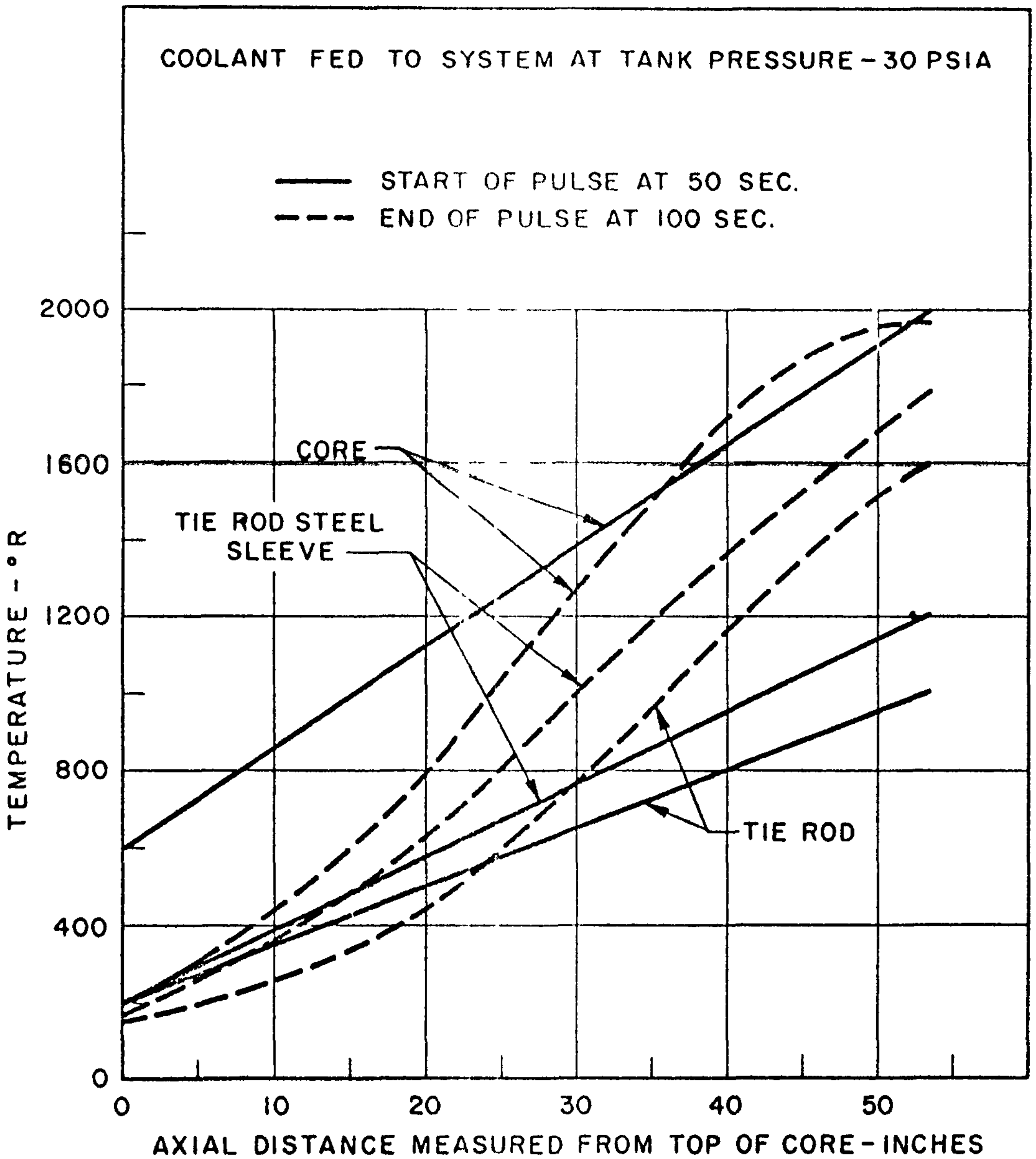

FIGURE 6 - 1ST PULSE AXIAL TEMPERATURE GRADIENTS

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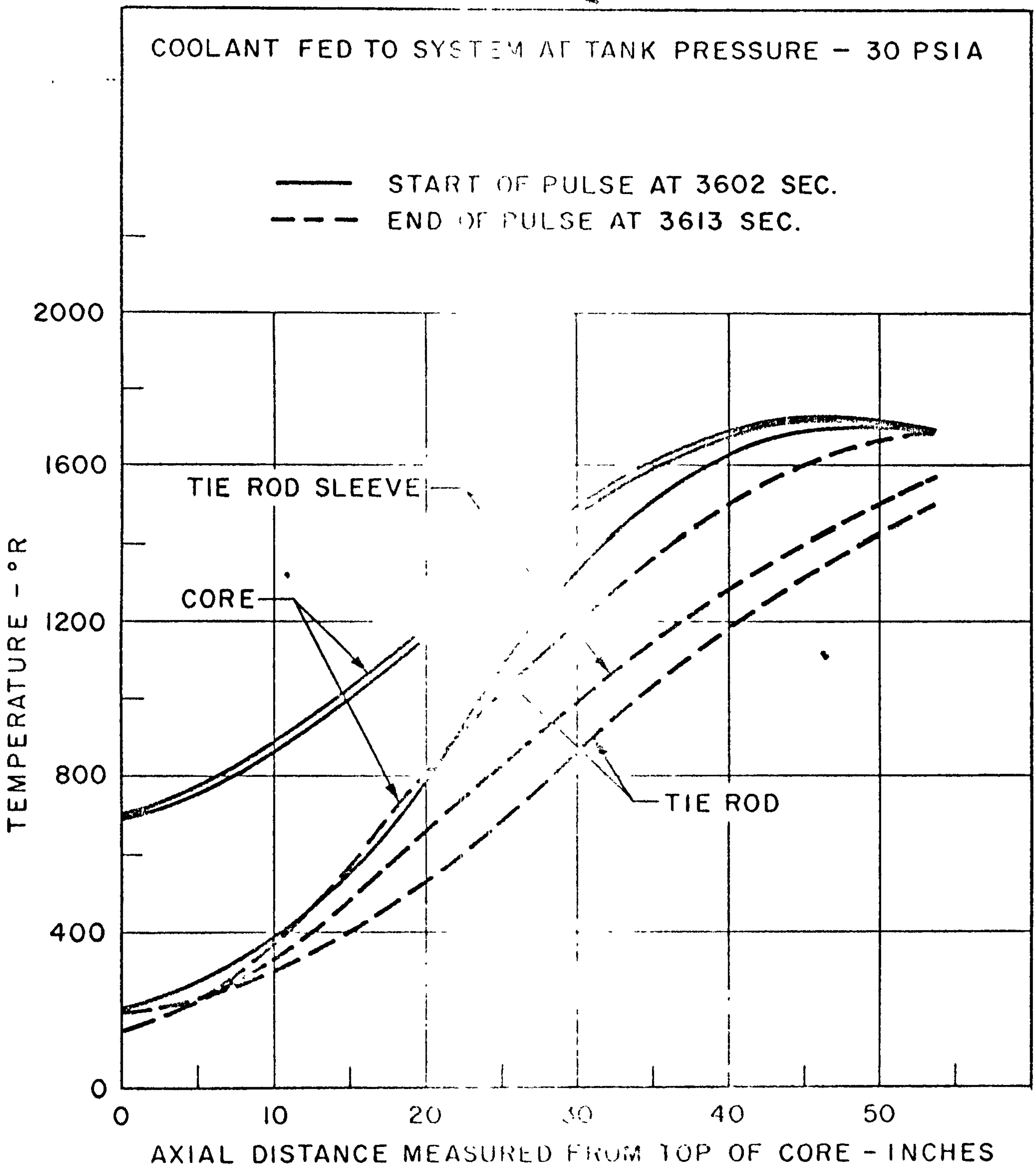

FIGURE 7 – 25TH PULSE AXIAL TEMPERATURE GRADIENTS

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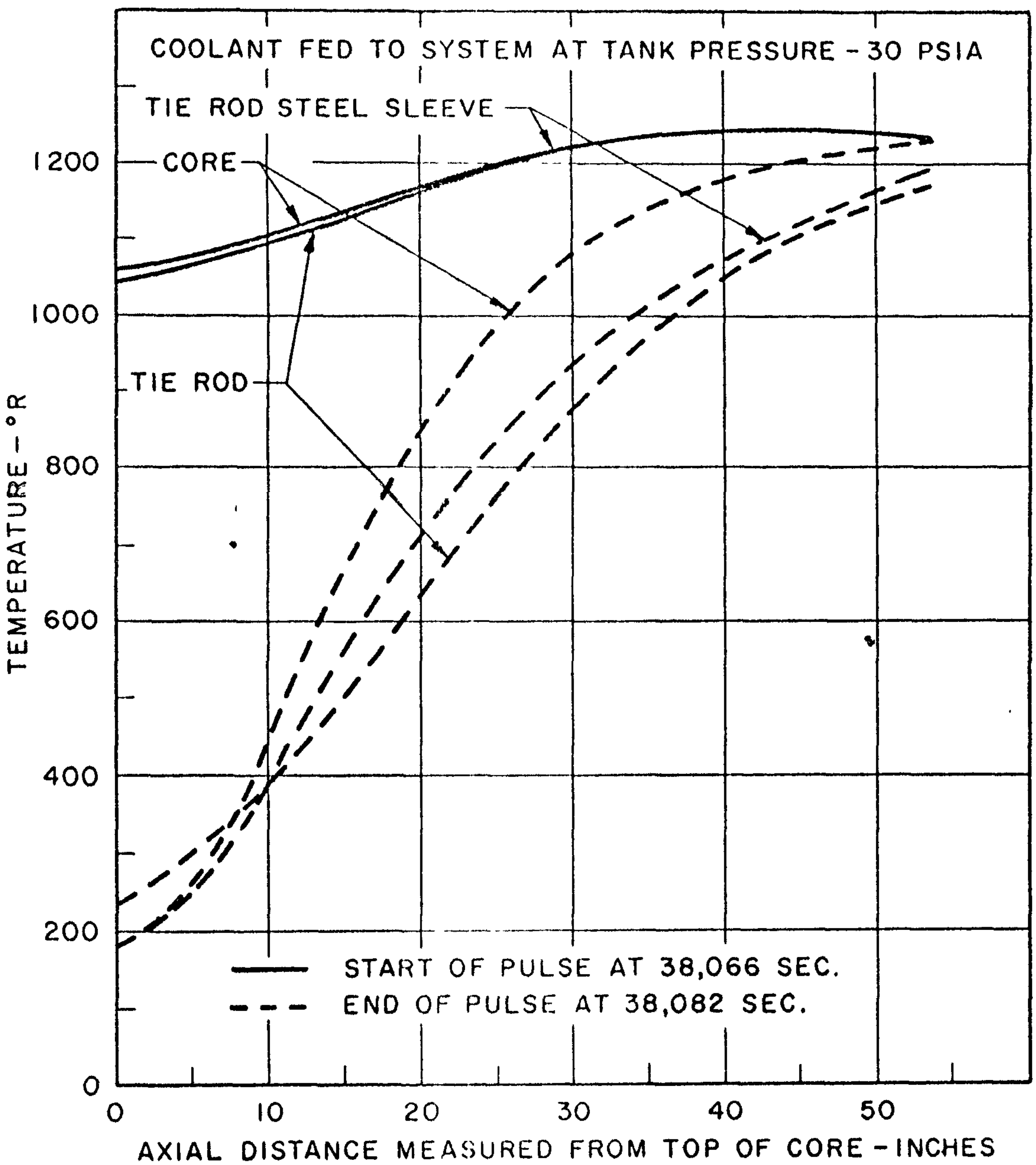

FIGURE 8 - 45TH PULSE AXIAL TEMPERATURE GRADIENTS

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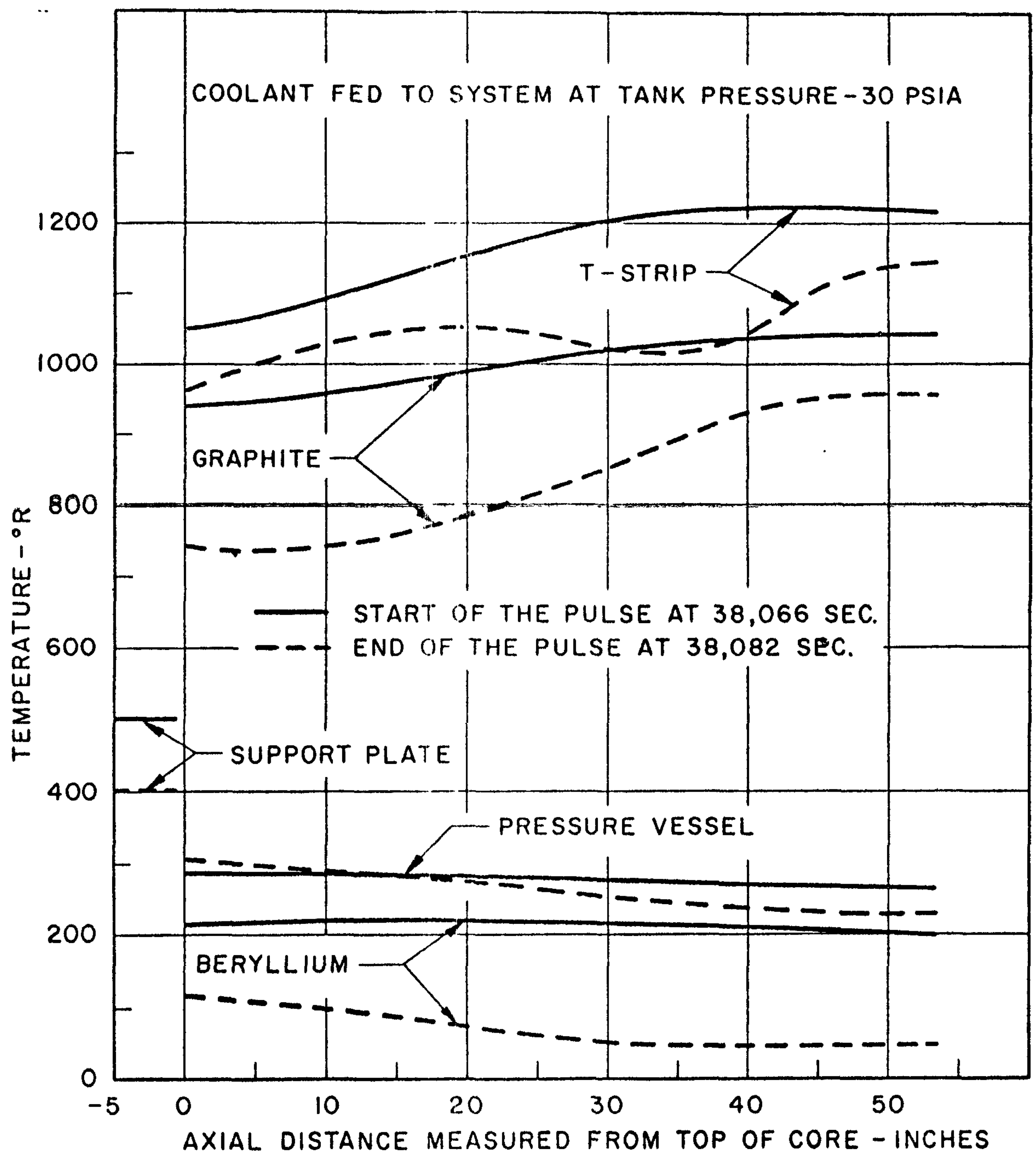

FIGURE 9 - 45TH PULSE AXIAL TEMPERATURE GRADIENTS

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