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November 1967

Westinghouse Astronuclear Laboratory

INITIAL STUDY OF SPACE ENVIRONMENT IN THE NUCLEAR SUBSYSTEM

(Title Unclassified)

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SUMMARY

An estimate of the pressure history of the nuclear subsystem was made for a lunar transfer and a manned Mars mission. The system was represented by a lumped parameter model, and gas sources due to graphite outgassing and propellant boiloff were considered.

A lower bound on the system pressure can be found by computing the steady state pressure in the core exit plenum since this represents the lowest pressure in the system. For the lunar transfer mission this pressure was found to be 7×10^{-6} torr prior to the suborbital start with a completely open nozzle, 8×10^{-4} torr prior to a cooling pulse early in the pulse cooling cycle, and 3×10^{-4} torr prior to a cooling pulse near the end of the pulse cooling cycle.

Two cases were considered for the manned Mars mission. If outgassing of water vapor is the only gas source considered the pressure in the core exit plenum for an open nozzle varied from 3.48×10^{-6} torr 100 minutes after launch to 7.23×10^{-10} torr 350 days after launch. If six pounds per day of propellant are bled into the system the core exit plenum pressure is 6.75×10^{-3} torr. If it is assumed that the bleed is divided equally among the pump discharge line, reflector inlet plenum, and upper plenum, the pressure at these locations for an open nozzle are 1.43 torr, 7.9×10^{-1} torr, and 4.7×10^{-1} torr, respectively. These pressures will not be affected greatly by the poison wire retraction plate unless it blocks more than 99.9% of the nozzle throat area.

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1. INTRODUCTION

The nuclear subsystem must be capable of operating after being subjected to a spectrum of operational and space environmental conditions. The detailed space environment that the reactor will be exposed to can be predicted only when the characteristics of that environment are known and when the specific missions are chosen. The characteristics of the space environment in the adjacent portion of the solar system have been the subject of investigation over the past decade, and sufficient information is available to provide an adequate description of those regions of immediate concern to the nuclear subsystem.

A number of missions have been proposed for the system such as lunar transfer, Venus or Mars flyby, and Mars landing. The Venus and Mars missions require that a complex system be assembled in a 400-mile Earth orbit, the time required for staging of the engine systems being of the order of 120 days. Separate stages are designed for each phase of the mission and are operated in a single-power cycle.* The lunar transfer mission, however, requires a suborbital reactor start and a restart after a 90-minute coast period. These two missions, manned Mars and lunar transfer, will subject the reactor system to quite different conditions. For the planetary mission, the reactor will be exposed primarily to high vacuum space conditions for periods of the order of 340 days; while in the lunar mission, the reactor will be subjected to a much shorter space exposure but must be capable of restart after a 90-minute coast period. During this time, the reactor is pulse-cooled to remove the decay heat being generated.

The environment to which the nuclear subsystem will be exposed will be quite different from the space environment external to the vehicle since the pressure vessel will afford a considerable degree of protection from meteoroids, electromagnetic radiations, and nuclear particles.[(1) (2) (3)] Thus the most important environmental parameter from the standpoint of the nuclear subsystem will be the pressure level. The internal atmosphere of the pressure vessel is, at present, very uncertain. It will depend upon a number of variables

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* Restart Capabilities may also be required during certain phases of the planetary missions.

which are not well defined at this time. It will be affected by the degree of nozzle blockage by the poison wire retraction mechanism; the amount of leakage of propellant or other gases into the pressure vessel; whether propellant boiloff will be deliberately bled into the system to maintain a significant pressure differential between the vehicle exterior and the various interstices, channels, and plena of the reactor vessel;outgassing and desorbing characteristics of various components of the reactor system, particularly the large volume of graphite present; reactor temperature during various phases of the mission, since this will markedly affect the outgassing and desorption rates of the various constituents and the gas species that will be present; environmental history of these components, particularly the graphite, prior to flight; effect of suborbital start and subsequent pulse cooling; and the impedance to gas evacuation inherent in the reactor assembly geometry.

Defining a reactor environment during flight is difficult due to the complexities of the system, lack of fixed design criteria in many areas, and scarcity of experimental data. In view of these facts, only a simplified parametric study can be made at this time to define the lower limits on the pressure environment in the nuclear subsystem.

The potential materials problems in the nuclear subsystem which may be induced by prolonged deep space exposure depend, of course, upon a number of variables other than pressure level. Adhesion or cold welding, for example, depends upon such diverse and complex factors as condition of the surface film, materials properties, such as crystal structure and hardness, gas species present, exposure time, contact stress, temperature, and presence of motion or vibration. Unfortunately, the effects of many of these variables can only be evaluated through careful and controlled experiments under simulated reactor environmental conditions. The estimation of the expected pressure history in the reactor system will, hopefully, serve to define the vacuum level required for these experiments and indicate under what circumstances the pressure level may be low enough to initiate materials problems.

2. PROBLEM ASSUMPTIONS

In order to reduce the problem of defining the pressure history in the nuclear subsystem to a tractable form, a number of simplifying assumptions are required. These include the selection of specific missions in order to predict the external environment as a function of time; a simplified geometric and hydraulic model of the reactor system for estimating flow conductances; an estimate of the gas sources such as graphite outgassing and desorption and leakage from the propellant tanks; and an estimate of the sealing effectiveness of propellant valves; anti-criticality flight wire retraction plate, skirt seal, and other penetrations. The assumptions made for purposes of analysis are outlined in the following sections.

A. Nuclear Subsystem

The hydraulic and geometric model chosen is intended to retain the important characteristics of the system and yet not be so complex as to cause computational difficulties. It was felt that a lumped parameter representation of the system would be adequate for the initial analysis. The system model is shown in Figure 1. The values of the conductances are based upon the existence of molecular flow at all points in the system. Due to the large conductances of the various parts of the system, viscous flow could exist only for very brief periods before the internal pressure would be reduced to the point where molecular flow theory was applicable. Where system design data was not available or not definitely established, conservative estimates of the conductances were made.

B. Missions

Two typical mission applications were chosen: a lunar transfer and a manned Mars mission. It was felt that this choice represented not only the most logical selection for which the nuclear subsystem could be used, but would also result in exposing the system to a wide variety of environmental conditions. Some of the more pertinent parameters of these missions are given in Tables 1 and 2.[3] [4]

C. Gas Sources

The gas available to the system is due to the following sources:

1. Leakage of hydrogen through the propellant valves.

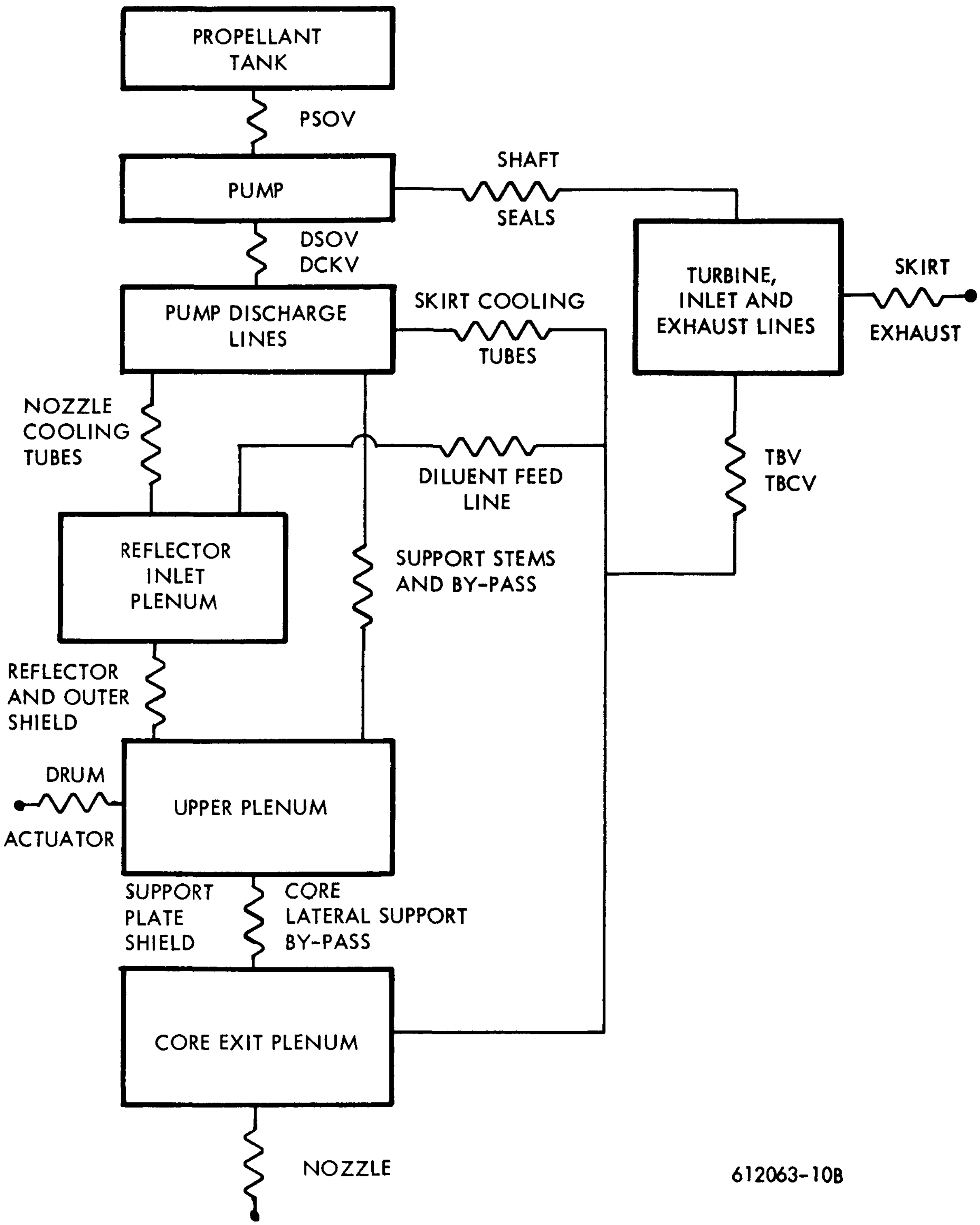

Figure 1. Lumped Parameter Model

TABLE 1. TYPICAL LUNAR TRANSFER MISSION

EVENT	TIME (SEC)	ALTITUDE (FT)	ATMOSPHERIC PRESSURE (TORR)
LAUNCH	0	0	760
SUBORBITAL NUCLEAR START	493 (0.137 HR)	538,000	1×10^{-7}
SHUTDOWN, START OF COAST AND START OF COOLING	933 (0.259 HR)	607,000	6×10^{-8}
REACH ORBITAL APOGEE	3970 (1.10 HR)	2,335,000	1×10^{-11}
NUCLEAR RESTART	6222 (1.73 HR)	997,254	5×10^{-9}

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TABLE 2. TYPICAL MANNED MARS MISSION

EVENT	TIME (DAYS)	EXTERNAL PRESSURE (TORR)
LAUNCH	0	760
FIRE NUCLEAR FIRST STAGE - EARTH ORBIT TO MARS TRANSFER TRAJECTORY	120	1×10^{-11}
ARRIVE MARS FIRE NUCLEAR SECOND STAGE	320	1×10^{-15}
LEAVE MARS FIRE NUCLEAR THIRD STAGE	340	1×10^{-15}

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2. Outgassing and desorption of water vapor and hydrogen from the core graphite.

3. Propellant boiloff.

Present design criteria require that the propellant leakage through the PSOV be a maximum of 5 scc/sec[(3)]. This indicates that the conductance of the valves will be about five orders of magnitude less than any other part of the system.

It was assumed that the volume of gas, V, in cc STP per 100 cc of graphite released up to time, t obeyed the relation[(5) (6)].

$$V = A \log_{10} t + B$$

where A and B are constants, depending upon the gas species released, graphite temperature, and type of graphite. The temperature of the graphite was assumed to be 556°K if the axis of the system is perpendicular to the sun, or 145°K if the propellant tanks are pointed at the sun[(7)]. This last assumption is more pertinent to the manned Mars mission than the lunar transfer mission. For the lunar mission, the reactor will be close to 300°K prior to suborbital start and near 1000°K during pulse cooling.

The propellant boiloff has been estimated to be 6 lb/day. This is less than the amount predicted in reference (8).

D. Sealing Effectiveness

The primary leakage paths of the system are the nozzle, valves, skirt, actuator, and shaft seals. Due to design uncertainties, it is not clear how effective the anti-criticality wire retraction plate will seal the nozzle. It was assumed that it blocked 90 to 99 percent of the nozzle throat area. As previously mentioned, the valves represent very low conductance paths; and for purposes of analysis, it was assumed that two valves in series acted as an effective seal against leakage. The actuator leakage path will have a conductance which is small compared to the other available exhaust paths and will be neglected. Similarly, the skirt leakage can be neglected since the skirt is effectively isolated from the main system by the TBV and TPCV.

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3. METHOD OF ANALYSIS

A. Lumped Parameter Representation of the System

From Figure 1 it is clear that in order for leakage from the propellant tank to enter the pressure vessel, it must pass through the PSOV, DSOV, and DCKV. These valves are very low conductances paths, at least five orders of magnitudes less than any other component of the system, and it is unlikely that any appreciable amount of this leakage will enter the pressure vessel. It will more likely escape through the pump seals into the turbine, through the turbine exhaust lines to the skirt, and vent into space unless sealing is provided. The turbine system is also well isolated from the pressure vessel because of the TBV and TPCV. The small leakage through the drum actuator will also be negligible compared to other leakage paths. In view of these considerations, a simplified version of the lumped parameter system is shown in Figure 2. A list of the numerical values of the various parameters is also given. The values given for the conductances are for hydrogen. For water vapor the values are one-third as large.

B. Calculation of Conductances

The conductances for the various parts of the system were computed in the following manner:

1. Nozzle: The nozzle was treated as a thin, sharp-edged orifice. This is a conservative assumption, since the conductance of any actual nozzle would be less than an orifice with a diameter equal to the throat diameter of the nozzle. The conductance of an orifice is given as:[9]

$$F = 3.64\ A\sqrt{T/M}$$

where A = area of orifice (cm^2).

T = gas temperature (^oK)

M = molecular weight of gas (gm/gm mol wt).

2. Cylindrical Tube: The method derived by Clausing was used to compute the conductance of long cylindrical tubes. The conductance is given by

$$F = K\ (3.64\ A\sqrt{T/M})$$

where K = Clausing factor, a function of the length to radius ratio of the tube.

3. Noncircular Tubes: For noncircular channels, the fundamental relation deduced by Knudsen was used to compute the conductance[9]. That is:

$$F = 4/3 \left(\frac{8 R_o T}{M}\right)^{1/2} \frac{1}{\int_0^L \frac{H}{A^2} dL}$$

where H = channel perimeter

A = channel cross sectional area

L = channel length

R_o = universal gas constant

with T and M defined as before.

For conductances in series, the total conductance F_T is given by

$$\frac{1}{F_T} = \sum_i \frac{1}{F_i}$$

in parallel, the total conductance is given as

$$F_T = \sum_i F_i$$

C. Differential Equations of the System

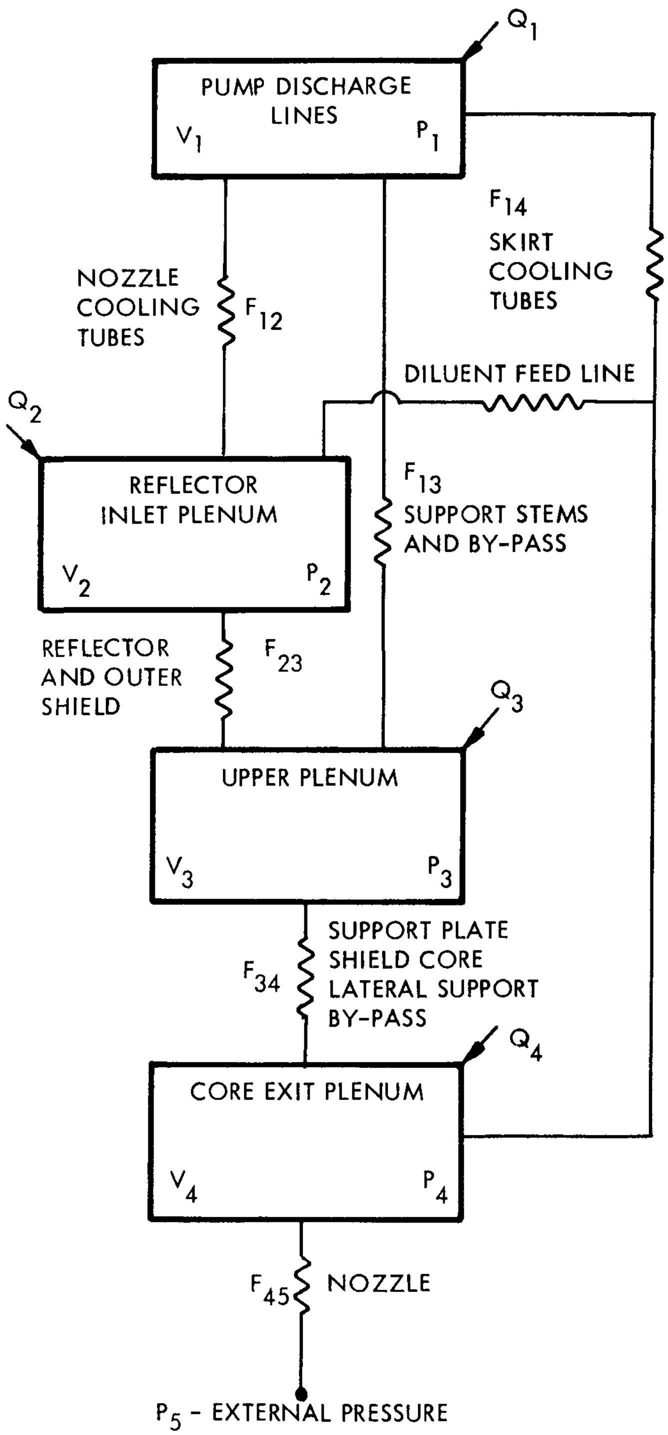
To determine the pressure history of the nuclear subsystem, it is necessary to describe the lumped parameter system mathematically. The behavior of the system is determined by solving a set of coupled, first order, linear, ordinary differential equations of the form

$$-V_i \frac{dp_i}{dt} = -Q_i - \sum_k F_{ki} (P_k - P_i) + \sum_j F_{ij} (P_i - P_j)$$

where P_i = pressure in volume V_i

Q_i = gas source for volume V_i

F_{ij} = conductance between volumes V_i and V_j.



CONDUCTANCES $\left(\frac{\text{LITERS}}{\text{SEC}}\right)$

		556°K	145°K
F_{12}	=	79.4	39.6
F_{13}	=	12.1	6.0
F_{14}	=	79.4	39.6
F_{23}	=	282	141
F_{34}	=	546	271
		445°K	**135°K**
F_{45}	=	64,600 (1)	35,300 (1)
		6,460 (2)	3,530 (2)
		646 (3)	353 (3)
F_{24}	=	200	110

(1) NOZZLE OPEN

(2) 90% FLOW AREA BLOCKED

(3) 99% FLOW AREA BLOCKED

VOLUMES (LITERS)

V_1	=	214
V_2	=	172.5
V_3	=	226
V_4	=	678

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Figure 2. Modified Lumped Parameter Model

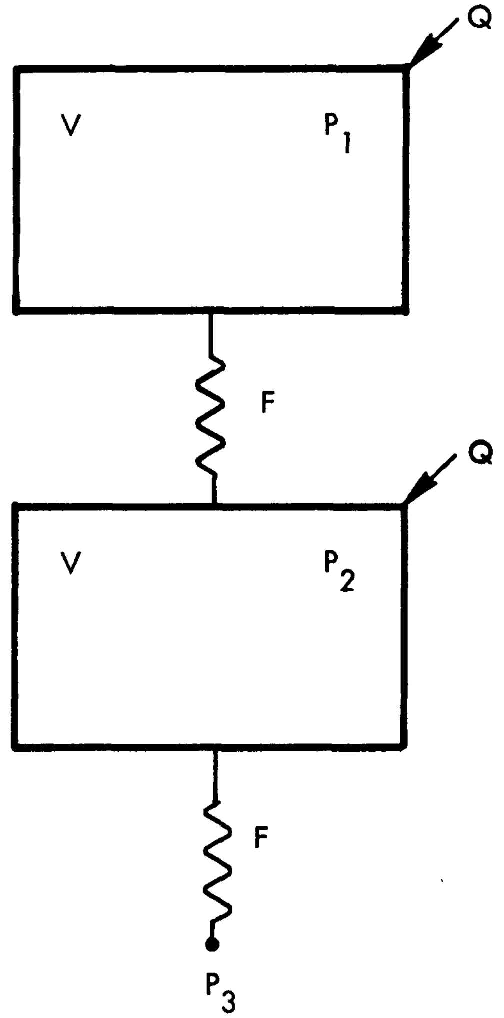
It is of interest to determine what information can be obtained from these time-dependent equations without attempting to solve them in detail. The time constants of the system, which are an indication of the length of time required for the system to come to equilibrium after an initial disturbance, can be easily estimated since they are related to the ratios F_{ij}/V_i. An examination of the values of these parameters indicate that, in the absence of sources, the system would come into equilibrium with its surroundings very quickly.

To clarify this point consider the simple system shown in Figure 3. The time dependent differential equations can be solved quite easily and the solutions are shown in Figure 4. The transient terms are simple exponentials with time constants N_1 and N_2. It can be seen that when N_1 and N_2 are of the order of unity the transient terms will decrease by over four orders of magnitude in ten seconds. The important consideration is that the system responds very quickly to outside disturbances and by considering the steady-state solutions, much useful information can easily be obtained. The steady-state solution for the system shown in Figure 2, assuming molecular flow exists at all points, is shown in Figure 5.

D. Gas Sources

Data on the outgassing characteristics of the reactor graphite at the temperatures of interest are almost nonexistent. It was necessary, therefore, to use what outgassing data does exist and attempt to extrapolate it to the reactor operating conditions. Although it is believed that the extrapolations were conservative in a direction that would tend to lower the system pressure, the validity of this procedure is open to serious doubt. Estimates of the system temperature[(7)] indicate that the reactor temperature will be 556°K if the axis of the system is perpendicular to the sun, and 145°K if the axis is parallel to the sun, with the pressure vessel shadowed by the propellant tank. The corresponding nozzle temperatures are 445°K and 135°K. At the higher temperature, the predominant gas species that will be outgassed from the graphite is water vapor. The data used in the analysis was taken from Reference 5 for outgassing of EGCR moderator graphite at 300°C. The volume outgassed V up to time t in Scc/100 cc graphite was found to be represented by an equation of the form

$$V = A \log_{10} t + B$$



DIFFERENTIAL EQUATIONS

$$-V \frac{dP_1}{dt} = -Q + F\ (P_1 - P_2)$$

$$-V \frac{dP_2}{dt} = -Q - F\ (P_1 - P_2) + F\ (P_2 - P_3)$$

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Figure 3. Example of Lumped Parameter System

STEADY STATE SOLUTIONS

$$P_2^{ss} = \frac{2Q}{F} + P_3$$

$$P_1^{ss} = \frac{Q}{F} + P_2 = \frac{3Q}{F} + P_3$$

TIME DEPENDENT SOLUTIONS

$$P_1 = C_1 e^{N_1 t} + C_2 e^{N_2 t} + P_1^{ss}$$

$$P_2 = \left(1 + \frac{N_1}{A}\right) C_1 e^{N_1 t} + \left(1 + \frac{N_2}{A}\right) C_2 e^{N_2 t} + P_2^{ss}$$

WHERE $N_1 = \frac{F}{V}\left\{\frac{-3+\sqrt{5}}{2}\right\} < 0$

$$N_2 = \frac{F}{V}\left\{\frac{-3-\sqrt{5}}{2}\right\} < 0$$

C_1 & C_2 = CONSTANTS DETERMINED BY INITIAL CONDITIONS

$$A = \frac{F}{V}$$

$P_1 > P_2$ FOR $t > 0$

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Figure 4. Example of Lumped Parameter System

$$P_4 = \frac{Q_1 + Q_2 + Q_3 + Q_4}{F_{45}} + P_5$$

$$P_j = \frac{1}{\| F \|} \bullet \sum_i M_{i_j} S_i$$

WHERE

$$S_j = Q_j + F_{j4} P_4$$

M_{i_j} = COFACTORS OF MATRIX $[F]$

$\| F \|$ = DETERMINANT OF MATRIX $[F]$

$$[F] = \begin{bmatrix} (F_{12} + F_{13} + F_{14}) & -F_{12} & -F_{13} \\ -F_{12} & (F_{12} + F_{23} + F_{24}) & -F_{23} \\ -F_{13} & -F_{23} & (F_{23} + F_{13} + F_{34}) \end{bmatrix}$$

SUBSCRIPTS

1. REFERS TO PUMP DISCHARGE LINES
2. REFERS TO REFLECTOR INLET PLENUM
3. REFERS TO UPPER PLENUM
4. REFERS TO CORE EXIT PLENUM
5. REFERS TO EXTERNAL ENVIRONMENT

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Figure 5. Steady-State Solutions for Modified Lumped Parameter Nuclear Subsystem

A and B are constant with time for any given test, but they depend upon the sample and the outgassing temperature. The lowest values given were used in the analysis. One fact which must be considered is that the test times were of the order of 3000 to 10,000 minutes. The time periods required for the manned Mars mission are one to two orders of magnitude longer. It was assumed that the previous logarithmic relation was valid throughout the mission. If the gas source in the graphite is exhausted before the end of the mission, the pressures computed will be too high. The results indicate, however, that even if the graphite continues to outgas as predicted by the previous relation, the system pressure will be quite low at the end of the mission, of the order of 10^{-7} torr with 99 percent of the nozzle throat blocked by the poison wire retraction plate.

If the system temperature is $145^{o}K$, it was assumed that no water vapor was outgassed and the system pressure will approach that of the space environment in the absence of any other sources.

For the period between launch and suborbital start, the reactor was assumed to be at $300^{o}K$ and the outgassing rate data used was a tenth of that for $556^{o}K$. This seemed to be a reasonable estimate based upon the temperature dependence of the outgassing data indicated in Reference 5.

To estimate the outgassing rate after pulse cooling, the data of Reference 6 was used. The hydrogen pressure used in the experiment described was only 100 torr, but the exposure time was 30 minutes and the outgassing temperature was $1358^{o}K$. The sample was made from nuclear graphite (TSP). It was found that the outgassing data again followed a logarithmic relation. To account for the longer exposure times and higher outgassing temperature, the data of Reference 6 was reduced by a factor of ten.

4. RESULTS

The pressure in the exit plenum for various phases of the lunar and manned Mars missions is shown in Tables 3 and 4. These results, of course, depend upon the assumptions made for the system model and the outgassing sources, and they are, at best, only order of magnitude estimates.

If the propellant boiloff is vented to the nuclear subsystem, the lowest pressure in the system will be in the exit plenum. Other points of the system will be at higher pressures. Table 5 lists the pressure in the exit plenum as a function of the propellant boiloff flow rate. The maximum available weight flow of hydrogen was taken as 6 lb M/day.

Table 6 lists the steady-state pressures in various parts of the nuclear subsystem assuming that 2 lb M/day of propellant is bled into the pump discharge lines, reflector inlet plenum and upper plenum for a total of 6 lb M/day. The nozzle is considered to be open, 90% blocked and 99% blocked. It is interesting to note that reducing the nozzle throat area by a factor of 100 has only a small effect on the system pressures. This is due to the fact that the conductance of the nozzle is so large that the exit plenum is almost as effective as the space external to the pressure vessel in exhausting the system. It is only when the nozzle conductance is reduced to a value comparable to the other conductances in the system that pressures in other parts of the system are affected to any extent. For the conditions listed, the system pressures would change to a much greater extent if the nozzle were to be constricted by another factor of ten to 99.9% blockage. This indicates that the poison wire retraction plate will not have a great effect on system pressures unless it acts as a very effective seal (blocking 99.9% of the nozzle throat). It must be remembered that these results apply to the particular case considered and care should be exercised in generalizing them.

TABLE 3. PRESSURE* IN CORE EXIT PLENUM LUNAR TRANSFER MISSION (GRAPHITE OUTGASSING)

TIME	CONDITION OF NOZZLE THROAT		
	OPEN	90% BLOCKED	99% BLOCKED
PRIOR TO NUCLEAR SUBORBITAL START	7×10^{-6}	7×10^{-5}	7×10^{-4}
PRIOR TO START OF A COOLING PULSE (EARLY PULSES)	8×10^{-4}	—	—
PRIOR TO START OF A COOLING PULSE (LATER PULSES)	3×10^{-4}	—	—

*PRESSURE IN TORR

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TABLE 4. PRESSURE* IN CORE EXIT PLENUM MANNED MARS MISSION (GRAPHITE OUTGASSING)

TIME AFTER LAUNCH (MINUTES)	CONDITION OF NOZZLE THROAT		
	OPEN	90% BLOCKED	99% BLOCKED
100 (~1.7 HR)	3.48×10^{-6}	3.48×10^{-5}	3.48×10^{-4}
1,000 (~16.7 HR)	3.62×10^{-7}	3.62×10^{-6}	3.62×10^{-5}
10,000 (~7 DAYS)	3.64×10^{-8}	3.64×10^{-7}	3.64×10^{-6}
100,000 (~70 DAYS)	3.65×10^{-9}	3.65×10^{-8}	3.65×10^{-7}
300,000 (~210 DAYS)	1.22×10^{-9}	1.22×10^{-8}	1.22×10^{-7}
500,000 (~350 DAYS)	7.23×10^{-10}	7.23×10^{-9}	7.23×10^{-8}

*PRESSURE IN TORR

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TABLE 5. PRESSURE* IN CORE EXIT PLENUM MANNED MARS MISSION (USING PROPELLANT BOILOFF)

PROPELLANT BOILOFF USED (#/DAY)	CONDITION OF NOZZLE THROAT		
	OPEN	90% BLOCKED	99% BLOCKED
0.09	1×10^{-4}	1×10^{-3}	1×10^{-2}
0.90	1×10^{-3}	1×10^{-2}	1×10^{-1}
6.00	6.75×10^{-3}	6.75×10^{-2}	6.75×10^{-1}
43.20	4.86×10^{-2}	4.86×10^{-1}	4.86×10^{0}

*PRESSURE IN TORR

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TABLE 6. NUCLEAR SUBSYSTEM PRESSURES*

ASSUMPTIONS:

I. 2#/DAY OF PROPELLANT BOILOFF BLED INTO
   A. PUMP DISCHARGE LINES
   B. REFLECTOR INLET PLENUM
   C. UPPER PLENUM

II. NOZZLE CONDITION
   A. OPEN
   B. THROAT AREA REDUCED BY 90%
   C. THROAT AREA REDUCED BY 99%

	NOZZLE CONDITION		
LOCATION	OPEN	90% BLOCKED	99% BLOCKED
NOZZLE PLENUM	6.75×10^{-3}	6.75×10^{-2}	6.75×10^{-1}
PUMP DISCHARGE LINES	1.43	1.48	2.02
REFLECTOR INLET PLENUM	7.90×10^{-1}	1.01	1.46
UPPER PLENUM	4.70×10^{-1}	5.30×10^{-1}	1.13

* ALL PRESSURES IN TORR

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5. RECOMMENDATIONS FOR FUTURE WORK

A. Nuclear Subsystem Model

For purposes of initial studies, it is felt that the hydrodynamic and geometric model used is an adequate representation of the system. Some effort should be devoted to the following items:

1. Update the model as design changes occur.
2. Obtain more definitive data on the conductances of the propellant valves and shaft seals, and how various parts of the system are to be sealed.
3. Consider the flow of the species outgassed in the small spaces between the fuel elements.
4. Obtain a more accurate temperature history of the system.

B. Gas Sources

The magnitude of the gas sources in the nuclear subsystem must be known as accurately as possible since they determine the system's equilibrium pressure. The following data is needed on the type of graphite to be used in the reactor core:

1. Outgassing rate as a function of time and temperature (long time and low temperature data are needed).
2. Species outgassed.
3. Outgassing characteristics after exposure to hydrogen flow.
4. Effect of radiation on outgassing characteristics.
5. Effect of prior environment.

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