MASTER

REON
SACRAMENTO PLANT

REPORT NO. RN-S-0140

TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

PRELIMINARY EVALUATION OF NUCLEAR HAZARDS ASSOCIATED
WITH ORBITAL START OF A NUCLEAR ROCKET ENGINE (U)

NERVA PROGRAM

CONTRACT SNP-1

SEPTEMBER 1964

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

AEROJET GENERAL CORPORATION
SACRAMENTO, CALIFORNIA

CONFIDENTIAL

(0718)

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

~~CONFIDENTIAL~~

AEROJET-GENERAL CORPORATION

SNPO-C

Ross

P.

TO, CALIFORNIA

SACRAMENTO PLANT

7120:0343L
GDJ:bas

27 October 1964

Space Nuclear Propulsion Office
Cleveland Extension
National Aeronautics and Space Administration
21000 Brookpark Road
Cleveland 35, Ohio 44135

Attention: L. C. Corrington

Subject: AGC Report No. RN-S-0140, Preliminary Evaluation
of Nuclear Hazards Associated with Orbital Start
of a Nuclear Rocket Engine, September 1964 (U)

Gentlemen:

Eight (8) copies of the subject report are forwarded in partial fulfillment of Subtask 2.7, Contract SNP-1.

Since Subtask 2.7 has been deleted from the work to be performed during Contract Year 1965, distribution of this report has been limited to that shown in Enclosure (2). A limited number of additional copies are available upon request.

Very truly yours,

AEROJET-GENERAL CORPORATION

If enclosure No. 1 is withdrawn (or not attached), the classification of this correspondence will be downgraded to UNCLASSIFIED.

H. E. Pharr
Manager of Contracts
Rocket Engine Operations - Nuclear

Enclosure:

- (1) AGC Report No. RN-S-0140 (CRD)
- (2) Distribution List (U)

~~RECEIVED~~
~~10/27/64~~

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~
~~RESTRICTED DATA~~

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

REPORT NO. RN-S-0140

TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

PRELIMINARY EVALUATION OF NUCLEAR HAZARDS ASSOCIATED
WITH ORBITAL START OF A NUCLEAR ROCKET ENGINE (U)

CONTRACT SNP-1 NERVA PROGRAM SEPTEMBER 1964

SP-001	TR U	4-20-82
DETERMINATION		
Class: 4		

Classification cancelled (or changed to)
by authority of DEC
by H.A.C. TIC, date SEP 10 1973

GROUP-1

~~EXCLUDED FROM AUTOMATIC DOWNGRADING
AND DECLASSIFICATION~~

~~RESTRICTED DATA
ATOMIC ENERGY ACT OF 1954~~

(0718)

~~CONFIDENTIAL~~
~~RESTRICTED DATA~~

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

...

...

...

...

...

...

ABSTRACT

The magnitude of the radiation hazards inherent to the orbital operation of a nuclear rocket engine is examined. Orbital lifetime prediction techniques are reviewed and predicted lifetimes are compared with observed data. A world population density model is described. A statistical analysis model is developed and used to evaluate the probability of radiation exposures to the earth's population following premature thrust termination of the engine. Various counter measure concepts are discussed in terms of their possible utilization in a total flight safety system for the NERVA engine.

PREPARED BY:

A handwritten signature in black ink, appearing to read "D S Duncan", with a long horizontal flourish extending to the right.

D. S. Duncan, Manager
Systems Safety Analysis

FOREWORD

This report has been prepared in partial fulfillment of Subtask 2.7,
Contract SNP-1.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	
I. INTRODUCTION	1
II. ORBITAL LIFETIME DATA	3
A. Lifetime Predictions	3
B. Comparisons of Observed and Predicted Lifetimes	5
C. Approximation of Orbital Lifetime vs Engine Operating History	9
III. WORLD POPULATION MODEL	12
IV. EARTH IMPACT HAZARDS	15
A. Potential Accidents	15
B. Radiation Levels on Impact	18
C. Exposure Probabilities	21
1. Analytical Model	21
2. Random Reentry of an Intact Reactor	28
3. Random Reentry of Fuel Elements	31
D. Physical Hazards	36
E. Hazards Summary	38
V. COUNTERMEASURES	41
A. Primary Concepts	42
1. Flight Poison	42
2. Explosive Disassembly	43
3. Post-Operational Destruct	44
4. Passive Disassembly	46
5. Auxiliary Chemical Propulsion.	47
6. Nuclear Destruct	48

TABLE OF CONTENTS (cont.)

	<u>Page</u>
B. Secondary Concepts	49
1. Trajectory Shaping	49
2. Fission-Product Boiloff.	50
3. Engine/Stage Separation	51
4. Chemical Preconditioning of Core	51
C. Conclusions and Recommendations	52

LIST OF SYMBOLS

LIST OF REFERENCES

~~CONFIDENTIAL~~

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Summary of Orbital Lifetime Predictions	4
2	Effect of Atmosphere Model on Lifetime	6
3	Population Density Distribution	13
4	Orbital Lifetimes for Assumed Vehicle Configuration	22
5	Impact Inventories	23
6	4-Day Dose at 1 Meter from 1/1600th of Core	24
7	Maximum 4-Day Dose at 1 Meter from 1/1600th of Core	27
8	Exposure Probabilities Following 12 Seconds Full-Power Operation from 100 N. Mi. Orbit	33
9	Expectation vs Engine Operating Time	34

~~CONFIDENTIAL~~

LIST OF TABLES

<u>Table</u>		<u>Page</u>
I	Comparison of Observed and Predicted Lifetimes	7
II	World Population Density Model	14
III	Assumed Parameters for Nuclear Engine and Stage	16
IV	Probability of at Least n People Receiving a Dose $\geq$ D	32
V	Injury Risk Comparison	39

I. INTRODUCTION

The safety problems peculiar to the operation of a nuclear rocket engine, as opposed to the more conventional chemical systems, can be divided into two principal categories: (1) the prevention of inadvertent criticality in or near the launch area, and (2) the disposal of the highly radioactive core following engine operation in a manner which precludes undue hazard to the earth population. This latter category may be further classified by operational mode; i.e., whether startup of the nuclear engine occurs prior to or following orbital injection. The content of this paper is limited to a review of the nuclear hazards associated with the orbital start mode. Its purpose is twofold: (1) to identify critical areas within the flight safety program where modifications or additions to the current effort are required, and (2) to provide a basis for establishing operational criteria for the engine countermeasure systems and safety features needed for orbital start operations.

In Sections II and III of this report, some of the basic information and data needed to evaluate potential hazards encountered during orbital start operations of the NERVA engine are developed. Section II reviews briefly orbital lifetime prediction techniques and compares predicted lifetimes with observed data. An analytical expression is also derived for the calculation of orbital lifetime as a function of engine operating history following startup in circular orbit. This expression is subsequently used in the determination of the fission-product inventory reaching the earth following orbital decay of the reactor. Section III describes a population density model based upon the estimated world population in 1975. In Section IV, with the aid of this model, earth impact hazards are evaluated in terms of exposure probabilities to the earth population for both

a startup excursion and for engine failures which result in premature thrust termination. The results obtained are compared with various well-known type accidents and with injury probabilities resulting from people being physically struck by reactor fuel elements on earth impact. In Section V, countermeasure concepts which may be used to preclude or to reduce the magnitude of the orbital start hazards are discussed in terms of their possible utilization in a total flight safety system for the NERVA engine.

II. ORBITAL LIFETIME DATA

A. LIFETIME PREDICTIONS

The magnitude of the hazards associated with reentry from orbit of a nuclear rocket engine that has been operated is strongly dependent upon the time required for orbital decay. Precise determination of lifetimes for elliptic orbits is complicated because of the variations in atmospheric density encountered by the orbiting body and the density perturbations resulting from the sun's gravitational field, solar radiation, sunspot activity, and the oblateness of the earth. Consequently, the general practice has been to obtain a two-dimensional computer solution to the equations of motion by assuming a symmetrical atmosphere surrounding a stationary earth for which the gravitational field is given by a simple inverse-square law. A simplified atmospheric density model which represents an idealized middle-latitude year-round mean, averaged over the range of solar activity between sun-spot minima and maxima is usually chosen. Thus, the relatively small density fluctuations caused by variations in the corpuscular and extreme ultraviolet fluxes from the sun and by variations in the sun with respect to a given point above the earth's surface are neglected.

A comparison of orbital lifetime predictions by three different authors (Refs. 3, 4, and 5) is illustrated in Figure 1. All of the calculations were performed using the AFDC 1959 model atmosphere (Ref. 1) which has been shown (Ref. 1) to agree quite well with the more recent 1962 U. S. Standard Atmosphere. The results by both Hargrove and Korx were obtained using the simplifying assumptions discussed above. The Lockheed analysis included several refinements such as oblateness of the earth and variations in atmospheric density caused by the earth's rotation (day and night effects) and the eleven-year cycle of solar activity. As

FIGURE 1
SUMMARY OF ORBITAL LIFETIME PREDICTIONS

can be seen from Figure 1, these refinements do not appear to significantly alter the predicted lifetimes for the launch date chosen. However, Lockheed has also shown in Reference 5 that solar flare activity can affect satellite lifetimes by as much as a factor of 3. An example of this variation is illustrated in Figure 2. It should be noted that use of the ARDC 1959 model atmosphere results in the minimum lifetime during the eleven-year solar flare cycle.

The lifetime data given in Figure 1 between perigee altitudes of 90 and 225 nautical miles can be approximated within a reasonable degree of accuracy over the range of eccentricities between 0 and 0.3 by the empirical expression

$$L = Z(0.0032 + 7.43E^{1.535}) \exp(0.0369h). \quad (1)$$

The closeness of fit to the computed data is shown by the dashed curves on Figure 1. Equation (1) will be used throughout the remainder of this study for predicting satellite lifetimes.

B. COMPARISONS OF OBSERVED AND PREDICTED LIFETIMES

In order to establish the validity of Equation (1) for lifetime prediction calculations, comparisons have been made with observed satellite lifetimes. The results of this comparison are tabulated in Table I. The description of the satellites and the actual lifetime data were taken from Reference 6.

As can be seen from Equation (1), the satellite lifetime is directly proportional to the ballistic parameter Z , which is defined as

$$Z = \frac{W}{C_D \bar{A}}, \quad (2)$$

where W is the weight of the satellite, C_D is the drag coefficient, and $\bar{A}$ is the effective cross-sectional area of the satellite perpendicular to the air stream. In determining the ballistic parameter, several difficulties exist: (1) most

FIGURE 2
EFFECT OF ATMOSPHERE MODEL ON LIFETIME

TABLE I
COMPARISON OF OBSERVED AND PREDICTED LIFETIMES

Satellite	Case	Perigee	Eccen- tricity (6)	Configuration (6)	Effective	Weight (6) W (lb)	Ballistic Parameter (C _D = 2.0)			Lifetime (days) (6)		L/L ₀
		Alt (6), h (n mi)			Area, A (ft ²)		Z	B	B ₀ *	L**	L ₀	
SPUTNIK I	1	125	0.051	1.9' dia sphere	2.83	184	32.5	0.49	0.69	259	92	2.86
SPUTNIK III	2	116	0.106	5.67' dia cone 11.67' high	33.0	2926	44.4	0.36	-	767	693	1.11
EXPLORER III	3	102	0.166	0.5' dia cyl 6.67' lg	2.72	31.7	5.8	2.78	3.69	118	93	1.27
EXPLORER IV	4	142	0.128	0.5' dia cyl 6.67' lg	2.72	37.1	6.8	2.37	1.55	408	455	0.90
SCORE ONE	5	100	0.089	10' dia cyl 8.5' lg	706	8800	6.22	2.60	2.98	45.6	34	1.34
DISCOVERER II	6	132	0.0088	5' dia cyl 16.5' lg	74.5	1400	9.4	1.71	1.50	10.3	13	0.79
DISCOVERER V	7	118	0.038	5' dia cyl 16.5' lg	74.5	1400	9.4	1.71	1.46	38.2	46	0.83
DISCOVERER VI	8	114	0.046	5' dia cyl 16.5' lg	74.5	1400	9.4	1.71	1.13	43.4	62	0.70
DISCOVERER VII	9	86	0.049	5' dia cyl 19.2' lg	85.1	1700	10.0	1.61	1.53	18.1	19	0.95
DISCOVERED VIII	10	104	0.101	5' dia cyl 16.5' lg	74.5	1400	9.4	1.71	1.38	96.9	109	0.89
DISCOVERED XI	11	90	0.032	5' dia cyl 16.5' lg	74.5	1400	9.4	1.71	1.65	10.6	11	0.96
DISCOVERER XIII	12	136	0.032	5' dia cyl 16.5' lg	74.5	1400	9.4	1.71	1.04	57.8	97	0.59
DISCOVERER XIV	13	96	0.046	5' dia cyl 16.5' lg	74.5	1400	9.4	1.71	1.30	22.2	29	0.77
DISCOVERER XV	14	108	0.041	5' dia cyl 16.5' lg	74.5	1400	9.4	1.71	1.50	29.4	35	0.83
DISCOVERER XVII	15	98	0.058	5' dia cyl 21.5' lg	94.0	1800	9.6	1.68	0.95	33.8	47	0.72

*Computed from initial observed decay rates of the semi-major axis (Ref. 3)
**Predicted lifetime using Equation (1)

satellite vehicles are not simple geometric bodies for which drag coefficients can be found by straightforward analytical methods; (2) in the case of tumbling satellites, there are difficulties in predicting the exact mode of motion with respect to the air stream, and accordingly there may arise a question about the correct reference area; and (3) in certain cases, reliable information about the weight of the satellite may not exist.

For the comparisons made in Table I, the weight of the satellite, as reported by Reference 6, was assumed to remain constant, and the drag coefficient was taken as 2.0 which is a valid first approximation for spherical and cylindrical satellites traveling at high Mach numbers (Ref. 3). To obtain the effective area, $\bar{A}$, it was further assumed that the satellite was tumbling such that any orientation was equally probable. Thus, the effective area can be approximated by the total wetted surface area divided by 4*; i.e.,

$$\bar{A} \approx A_{\text{surface}}/4. \quad (3)$$

The results listed in Table I are remarkably good. In 13 out of the 15 examples shown, the predicted lifetimes are within 35% of the actual values. Furthermore, the weighted spread in the calculated values is almost equally distributed above and below the observed lifetimes. Though the range of perigee altitudes, eccentricities, and ballistic parameters given in Table I do not cover

*For the reentry of tumbling bodies with very large L/d ratios (such as a reactor fuel element), a preferable method for calculating the effective area is to multiply the average longitudinal cross-sectional area of the body by the average cosine of the angle between the longitudinal axis of the body and the air stream. Thus, for completely random tumbling of bodies with large L/d ratios,

$$\bar{A} \approx A_{\text{long. x-sect.}} \times 2/\pi.$$

the entire range of interest to this study, and though the agreement may be somewhat fortuitous, the results of this comparison do indicate that satellite lifetimes can be predicted from Equation (1) with a fair degree of confidence.

C. APPROXIMATION OF ORBITAL LIFETIME VS ENGINE OPERATING HISTORY

Using the empirical lifetime prediction equation given in Section II-A an expression for orbital lifetime as a function of engine operating history can be derived. This relationship can then be used in the calculation of impact inventories following orbital decay.

Consider startup of a nuclear stage in a circular orbit of altitude h . The engine is operated at a thrust T for t seconds. Thrust is applied tangentially to the circular orbit path. Thus, the velocity increment added during the time t is (Ref. 7)

$$\Delta v = \frac{T}{\dot{W}} g \ln \frac{W}{W - \dot{W}t}, \quad (4)$$

where $\dot{W}$ is the propellant flow rate, W is the vehicle weight at engine startup, and g is the gravitational acceleration given by

$$g = g_0 \left(\frac{R_0}{R_0 + h} \right)^2. \quad (5)$$

By expanding Equation 4 in series, the velocity increment becomes

$$\Delta v = \frac{T}{\dot{W}} g \left[\frac{\dot{W}t}{W} + \frac{1}{2} \left(\frac{\dot{W}t}{W} \right)^2 + \dots \right], \quad (6)$$

which, for $\frac{\dot{W}t}{W} \ll 1$, reduces to

$$\Delta v \approx \frac{Tgt}{W} = \frac{T g_0 t}{W_0}, \quad \dot{W}t \ll W \quad (7)$$

where W_0 is the vehicle weight referenced to the earth's surface.

The eccentricity of an orbit can be expressed as

$$\epsilon = \sqrt{1 - V (2-V) \cos^2 \gamma}, \quad (8)$$

where γ is the angle between the velocity vector and the local horizontal, and V is defined by

$$V = \frac{v^2}{v_c^2} = \frac{(v_c + \Delta v)^2}{v_c^2} = 1 + 2 \frac{\Delta v}{v_c} + \left(\frac{\Delta v}{v_c}\right)^2. \quad (9)$$

v_c is the circular orbit velocity given by

$$v_c = R_o \sqrt{g_o / (R_o + h)}. \quad (10)$$

As can be seen from Equation 8, $\epsilon = V-1$ for $\gamma = 0$. Thus, by substitution of Equation 9,

$$\epsilon = \frac{\Delta v}{v_c} \left(2 + \frac{\Delta v}{v_c}\right), \text{ for } \gamma = 0 \quad (11)$$

which is also a good approximation to ϵ for any value of γ less than about 5° .

Substitution of Equations 7 and 10 into Equation 11, results in

$$\epsilon = \frac{Tt \sqrt{g_o (R_o + h)}}{W_o R_o} \left[2 + \frac{Tt \sqrt{g_o (R_o + h)}}{W_o R_o} \right]. \quad (12)$$

For $T/W_o < 0.3$ and $t < 500$ seconds,

$$\frac{Tt \sqrt{g_o (R_o + h)}}{W_o R_o} < 0.2,$$

and Equation 12 reduces to

$$\epsilon \approx \frac{2Tt \sqrt{g_o (R_o + h)}}{W_o R_o}, \text{ (for } \gamma < 5^\circ, T/W_o < 0.3, t < 500 \text{ sec).} \quad (13)$$

Finally, substitution of Equation (13) into Equation (1) gives the desired result;
i.e.,

$$L = a + bt^{1.535}$$

$$\text{where: } a = 0.0032Ze^{0.0369h}$$

$$b = 21.5 \left[\frac{T \sqrt{g_o (R_o + h)}}{W_o R_o} \right]^{1.535} Ze^{0.0369h} \quad (14)$$

III. WORLD POPULATION MODEL

As will be shown in Section IV-C, the analysis of exposure probabilities resulting from the random reentry of radioactive materials from space requires detailed knowledge of the distribution of people over the earth's surface. For this reason, the demographic model described below was developed. The model is based upon the estimated world population in 1975.

The mid-year 1962 world population has been estimated by the Statistical Office of the United Nations to be 3.15×10^9 people (Ref. 9). By 1975, this number is expected to increase to 3.74×10^9 people (Ref. 10). Since the total surface area of the earth is approximately 1.97×10^8 mile², the mean population density of the world in 1975 will be approximately 19.0 people/mi². The populated areas* of the earth comprise about 26.5% of the earth's surface (Ref. 9) so that the mean population density of the populated areas in 1975 will be approximately 71.7 people/mile².

Very little information exists on the distribution of these people over the earth's surface; however, Reference 8 gives an approximate density distribution which, supposedly, is based upon the best information available. Some slight modifications to this distribution were required in order to make it correspond with the assumed world population for 1975 and to satisfy the population-area requirement of 26.5%. The modified distribution is graphically shown in Figure 3 and listed in Table II. The 12-group population-density model given in the table will be used in the analysis of exposure probabilities described in Section IV.

*Including land area and inland waters, but excluding uninhabited polar regions and some uninhabited islands.

FIGURE 3
POPULATION DENSITY DISTRIBUTION

TABLE II
WORLD POPULATION DENSITY MODEL

Population Group, k	Population Density, β_k (people/mi ²)		Fraction of Earth's Surface, f_k	$\sum_k \beta_k f_k$ (people/mi ²)
	Range	Log Mean, β_k		
1	< 1	~0	0.735	0
2	1 - 3	1.73	0.070	0.12
3	3 - 7.5	4.75	0.041	0.20
4	7.5 - 20	12.2	0.042	0.51
5	20 - 54	32.9	0.044	1.4
6	54 - 100	73.5	0.036	2.6
7	100 - 200	141	0.024	3.4
8	200 - 500	316	0.0058	1.8
9	500 - 1,300	806	0.00086	0.69
10	1,300 - 5,000	2,550	0.00058	1.48
11	5,000 - 10,000	7,070	0.00041	2.9
12	> 10,000	11,000	<u>0.00035</u>	<u>3.9</u>
TOTALS			1.00000	19.0 p/mi ²

IV. EARTH IMPACT HAZARDS

This section will examine the potential hazards to the earth's population associated with the startup and operation of a nuclear rocket engine from circular orbit. The orbital start altitude will be varied between 100 and 200 nautical miles. The assumed vehicle configuration will be that of the Saturn V/N, S-NA using the Mod 1 NERVA engine as described in Reference 11. The pertinent parameters associated with this vehicle configuration are listed in Table III.

A. POTENTIAL ACCIDENTS

Before attempting to evaluate earth impact hazards resulting from orbital start, a brief review of the potential accidents associated with this operating mode is appropriate. A discussion of the countermeasures which may be used to preclude or to reduce to within acceptable limits the consequences of these accidents will be given in Section V.

The potential accidents or hazards associated with the orbital operation of a nuclear rocket engine may be categorized into five groups:

- (1) failure to achieve orbit,
- (2) failure to start,
- (3) startup excursion,
- (4) engine failure following start, and
- (5) disposal.

Failure to achieve orbit can result from an aborted firing of a booster or second stage, a vehicle guidance failure, or a premature separation of the nuclear stage from the vehicle. Should one of these malfunctions occur, a nuclear excursion ranging in magnitude from 10^4 to 10^5 Mw-sec could result on earth impact through either core compaction or water flooding, depending upon the impact location. The consequences of this excursion would depend strongly upon the concentration of people in the impact area.

~~CONFIDENTIAL~~

~~RESTRICTED DATA~~

TABLE III

ASSUMED PARAMETERS FOR
NUCLEAR ENGINE AND STAGE

Reactor Power, P(Mw)	1,120
Engine Thrust, T(lb)	56,100
Propellant Flow Rate, $\dot{w}$ (lb/sec)	75.0
Firing Duration, (sec)	1,200
Engine System (Mod 1 NERVA)	
Weight, W_o (lb)	15,000*
Surface Area, (ft ²)	194
Ballistic Parameter, Z (lb/ft ²)	155**
Stage (S-NA)	
Startup Weight, W_o (lb)	238,000
Surface Area, (ft ²)	7,680
Ballistic Parameter, Z (lb/ft ²)	62**

*Estimated weight from Reference (12) assuming 2400 lb shield

**Calculated using Equations (2) and (3) and assuming $C_D = 2.0$

~~CONFIDENTIAL~~

~~RESTRICTED DATA~~

Failure to start after achieving orbit would result in the reentry of a cold reactor with the possibility of consequences similar to those mentioned above. However, in this case the impact point would be at a more random location on the earth's surface and the countermeasure system required for the prevention of criticality on earth impact in the event of a failure prior to achieving orbit, may have been removed or deactivated in order to accomplish reactor start.

A startup excursion resulting from a malfunction of the reactor control system could conceivably produce up to 10^4 Mw - sec of integrated reactor power. Since little or no Δv would have been supplied to the stage, the starting orbit would remain essentially unaltered and re-entry would occur much sooner and with a greater fission-product inventory than had this integrated power been produced during normal operation. For startup orbits between 100 and 200 nautical miles, the level of activity reaching the earth following a 10^4 Mw-sec excursion would require some dispersion of the fuel material in order to reduce the magnitude of the potential radiation exposures to within acceptable limits.

Following startup of the engine, both the fission-product inventory and the orbital lifetime will increase as a function of engine operating time. Thus, in the event of an aborted firing of the engine, the fission-product activity returning to the earth's surface will depend upon the time of failure. As will be shown in the next section, full-power operation for approximately 12 seconds prior to failure will result in the maximum activity reaching the earth's surface.

Finally, some consideration must be given to return of the reactor to the earth following successful completion of engine operation. Relatively small errors in vehicle guidance for certain trajectories could return the engine to the earth's atmosphere on the initial decay orbit if escape velocity had not been achieved.

The preliminary evaluation of hazards which follows will be limited to consideration of the consequences associated with only the Group 3 and Group 4 accidents, i.e. the startup excursion and engine failure following start; however, countermeasure concepts applicable to all accident groups will be discussed in Section V. In addition, radiation exposures resulting from inhalation or ingestion of fuel particles will not be discussed since, as will be shown, the fragmentation of the core into very small particles prior to earth impact is not necessary for the reduction of hazards inherent to orbital start operations.

B. RADIATION LEVELS ON IMPACT

For reactor operating times ranging from 10 to 10^3 seconds and for orbital decay times ranging from 10^{-2} to 10^3 days, the core activity on impact can be approximated by (Ref. 16).

$$I = 1.91 \text{ PtL}^{-1.2} \text{ curies,} \quad (15)$$

where t is the engine operating time in seconds, P is the reactor power level in Mw, and L is the orbital lifetime in days. Assuming one photon of 0.75 Mev is emitted per disintegration, the dose rate received at a distance of 1 meter from $\frac{1}{M}$ th of the core is

$$d = \frac{0.853}{M} \text{ PtL}^{-1.2} \text{ r/hr.} \quad (16)$$

The dose received at a distance of 1 meter over a period of 4 days* is

$$D = \frac{102.3}{M} \text{ Pt} \left[L^{-0.2} - (L + 4)^{-0.2} \right], \quad (17)$$

or, for $L \gg 4$ days,

$$d \approx \frac{82}{M} \text{ PtL}^{-1.2}, \text{ } L \gg 4. \quad (18)$$

*Equivalent to the dose received in 9 hours at a separation distance of 1 foot.

The impact activity I, the dose rate, and the 4-day dose D are maximum when $t_L^{-1.2}$ is maximum, i.e., when

$$\frac{d(t_L^{-1.2})}{dt} = 0. \quad (19)$$

From Equation (14),

$$t_L^{-1.2} = t(a + bt^{1.535})^{-1.2}, \quad (20)$$

so that

$$\frac{d(t_L^{-1.2})}{dt} = (a + bt^{1.535})^{-1.2} - 1.842 bt^{1.535} (a + bt^{1.535})^{-2.2} = 0, \quad (21)$$

$$\text{and } a + bt^{1.535} - 1.842bt^{1.535} = 0. \quad (22)$$

Therefore, Equations (15), (16), and (18) are maximum when

$$t = \left[\frac{a}{0.842b} \right]^{1-1.535} \quad (23)$$

$$= 3.58 \times 10^{-3} \frac{W_o R_o}{T \sqrt{g_o (R_o + h)}} \quad (24)$$

Thus,

$$(t_L^{-1.2})_{\max} = \frac{1.38 W_o R_o Z^{-1.2} e^{-0.0443h}}{T \sqrt{g_o (R_o + h)}} \quad (25)$$

For the parameters listed in Table III and for h equal to 150 nautical miles, evaluation of Equation (24) gives 12.0 seconds as the time of failure after engine startup which will result in the maximum fission-product inventory on earth

impact. Since this time varies by less than 1% for start altitudes between 100 to 200 nautical miles, it can be considered constant over this altitude range.

It is also of interest to consider the possible variations in the maximum impact inventory which would result from changes in the input parameters. Combining Equations (2), (15), and (25) and assuming that the thrust T is proportional to the reactor power level P , leads to the approximate expression

$$I_{\max} \sim \frac{\bar{A}^{1.2}}{W^{0.2} e^{0.0443h}} \quad (26)$$

As can be determined from this relationship, a factor of two reduction in the effective surface area $\bar{A}$, reduces $I_{\max}$ by a factor of 2.3, while a corresponding reduction in W increases $I_{\max}$ by only 13%. Furthermore, an increase of approximately 16 nautical miles in the orbital start altitude reduces the maximum impact inventory by a factor of two. Thus, $I_{\max}$ is seen to be strongly dependent upon both the effective surface area of the orbiting configuration and the initial start altitude, but relatively insensitive to large variations in the initial stage weight.

The data listed in Table III have been used in Equations (14) and (15) to calculate the orbital lifetimes and impact inventories of the engine and stage as a function of engine operating time for start altitudes of 100, 150, and 200 nautical miles. These results are illustrated in Figures 4 and 5. The dashed curves represent the case where the engine is separated from the stage immediately following engine failure. As can be seen from these figures, this separation increases the orbital lifetime of the engine by a factor of 2.5 (corresponding to the ratio of the ballistic parameter for the engine to that of the stage), and

decreases the impact inventory by a factor of 3 (corresponding to the ratio of the ballistic parameters to the 1.2 power). Thus, a significant reduction in hazard to the earth's population can be achieved by causing engine/stage separation in the event of a premature engine failure.

The 4-day dose at 1 meter from a single fuel element has been calculated using Equation (18) and assuming 1600 fuel elements in the core (i.e., $M = 1600$). These results are illustrated in Figure 6 as a function of engine operating time. The maximum 4-day dose as a function of orbital start altitude is illustrated in Figure 7. In addition, Figure 7 also illustrates the 4-day dose resulting from a 10^4 Mw-sec startup accident which is seen to be almost a factor of 2 higher than the maximum 4-day dose resulting from engine failure.

C. EXPOSURE PROBABILITIES

The previous section gave the exposure levels which would result over a period of 4 days for a fixed separation distance of 1 meter between source and receptor. If it is assumed that this distance corresponds to the closest "effective" distance achievable between a fuel-element source and the "whole body", then the doses indicated by the curves on Figure 6 can be interpreted as representing the maximum exposures which could result from a source-population interaction following a vehicle failure at a given time t . In this section the probabilities associated with people receiving exposures up to and including these maxima will be examined.

1. Analytical Model

It was shown in Reference 15 that if a total of m fuel fragments of equivalent gamma-ray source strength are randomly distributed over a large populated area A (i.e., large enough so that boundary effects can be neglected),

FIGURE 4
ORBITAL LIFETIMES FOR ASSUMED VEHICLE CONFIGURATION

FIGURE 5

IMPACT INVENTORIES

~~CONFIDENTIAL~~

~~RESTRICTED DATA~~

FIGURE 6

4-DAY DOSE AT 1 METER FROM 1/1600th OF CORE

~~CONFIDENTIAL~~

~~RESTRICTED DATA~~

CONFIDENTIAL

FIGURE 7

MAXIMUM 4-DAY DOSE AT 1 METER FROM 1/1600TH OF CORE

CONFIDENTIAL

~~RESTRICTED DATA~~

then the probability of at least n people receiving a dose $\geq D$ during L days of continuous exposure is given by a cumulative Poisson distribution, i.e.,

$$p_{\geq n} = \sum_{r=n}^N \frac{(Nq)^r e^{-Nq}}{r!}; \quad n \ll N \gg 1, \quad q \ll 1, \quad (27)$$

where N is the number of people in A , and q is the probability that an arbitrarily chosen dose point within this area receives a dose $\geq D$. The product Nq represents the most probable number of exposures which occur and is usually referred to as the expectation, E . Reference 15 also indicated that $q \approx Sm/AD$ when $q \ll 1$; hence

$$E \approx \frac{NSm}{AD}, \quad (28)$$

where S is a source constant defined by the expression

$$S = \frac{CP}{4M} \int_L^{L+4} K(t, \tau) d\tau, \quad (29)$$

in which C = conversion factor from gamma-ray energy flux to dose rate, $\text{mi}^2\text{-r/Mev}$

$K(t, \tau)$ = ratio of decay gamma power to operating power, Mev/Mw-day

τ = time after reactor shutdown, days,

and the remaining terms are as previously defined. For reactor operating times ranging from 10 to 10^3 seconds and for orbital decay times ranging from 10^{-2} to 10^3 days, the ratio of decay gamma power to operating power can be approximated by (Ref. 16).

$$K(t, \tau) = 4.59 \times 10^{15} t \tau^{-1.2}. \quad (30)$$

~~CONFIDENTIAL~~

~~RESTRICTED DATA~~

Assuming that the average energy of the photons emitted by the fuel fragment is 0.75 Mev, then $C = 2.16 \times 10^{-20} \text{ mi}^2 \text{ -r/Mev}$, and by substitution of Equations (29) and (30) into Equation (28),

$$E = 2.48 \times 10^{-5} \frac{NmPt}{MAD} \int_L^{L+4} \tau^{-1.2} d\tau. \quad (31)$$

For the case where the lifetime L is appreciably greater than the 4-day exposure period, the integrand of Equation (31) will remain approximately constant over the range of integration, so that

$$E = 9.92 \times 10^{-5} \frac{NmPtL^{-1.2}}{MAD}; L \gg 4. \quad (32)$$

Thus, for fuel fragments randomly dispersed over a large area which contains N people, Equations (27) and (32) can be used to calculate exposure probabilities irregardless of the population distribution in A .

As was shown in Reference 15, when q is small, a dose $\geq D$ is attributable almost exclusively to a single fuel fragment. Therefore, if both m and N are large, the exposure probabilities associated with a random distribution of N people in an area A containing m fuel fragments are the same as those which result from a random distribution of the fuel fragments in the same area with the N people arbitrarily distributed. This can also be inferred from an examination of Equation (32), in that, the expectation remains unaltered when the values of N and m are interchanged. Thus, it is concluded that if either the population or a large number of fuel fragments are randomly distributed in A , Equations (27) and (32) are equally valid for the calculation of the exposure probabilities.

~~CONFIDENTIAL~~

~~RESTRICTED DATA~~

~~CONFIDENTIAL~~

~~RESTRICTED DATA~~

2. Random Reentry of an Intact Reactor

Let us now consider the return to the earth's surface of an engine that has been operated and then aborted in orbit. It will be assumed that the engine with the reactor intact, enters the earth's atmosphere at a random location and that the temperatures and forces encountered during the reentry process cause the reactor core to disassemble into 1600 individual fuel fragments which are subsequently dispersed over a relatively small area on the earth's surface. The area will be assumed to have a uniform population density equal to $\bar{\beta}_k$ with probability of occurrence f_k (see Table II, Section III). Thus, the expected number of exposures in population group k is

$$E_k = f_k N_k q_k \quad (33)$$

$$= f_k \times 9.92 \times 10^{-5} \frac{N_k \text{ MPtL}^{-1.2}}{MA_k D} \quad (34)$$

but $N_k/A_k = \bar{\beta}_k$ so that,

$$E_k = 9.92 \times 10^{-5} \frac{\text{PtL}^{-1.2}}{D} f_k \bar{\beta}_k, \quad (35)$$

and the total expectation resulting from the random reentry of the engine is

$$E = \sum_k (E_k) \quad (36)$$

$$= 9.92 \times 10^{-5} \frac{\text{PtL}^{-1.2}}{D} \sum_k (f_k \bar{\beta}_k) \quad (37)$$

$$= 9.92 \times \frac{10^{-5} \text{ PtL}^{-1.2} \bar{\beta}_E}{D}, \quad (38)$$

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

where β_E is the average population density of the earth. Thus, the total expectation, E , for this event is independent of the actual distribution of people over the earth's surface. However, as will be shown below, exposure probabilities do depend upon the population distribution.

Since the probability of fuel fragments being dispersed in population group k is f_k , the probability of n exposures in group k is

$$p_{n,k} = f_k \frac{(N_k q_k)^n e^{-N_k q_k}}{n!}, \quad (39)$$

where

$$N_k q_k = 9.92 \times 10^{-5} \frac{P_t L^{-1.2} \bar{\beta}_k}{D}. \quad (40)$$

Thus, the probability of at least n exposures is given by

$$p_{\geq n,k} = \sum_{r=n}^{N_k} p_{r,k}. \quad (41)$$

Since it has been assumed that the exposures to the separate population groups are mutually exclusive (i.e., following reentry disassembly, all of the fuel fragments are dispersed within a single area having a uniform population density), the total probability of at least n exposures is

$$p_{\geq n} = \sum_{k=1}^{12} p_{\geq n,k}, \quad (42)$$

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

which upon substitution of Equations (39) and (41) becomes

$$p_{\geq n} = \sum_{k=1}^{12} f_k \sum_{r=n}^{N_k} \frac{(N_k q_k)^r e^{-N_k q_k}}{r!} . \quad (43)$$

For large values of N_k , this expression is readily evaluated using standard tables of the cumulative terms of the Poisson distribution (e.g., see Ref. 17).

Equations (38), (40) and (43) will now be used in a specific example. Assume engine failure occurs after 12 seconds of full-power operation from 100 nautical - mile orbit. Then, using Equation (14) and the parameters listed in Table III, the lifetime of the decay orbit will be

$$L = 0.278 Z \text{ days} . \quad (44)$$

Substitutions into Equations (38) and (40) give

$$E = \frac{117.8}{Z^{1.2}_D} , \quad (45)$$

and

$$N_k q_k = 6.20 \frac{\bar{\beta}_k}{Z^{1.2}_D} . \quad (46)$$

The probabilities associated with at least n people receiving exposures in excess of 3 and 30r were calculated from Equation (43) assuming orbital decay of the intact stage ($Z = 62$). Since $p_{\geq n}$ is a function of only the single variable $(N_k q_k)$, it can be seen from Equation (46) that the results of this calculation also apply to exposures of 1 and 10r if engine /stage separation is assumed prior to orbital decay (i.e. $Z = 155$). Furthermore, it can be shown using Equation (40) and the circular orbit lifetime given by Equation (14), that these results also apply to either startup excursion of 5.3×10^3 Mw-sec, or an excursion of 10^4 Mw-sec with exposure levels 1.89 times those specified above.

~~CONFIDENTIAL~~
~~RESTRICTED DATA~~

~~CONFIDENTIAL~~
~~CONFIDENTIAL~~

The exposure probabilities obtained for the example discussed are summarized in Table IV and are illustrated graphically in Figure 8. Figure 9 illustrates the expectation of exposures to a dose $\geq 1r$ as a function of engine operating time for startup in 100 nautical-mile circular orbit.

3. Random Reentry of Fuel Elements

It is also of interest to consider the exposure probabilities which would result if a portion of the fuel elements are lost from the reactor at the approximate time of engine failure. The fuel-element loss might occur as the direct consequence of an engine component failure, or as a secondary effect caused by high post-operational temperatures in the reactor.

Let us assume that, as a result of engine failure, a total of m fuel elements are separated from the reactor in such a manner that they reenter the earth's atmosphere individually at completely random locations. Again, it will be assumed that the engine is started at 100 nautical miles and that 12 seconds of full-power operation occur before failure. Then, the lifetimes for the individual fuel elements can be obtained from Equation (44).

~~CONFIDENTIAL~~
~~CONFIDENTIAL~~

~~CONFIDENTIAL~~
~~CONFIDENTIAL~~ A

TABLE IV
PROBABILITY OF AT LEAST n
PEOPLE RECEIVING A DOSE $\geq D$

Orbital Start
Altitude = 100 n. mi.

Case Description			E	n	P $\geq n$
Random Reentry Configuration	Exposure Level, D(r)	Engine Operating History			
Intact Engine	1.0	12 seconds full-power operation,	0.278	1	8.12(-2)*
				2	3.78(-2)
				3	1.97(-2)
				6	4.43(-3)
				10	2.11(-3)
Intact Stage	3.0	5.3x10 ³ or Mw-sec start-up excursion		20	1.36(-3)
				40	9.53(-3)
				100	7.37(-4)
Intact Engine	10.0	12 seconds full-power operation,	0.028	1	1.55(-2)
				2	2.71(-3)
				3	1.38(-3)
				6	8.32(-4)
				10	5.60(-4)
Intact Stage	30.0	5.3x10 ³ or Mw-sec start-up excursion		20	6.81(-5)
				40	1.19(-8)
				100	<10 ⁻⁸
55 Individual Fuel Elements	1.0	12 seconds full-power operation,	0.278	1	2.43(-1)
				2	3.22(-2)
				3	2.91(-3)
				6	5.0 (-7)
				10	<10 ⁻⁸
165 Individual Fuel Elements	3.0	or 8.5 x 10 ³ Mw-sec start-up excursion			
55 Individual Fuel Elements	10.0	12 seconds full-power operation,	0.028	1	2.76(-2)
				2	3.85(-4)
				3	3.57(-6)
				6	<10 ⁻⁸
				10	-
165 Individual Fuel Elements	30.0	or 8.5 x 10 ³ Mw-sec start-up excursion			

* The numbers in parenthesis indicate the power of ten by which the tabulated values are multiplied. For example, 8.12(-2) $\approx$ 8.12x10⁻².

~~CONFIDENTIAL~~
~~CONFIDENTIAL~~

CONFIDENTIAL

FIGURE 8

EXPOSURE PROBABILITIES FOLLOWING 12 SECONDS FULL-POWER OPERATION FROM 100 N. MI. ORBIT

CONFIDENTIAL

FIGURE 9
EXPECTATION VS ENGINE OPERATING TIME

The ballistic parameter, Z , is calculated from Equation (2) in which $C_D = 2.0$ and the fuel-element weight is approximately 1.5 pounds. Assuming a random tumbling motion, the effective area, $\bar{A}$, can be calculated in one of two ways; either from Equation (3) which results in $\bar{A} = 0.236 \text{ ft}^2$, or by multiplying the average longitudinal cross-sectional area of the fuel element by the average cosine of the angle between the longitudinal axis of the element and the air stream (i.e., $2/\pi$). This latter method results in an $\bar{A}$ of 0.187 ft^2 which, for a tumbling element with its large ℓ/d ratio, is considered to be preferable to that obtained using Equation (3). Thus, the ballistic parameter for the fuel-element is

$$Z = \frac{1.5}{2.0 \times 0.187} = 4.0 \text{ lb/ft}^2, \quad (47)$$

and, by substitution into Equation (44), its orbital lifetime becomes 1.11 days. The total expectation for the random reentry of the m fuel elements is, from Equation (31)

$$E = 5.06 \times 10^{-3} \text{ m/D}, \quad (48)$$

and, by substitution of this expression into Equation (27), the probability of at least n people receiving exposures $\geq D$ becomes

$$P_{\geq n} = \sum_{r=n}^N \frac{(5.06 \times 10^{-3} \text{ m/D})^r \exp(-5.06 \times 10^{-3} \text{ m/D})}{r!}. \quad (49)$$

Using Equations (48) and (49) and the radiation exposure levels considered previously, the exposure probabilities resulting from losses of 55 and 165 fuel elements from the reactor at the time of engine failure were evaluated. As may be seen from a comparison of the results listed in Table IV, the expectations associated with the random reentry of these fuel elements are equal to those

~~CONFIDENTIAL~~

calculated for the random reentry of a reactor while still intact. However, there are two important differences in the hazards between those which result from the intact reactor reentry and those which result from the reentry of individual fuel elements: (1) since the 4-day dose is inversely proportional to the ballistic parameter raised to the 1.2 power, the maximum exposures which can result from the random reentry of individual fuel elements are about 27 times those which can result following the reentry of an intact stage and about 81 times those following the reentry of an intact engine, and (2) the probabilities of exposure to a specified group of people for the two events differ considerably even though their expectations are the same. This latter effect is evidenced by the results listed in Table IV.

D. PHYSICAL HAZARDS

Finally, though the primary purpose of this paper is to evaluate the nuclear hazards associated with nuclear rocket operations, it is interesting, for the sake of comparison, to briefly examine the magnitude of non-nuclear hazards associated with earth impact of the individual reactor fuel elements following reentry disassembly of the reactor core.

The probability that at least n people will be struck by fuel elements following the reentry disassembly of a reactor core can be obtained using Equations (40) and (43) as follows. The 4-day dose received at a distance R from a single fuel element (see Section IV-B) is given by

$$D = \frac{82PtL^{-1.2}}{MR^2}. \quad (50)$$

Substitution of this expression together with Equation (40), into Equation (43) gives the probability that fuel elements will land within a distance R from at least n people following reentry disassembly of the core, i.e.,

~~CONFIDENTIAL~~

* RESTRICTED DATA

~~CONFIDENTIAL~~

~~RESTRICTED DATA~~

$$P_{\geq n} = \sum_{k=1}^{12} f_k \sum_{r=n}^{N_k} \frac{(1.21 \times 10^{-6} \bar{B}_k MR^2)^r \exp(-1.21 \times 10^{-6} \bar{B}_k MR^2)}{r!} \quad (51)$$

It is now assumed that the people located within a distance of 0.3 meters of the impact point will be struck by the fuel elements and, as a result, either seriously injured or killed. Thus, for $M = 1600$, the probability of serious injury or death becomes

$$P_{\geq n} = \sum_{k=1}^{12} f_k \sum_{r=n}^{N_k} \frac{(1.743 \times 10^{-4} \bar{B}_k)^r \exp(-1.743 \times 10^{-4} \bar{B}_k)}{r!} \quad (52)$$

Using the population data listed in Table II, the results obtained from this expression are:

<u>n</u>	<u>$P_{\geq n}$</u>
1	2.66(-3)
2	4.14(-4)
3	1.64(-4)
6	5.38(-6)
10	$< 10^{-8}$

Though these probabilities are considerably less than those which were calculated for the specific example given in Section IV-C-2, it is interesting to note that they are equivalent to those which would have been obtained for $D = 84r$ and $Z = 155 \text{ lb/ft}^2$ (orbiting engine) or for $D = 252r$ and $Z = 62 \text{ lb/ft}^2$ (orbiting stage). However, since it was shown in Section IV-B that 4-day exposure levels of these magnitudes cannot result from individual fuel elements, it is concluded that the physical hazard to the earth population resulting from the reentry disassembly of

~~CONFIDENTIAL~~

~~RESTRICTED DATA~~

~~CONFIDENTIAL~~

the reactor into individual fuel elements may well be greater than the radiation exposure hazard which could result from this event.

Finally, in order to allow comparison of the potential hazards from orbital start of nuclear rockets with other more well-known hazards, the probability data contained herein are summarized in Table V along with injury and death probabilities for various other accidents on a per year basis (Ref. 8). Though this type of comparison neglects the social and political implications associated with radiation exposures to the world population, it does serve to convey an intuitive appreciation for the extremely small risks inherent to the operation of nuclear rockets from orbit when core disassembly prior to earth impact is assured.

E. HAZARDS SUMMARY

Some of the significant conclusions which can be drawn from the results of the hazard analysis described in this section are summarized below:

1. For the assumed analytical model, the probability of receiving a given exposure less than some predetermined maximum is not dependent upon the size of the fuel fragments. However, the maximum dose which can be received (with a corresponding decrease in its probability of occurrence) is dependent upon the fuel-fragment size. This is a direct consequence of the fact that if a large number of people are randomly distributed in a given area, then the exposure probabilities are independent of the fuel fragment distribution in that area; and conversely, if a large number of fuel fragments are randomly distributed in the area, then the exposure probabilities are independent of the population distribution.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

2. The potential hazards associated with the return of a reactor to the earth following its operation in orbit do not appear excessive if disassembly of the core during reentry can be assured. The degree of disassembly required, and hence the maximum possible exposure that can be received from an individual fuel element, will depend upon the orbital start altitude and the configuration in which the fuel is contained during orbital decay; however, on the basis of the cases considered herein, disassembly of the core beyond individual fuel elements does not appear necessary even for engine starts in low orbits.

TABLE V

INJURY RISK COMPARISON

	<u>Expected No. of Injuries to World Population, E (people)</u>	<u>Injury Probability (per individual)</u>
Total Injuries/Year (all accidental sources)	1.1×10^8	5×10^{-2}
Total Deaths/Year (all accidental sources)	1.5×10^6	4×10^{-4}
Fires, Burns (deaths/yr.)	1.5×10^5	4×10^{-5}
Lightning (deaths/yr.)	2.6×10^3	7×10^{-7}
Venomous Animals (deaths/yr.)	1.1×10^3	3×10^{-7}
REENTRY DISASSEMBLY OF REACTOR		
Radiation Exposure $\geq 3r$ (stage config.)	2.8×10^{-1}	7×10^{-11}
Radiation Exposure $\geq 30r$ (stage config.)	2.8×10^{-2}	7×10^{-12}
Impact Injury	3.3×10^{-3}	9×10^{-13}

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

3. A countermeasure system which will assure adequate core disassembly during reentry must be effective during all phases of engine operation, from startup to final disposal.

4. An increase of approximately 50 miles in the orbital start altitude reduces the impact inventory following engine failure by an order of magnitude.

5. Separation of the engine from the stage soon after a premature thrust termination or a startup excursion reduces the impact inventory by approximately a factor of 3.

6. Thrust termination following approximately 12 seconds of full-power engine operation produces the maximum impact inventory from this type of failure.

7. A startup excursion of 5.3×10^3 Mw-sec produces an impact inventory of approximately the same magnitude as the maximum inventory which results from premature thrust termination, provided the reentry configuration is the same for each case.

8. Finally, though up to 1% of the fuel elements can be lost from the core at the time of engine failure without appreciably increasing the exposure probabilities, this loss should be avoided since the maximum exposures which could result would be between one and two orders of magnitude higher than if all of the fuel elements remained with the core during orbital decay.

~~CONFIDENTIAL~~

V. COUNTERMEASURES

In the final selection and development of a total safety system for a nuclear rocket engine a number of factors must be considered: (1) permissible radiation exposure limits in terms of the magnitude of exposure, the number of people involved, and the probability of its occurrence, (2) the vehicle failure probability at any time during flight and the effects of these failures upon the system performance and the vehicle configuration, (3) the mission profile including a description of the initial pre-start orbit, the time and position of orbital start, and the trajectory path out of orbit, and (4) the vehicle description including both its performance and physical characteristics. At the present time very little, if any, information exists in these areas, consequently, it is not possible to establish firm criteria for a total safety system at this time. However, based on the results of studies which have been or are being performed to establish the feasibility of the most promising countermeasure concepts and to determine the behavior of the engine system under both normal and abnormal conditions, a number of conclusions can be drawn as to the safety of potential missions and the type of countermeasure systems which would be suitable.

This section will discuss briefly the various countermeasures which have been or are being considered for use during orbital start operations of the NERVA engine. The countermeasures have been classified into two groups; primary concepts and secondary concepts. Primary concepts are those which can preclude or substantially reduce specific hazards associated with orbital operations of the engine. Secondary concepts are those which, in themselves, cannot preclude or reduce to within acceptable limits potential hazards, but in conjunction with the primary concepts would be a necessary adjunct or would provide an additional

margin of safety to the flight operation. In order to encompass all potential accidents or malfunctions throughout the entire flight profile, it may be necessary that the total engine safety system be composed of one or more concepts from each group.

A. PRIMARY CONCEPTS

1. Flight Poisons

The purpose of the Flight Poison System is to prevent inadvertent criticality of the reactor in the event of an accident or malfunction of the flight vehicle at any time before engine operation. The system as currently conceived (Ref. 18) consists of an arrangement of poison wires inserted in the reactor coolant channels and connected to a mechanical withdrawal actuator. The withdrawal actuator is mounted in the nozzle and, on a given signal, pulls the wires out of the coolant channels. Following the wire withdrawal, the actuator and wires are physically separated from the engine. With approximately 2600 poison wires distributed uniformly in the reactor core, and with the reactor control drums in their full-out position, the reactor will remain subcritical when fully immersed in water or other hydrogenous media, or when mechanically compacted to its most reactive geometry. The mechanical and functional feasibility of this concept for use with the present engine configuration has been established (Ref. 18).

The Flight Poison System has several advantages over other concepts which could be used to prevent criticality of a cold reactor following its reentry from space:

a. The system is passive in that the countermeasure does not require activation following an accident or malfunction to perform its intended function.

b. The system is highly desirable for use with the engine in the launch area and during boost; consequently, the extension of this application to the

prevention of excursions following the reentry of a cold reactor would not increase the complexity or weight of the flight system.

c. The system provides positive assurance that the reactor and all portions thereof will remain subcritical from the time the wires are inserted to the time of their withdrawal.

d. Premature activation of the system will not, in itself, jeopardize the accomplishment of the mission objectives.

e. Demonstration of the system's effectiveness as a reliable countermeasure for the prevention of excursions is relatively simple.

The major disadvantage to the Flight Poison System is its effect on total mission reliability. Extreme care must be exercised to assure that the system does not damage the reactor or nozzle, and that the wire withdrawal and detachment of the system from the engine can be accomplished with almost 100 per cent certainty.

2. Explosive Disassembly

In Section IV it was shown that in order to provide adequate protection to the earth population in the event of a startup excursion or a failure of the vehicle system following engine operation, disassembly and dispersion of the reactor core must be assured prior to earth impact. Furthermore, this disassembly process should not occur until the approximate time that the reentry phase of the orbital decay is initiated. Based on these results, several basic requirements for an explosive disassembly countermeasure system can be established.

a. The system must be able to withstand all credible accidents without impairing its functional capability.

b. It must maintain its functional capability after long residence times in space (of the order of one year).

c. High reliability of the system must be assured in terms of its ability to perform properly when a command signal is given and not to operate prematurely as the result of spurious signals or vehicle system failures.

d. The engine system must be maintained intact during the initial period of orbital decay and large numbers of fuel elements must not be lost from the reactor.

e. In conjunction with the reentry environment, the countermeasure system must be capable of assuring core disassembly to approximately fuel-cluster size or smaller, depending upon the specific conditions associated with the flight operation.

A number of explosive systems which are capable of producing core fragmentation have been investigated (Refs 19 to 21). The results of these studies indicate that one of the most promising disassembly concepts would consist of a single projectile which could be fired into the reactor from a launcher located between the dome of the reactor pressure vessel and the propellant tank. A dual or redundant system could be used if necessary to achieve the required countermeasure reliability. Time delay fuses which would be automatically armed during the normal flight sequence might serve to eliminate or supplement a requirement for activation of the countermeasure system by an external signal source. The total weight of a single system of this type is estimated to be approximately 250 pounds. A major advantage to the explosive disassembly concept over passive disassembly, which is discussed below, is that its effectiveness can be demonstrated with relative certainty provided its activation can be assured after long residence times in space and in the radiation environment produced by the reactor.

3. Post-Operational Destruct

The Post-Operational Destruct System (PODS) was conceived primarily as a countermeasure against the potential hazards inherent to suborbital

start, however, the system may also function effectively during orbital start operations. The concept differs from Explosive Disassembly in that a relatively large quantity of explosive is used to fragment the core into small particles with diameters considerably less than one inch (Ref. 20). Thus, a possible advantage to PODS over Explosive Disassembly is that activation of the system need not be delayed for an extended period of time following a premature thrust termination of the engine since the small particles produced would not require the long residence times in orbit which are required for fuel elements for reduction in their fission-product inventory. (For example, one day after reactor shutdown a 1/4 - inch - diameter fuel fragment has approximately the same fission-product inventory as would be contained in a reactor fuel element which has been allowed to decay for a period of two years.) The significance of this advantage to the Post-Operational Destruct System depends strongly upon how well the arming and firing mechanism for an Explosive Disassembly System can be made to reliably withstand long residence times in the space environment. Another possible advantage to PODS over Explosive Disassembly is that the reactor would not have to be maintained intact during the orbital decay period, so that the after-shutdown cooling requirements for the engine would be less stringent.

As compared to Explosive Disassembly, the Post-Operational Destruct System has several disadvantages: (1) the total weight of the system is large, (2) it is an expensive system to develop since it is necessary to demonstrate that complete fragmentation of the core to within an acceptable size distribution can be reliably achieved, (3) the design of the countermeasure is expected to be relatively sensitive to the engine/reactor configuration so that its use on second generation engines will probably require additional development efforts which

would not be required if Explosive Disassembly were employed, and finally, (4) using PODS, a larger fission-product inventory would be returned to the earth's surface, and furthermore, because of the creation of a large number of highly-radioactive micron-size fuel particles, additional modes of exposure (e.g. inhalation and ingestion) may become significant. A comparison between the radiation exposure probabilities which would result from the use of PODS and Explosive Disassembly was not included in this study because of the extensive nature of the analysis involved and since a valid destruct model is not currently available. However, based upon current information and the advantages and disadvantages enumerated above, it would appear that the explosive-disassembly concept is more desirable than PODS for use in a total engine safety system for orbital start operations of the NERVA engine.

4. Passive Disassembly

Passive disassembly is another concept for assuring disassembly of the reactor core prior to earth impact. The temperatures and forces imposed upon the reactor by the reentry environment may be sufficient to remove the reactor pressure vessel, destroy the core support structure, and separate the individual fuel elements or clusters from the remainder of the reactor hardware. System feasibility is currently being investigated by Westinghouse who expects to complete this effort by the fall of 1965. The Westinghouse program is predicated upon starting with a bare reactor and nozzle in orbit and determining the sequence of events which take place during the orbital decay. However, the total countermeasure system must provide a means for separating the reactor from the vehicle system, and may require that special design features be incorporated into the pressure-vessel and reactor configurations to enhance the disassembly process.

The separation of the reactor from the vehicle system can be readily accomplished through the use of explosives, but this again poses some of the same difficulties encountered with the Explosive Disassembly System in that detonation of the explosive at the proper time must be assured. However, the requirements for this concept are much less stringent than for explosive disassembly since the explosive separation can be accomplished immediately following the system failure, thereby eliminating the requirement for reliable operation after long residence times in space. In fact, as was shown in Section IV, early separation of the engine from the stage will increase the orbital lifetime by increasing the ballistic parameter with a concomittant reduction in the impact inventory.

Before the desirability of passive disassembly over other concepts can be properly assessed, two major questions must be answered; is the system feasible without necessitating major redesign or modification of the engine system, and can the system be demonstrated to function adequately and with high reliability under all credible accident conditions? It is hoped that the answers to both of these questions will be forthcoming from Westinghouse during Contract Year 1965.

5. Auxiliary Chemical Propulsion

Auxiliary chemical propulsion offers the advantage of preventing any radioactive debris from landing on inhabited areas of the earth. The system can be used to return the engine (and stage) intact to a safe disposal area on the earth's surface or to provide thrust for disposal of the engine in deep space. An additional advantage is that it can be used immediately following a vehicle system failure and hence, the countermeasure will not be degraded by long residence time in space. The major disadvantages to the system are that the total weight of the system is excessive (of the order of thousands of pounds), and the reliability required of the guidance and control system is extremely high. There is also some question

as to whether the connection between the countermeasure and the reactor could be maintained under all credible accident conditions. As a result of these considerations and on the basis of a preliminary study of this concept performed by Lockheed (Ref. 5), it is concluded that auxiliary chemical propulsion is not a suitable countermeasure against the hazards inherent to orbital start operations.

6. Nuclear Destruct

The feasibility of nuclear destruct is currently under investigation by the Los Alamos Scientific Laboratory. Calculations and inpile experiments have shown that it may be possible to produce a very rapid nuclear transient in the reactor which will result in complete fragmentation of the fuel into very fine particles. The time required for these particles to reach the earth's surface and the amount of dispersion which would occur during their passage through the atmosphere should preclude a radiation hazard to the earth's population. The particular concept which appears to have the greatest potential at the present time consists of a launching mechanism which would fire a hydrogenous projectile into the core in a manner similar to that contemplated for explosive disassembly. Calculations indicate that a projectile of this type can produce the required transient.

Nuclear destruct has several important advantages over some of the other concepts considered; (1) the system can be activated at the time of vehicle failure, thus eliminating the requirement for the countermeasure to withstand long residence times in space, (2) assuming that complete fragmentation of the core into very fine particles can be accomplished, the magnitude of the radiation hazard to the earth's population as the result of a vehicle failure should be negligible, and (3) the system has considerable promise as a suitable countermeasure against the potential hazards inherent to suborbital start operations. Unfortunately, there

is a sizeable effort still required before the feasibility of nuclear destruct can be demonstrated. Consequently, until such time as this is accomplished, it will be necessary to rely entirely upon other concepts to provide the necessary countermeasure capability.

B. SECONDARY CONCEPTS

1. Trajectory Shaping

The shape and orientation of the prestart orbit and the flight trajectory of the vehicle out of orbit will strongly influence the magnitude of the potential hazards inherent to orbital start operations. For example, it was shown in Section IV that an increase of only 50 miles in the orbital start altitude can reduce the earth-impact inventory by approximately an order of magnitude. In addition, the number of people located within the potential earth-impact areas will vary with the orientation of the orbital plane. Thus, it should be possible to choose the initial orbit so that the probability of impact in densely populated areas following premature thrust termination is minimized, with the result that the exposure probabilities are reduced. It is also possible to decrease potential hazards by choosing a flight path out of orbit such that the perigee altitude increases as a function of engine operating time. Thus, an optimum flight path could be constructed which would result in the maximum orbital lifetime for any specified time of vehicle failure. Finally, consideration must be given to the possibility of substantial reduction in orbital lifetime as a result of relatively small errors in vehicle guidance. These errors would be particularly significant after long engine operating times for which a high core inventory, truncation of vehicle guidance errors, and limitations of earth tracking stations to pinpoint the exact vehicle position, could combine to produce the greatest potential risk of excessively large fission-product inventories returning to the earth.

The extent by which the trajectory shape can reduce the magnitude of potential earth-impact hazards for specific mission applications, and the effects this type of countermeasure may have on the optimum mission profile, the gross payload weight and the mission reliability, have not been thoroughly examined at this time. However, because of the importance of the trajectory shape on the requirements for a total safety system it is expected that much more attention will be given to this task in the future.

2. Fission-Product Boiloff

The reduction of the fission-product inventory in the fuel by diffusion during normal operation of the engine and during the reentry of fuel fragments has been shown to be negligible (Ref. 22). However, if the core is not cooled following engine operation, the fuel will reach sufficiently high temperatures for a significant amount of fission-product diffusion to occur. After sustained periods of engine operation, preliminary experimental results indicate that it may be possible to reduce the fission-product inventory in the core by a factor of from 3 to 5 (Ref. 22). It must be remembered, however, that for the type of flight profile postulated in Section IV, the maximum impact inventory occurs as the result of a startup excursion or as the result of premature thrust termination following relatively short periods of engine operation (of the order of 12 seconds). For these type accidents, the post-operational temperatures generated in the core will not be sufficient for boiloff to significantly decrease the fission-product inventory.

Following sustained periods of engine operation, another factor to be considered in utilizing fission-product boiloff is the possibility of fuel elements or fragments being released into space because of temperature-induced failures of the structural members of the uncooled core. As was shown in Section IV, these fuel fragments would reenter the earth's atmosphere much sooner than the

intact reactor, and, as a consequence, a greater impact inventory would result. On the basis of the results described in this study, it would appear that if much more than 1% of the core was lost in this manner, any advantages to fission-product boiloff would disappear, in fact, it could be detrimental to safety.

In view of the above considerations, a significant reduction in the total radiation hazard to the earth population through fission-product boiloff does not appear promising.

3. Engine/Stage Separation

It was shown in Section IV that early separation of the engine from the nuclear stage following thrust termination will decrease the impact inventory by approximately a factor of three. The desirability of making this separation will depend upon the type of primary countermeasure system used, its design, and the difficulties involved in assuring that separation takes place. However, the reduction in the exposure probabilities that would result from this type of countermeasure certainly warrants its continued consideration in the development of the total safety system for the engine.

4. Chemical Preconditioning of Core

This concept arises out of the studies performed by Westinghouse on chemical destruction of the reactor core (Ref. 23). However, the concept as envisioned here does not necessarily need to degrade all of the fuel into small particles, but rather must only reduce the structural integrity of the reactor to a point where the reentry environment can complete the disassembly process. Thus, chemical preconditioning of the core might be used to supplement passive disassembly in the same manner that an explosive device might be used to separate the reactor from the engine assembly prior to reentry. The specific time at which the chemical would be injected into the core would depend strongly upon the chemical reagent

used and the reliability of this type of system after long residence times in space. A desirable reagent would be one that would be effective over a fairly wide temperature range and which would not result in appreciable core disassembly until reentry occurs. For example, a relatively small quantity of oxygen injected into the hot core soon after shutdown might be sufficient to partially "burnout" the tie rods and other structural supports but not result in a significant loss of fuel fragments from the reactor during the orbital decay period.

C. CONCLUSIONS AND RECOMMENDATIONS

The Flight Poison System should provide adequate countermeasure protection against all potential radiation hazards resulting from vehicle system failures from launch to the time of wire withdrawal prior to nuclear engine start. The magnitude of the hazards inherent to vehicle system failures during or subsequent to engine start can be reduced to within acceptable limits by assuring reactor disassembly during or just prior to the reentry phase of orbital decay. Additional margins of safety can be provided by suitable selection of the trajectory path out of orbit, but the penalties in gross payload weight and mission reliability that would result are currently undefined.

The two most promising methods of assuring reactor disassembly during re-entry are Explosive Disassembly and Passive Disassembly. Of the two concepts, only Explosive Disassembly has been demonstrated to be feasible; however, Passive Disassembly is considered preferable because of its higher inherent reliability characteristics.

Since it has not been demonstrated as of this date that the passive-disassembly concept can be used to reliably disassemble the reactor during reentry, it is recommended that design concepts for an Explosive Disassembly System be

prepared and evaluated, concurrently with the WANL investigations of passive-disassembly feasibility. A significant portion of this effort should be directed at the design and development of an arming and firing mechanism that is capable of extremely reliable operation after long residence times in space and in the radiation environment surrounding the reactor. In addition, methods which may be required to supplement passive disassembly such as reactor/engine separation and chemical preconditioning, should be evaluated.

Finally, it is recommended that additional efforts be directed at defining the requirements for a total engine safety system for the orbital start of a nuclear rocket engine. These efforts should include:

- (1) establishing acceptable exposure-probability criteria,
- (2) assessing various safety systems, operational constraints and flight profiles, and determining mission performance penalties associated with their use, and
- (3) examining modes of abnormal performance or failure of the engine and stage which could give rise to premature termination of flight, and evaluating the effects such events would have on the total vehicle system.

LIST OF SYMBOLS

a	circular orbit lifetime (see Equation (14)), days
$\bar{A}$	effective cross-sectional area of reentry body perpendicular to air stream, ft^2
A_k	area of the earth's surface which contains population group k, mi^2
b	lifetime parameter defined by Equation (14)
B	ballistic parameter equal to $C_D A / 2m_s$, ft^2/slug
B_o	observed value of B during initial decay of orbit, ft^2/slug
C	conversion factor from gamma-ray energy flux to dose rate, $\text{mi}^2\text{-r}/\text{Mev}$
C_D	drag coefficient
d	dose rate at 1 meter from source, roentgens/hr
D	dose received from fuel-fragment source over a period of 4 days, roentgens
E	expectation or the number of people expected to receive a dose $\geq D$
f_k	fraction of earth's surface with log-mean population density β_k
g	gravitational acceleration at orbital altitude h, $\text{n.mi.}/\text{sec}^2$
g_o	gravitational acceleration at earth's surface equal to $5.30 \times 10^{-3} \text{ n.mi.}/\text{sec}^2$
h	perigee altitude, nautical miles
I	core inventory at time of earth impact, curies
$K(t, \tau)$	ratio of decay gamma power to operating power, $\text{Mev}/\text{Mw-day}$
k	population group designation
L	lifetime of elliptic orbit, days
L_o	observed orbital lifetime, days

LIST OF SYMBOLS (cont.)

m	number of equally-sized fuel segments which are randomly distributed over a large area A
m_s	satellite mass, slugs
M	total number of equally-sized fuel segments into which core is disassembled upon re-entry
n	number of people receiving a dose $\geq D$, people
N_k	number of people in A_k
p_n	probability of exactly n people receiving a dose $\geq D$
$p_{\geq n}$	probability of at least n people receiving a dose $\geq D$
P	reactor operating power, Mw
$P_{\geq n}$	probability of at least n people being struck by fuel fragment
q_k	probability that randomly chosen dose point in A_k receives a dose $\geq D$
R	separation distance between fuel-fragment source and dose point, meters
R_o	radius of earth equal to 3444 n.mi.
S	source constant defined by Equation (29), $\text{mi}^2\text{-r/fuel fragment}$
t	reactor operating time, sec
T	nuclear engine thrust, lb
v	magnitude of instantaneous velocity, n.mi./sec
v_c	circular orbit velocity, n.mi./sec
V	eccentricity parameter defined by Equation (9)
$\dot{w}$	propellant flow rate, lb/sec
W	initial stage weight in orbit, lb
W_o	initial stage weight referenced to the earth's surface, lb
Z	ballistic parameter as defined by Equation (2), lb/ft^2
β_E	average population density of the earth, people/ mi^2

LIST OF SYMBOLS (cont.)

$\bar{\beta}_k$	log-mean population density of population group k, people/mi ²
γ	angle between velocity vector and local horizontal, degrees
Δv	velocity increment added during time t, n.mi./sec
ϵ	eccentricity of elliptic orbit
τ	time after reactor shutdown, days

REFERENCES

1. R.A.Minzner, K.S.W. Champion, H.L. Pond, "The ARDC Model Atmosphere 1959," Air Force Surveys in Geophysics No. 115, AFCRC - TR-59-267, August 1959. (U)
2. U. S. Standard Atmosphere, 1962, U. S. Government Printing Office, Washington D. C., December 1962. (U)
3. J. Kork, "Satellite Lifetimes in Elliptic Orbits," Journal of Aerospace Sciences, Vol. 29, No. 11, November 1962. (U)
4. H. G. Hargrove, D. Hoecker. "Flight Mechanics of NERVA Re-Entry and Orbital Lifetime Studies," WANL-TME-635, December 1963. (U)
5. "Nuclear Vehicle Flight Safety Study, Summary Report for Phases I and II (U)," LMSC-BO61396, July 1963. (C-RD)
6. W. H. Stafford, R. M. Croft, "Artificial Earth Satellites and Successful Solar Probes, 1957 - 1960," NASA TN D-601, March 1961. (U)
7. G. P. Sutton, Rocket Propulsion Elements, 3rd Ed., John Wiley and Sons, Inc., New York, 1963. (U)
8. "SNAP 10A Reactor Progress Report, October - December 1963 (U)," NAA-SR-9293, 1964. (Conf.)
9. 1964 World Almanac, New York World-Telegram, 1962.
10. K. Davis, "Population," Scientific American, Vol. 209:3, September 1963.
11. "Nuclear Lunar Logistics Study - Final Report (U)," LMSC-BD61610, December 1963. (C-R/D)
12. "NERVA Engine Component Weight, Balance, and Material (U)," RN-S-0044, January 1964. (C-R/D)
13. R. S. Decker, "Some Fundamental Characteristics of the Safety Problems Associated with the Orbital Operation of Nuclear Rockets," U. S. Government
14. B. J. Cain, "Nuclear Rocket Hazards Study: Activity Loss During Orbital Lifetime," Missile and Space Division, General Electric Co., 1963. (U)
15. D. S. Duncan, "Dose Probability Considerations Associated with the Re-entry of a Fragmented Nuclear Rocket Engine (U)," RN-S-0077, May 1964. (Conf.)
16. M. R. Smith, "The Activity of the Fission Products of U²³⁵ (Program 408)," XDC 60-1-157, 10 December 1959, (U)

REFERENCES (cont.)

17. Tables of the Individual and Cumulative Terms of Poisson Distribution; Defense Systems Department, General Electric Company; D. Van Nostrand Co., Princeton, N.J., 1962.
- 18/ E. W. Lohr and G. E. Parker, "Status Report, Anticriticality Poison System (ACPS) (U)," WANL-TNR-155, 6 March 1964. (CRD)
19. "Evaluation of Anticriticality Destruct System (U)", RN-S-0022, May 1964. (CRD)
20. "Evaluation of Post-Operational Destruct System Concepts (U)", RN-S-0033, May 1964. (CRD)
21. "Status Report for Bi-Functional Destruct System (U)", RN-S-0072, April 1964. (CRD)
22. W. S. Brown, "WANL Source Term Program, Status Report, Volume I of II (U)", WANL-TME-796, May 1964. (CRD)
23. J. A. Roll, R. M. Vollmer and P. H. Wilks, "Summary Screening Report on Chemical Destruct System (U)", WANL-TME-399, June 1963. (CRD)

DISTRIBUTION LIST

P. Zigman
U.S. Naval Radiological Defense Lab.
San Francisco 24, California
(1 copy)

Major J. Rawers, NTO RS
Chief, Technical Branch
Missile Operation Division
AFMTC - Patrick AFB
Florida
(3 copies)

Morton I. Goldman
Nuclear Utilities Services, Inc.
1730 M Street N. W.
Washington, D.C. 20036
(1 copy)

Major R. C. Hock
National Aeronautics & Space Admin.
Launch Operations Center
Cocoa Beach, Florida
(1 copy)

J. C. Whiton
National Aeronautics & Space Admin.
George C. Marshall Space Flight Center
Huntsville, Alabama
(1 copy)

H. Radd
Lockheed Missile & Space Company
Nuclear Systems Program Division
Post Office Box 504
Sunnyvale, California
(1 copy)

C. T. Donneworth
Lockheed Missile & Space Co.
Sunnyvale, California
(3 copies)

Earl Hesse
Lockheed Missile & Space Company
Nuclear Systems Program Division
Post Office Box 504
Sunnyvale, California
(1 copy)

Dr. C. Rogers McCullough
Nuclear Utilities Services, Inc.
1730 M Street N. W.
Washington D. C. 20036
(1 copy)

L. D. P. King
LASL
Post Office Box 1663
Los Alamos, New Mexico
(3 copies)

H. A. Bechtel
Aberdeen Proving Ground
Aberdeen, Maryland
(1 copy)

Lt. Col. R. S. Decker
Chief - Safety Branch
Space Nuclear Propulsion Office
U. S. Atomic Energy Commission
Washington 25, D.C.
(3 copies)

L. C. Corrington
Space Nuclear Propulsion Office
National Aeronautics and Space Administration
21000 Brookpark Road
Cleveland 35, Ohio 44135
(8 copies)

Col. W. S. Fellows
Chief, Nuclear Vehicle Projects Office
M-P&VA-N
National Aeronautics & Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama