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INTERIM STATUS REPORT
NUCLEAR ROCKET SAFETY STUDY

April 9, 1961

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FOREWORD

This report was prepared by The Martin Company for the United States Atomic Energy Commission under Contract AT(30-1)-2699.

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SUMMARY

This interim status report covers work performed under the Nuclear Rocket Safety Study during the period January 9 to April 9, 1961. The effort under this program has been directed to the analysis of nuclear rocket safety problems and the postulation of an integrated safety test program for the nuclear rocket. The latter is reported in detail in Volumes I and II of the Safety Test Program Report, MND-2515.

The analytical investigation has covered a number of areas of nuclear rocket safety. An operations analysis was performed in which the major safety problems were isolated for both successful and aborted missions. An extensive aerothermodynamic analysis was performed in which the re-entry behavior of graphite was investigated. Reactor analyses were performed to examine the effects of immersion in hydrogeneous media, control malfunctions and reactivity as a function of core fragment size. The three countermeasures under investigation are anticriticality destruct, additives and thermochemical destruct techniques. The fission product inventory of the engine was computed for both ballistic and orbital injection missions and engine activation products were also computed. A parametric study was carried out on cloud dissemination factors for launch pad accidents. The orbital startup mission was examined in detail to ascertain the effects of thrust and guidance failures occurring after startup.

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I. INTRODUCTION

The work performed by The Martin Company in the first three months of the nuclear rocket safety study is detailed in this report. The objective of this study is to develop a two-fold analytical and empirical program to attack and resolve the safety problems associated with nuclear rockets. In the analytical portion of the program the safety problems are defined and isolated, their consequences appraised and countermeasures developed to either minimize or preclude the problems. A safety test program, based upon the analytical study, has been postulated. In postulating this program consideration has been given to its justification, the value of the empirical data to be derived, the various applicable test facilities and the schedules and cost of the program.

Three missions that are being examined as part of this study consist of:

- (1) Ballistic mission--The ballistic mission is accomplished by using a Saturn C-1 configuration consisting of a S-1 chemical booster and a nuclear second stage, as shown in Fig. 1. The performance curves are shown in Fig. 2. The nuclear stage is started at an altitude of 85 kilometers, 90 kilometers downrange, fired into a ballistic trajectory and impacted downrange at sea.
- (2) Orbital injection mission--In the orbital injection mission the nuclear stage injects itself into a 100-nautical mile orbit. This is accomplished with a Saturn D-2 configuration consisting of S-1, S-2 chemical stages with a nuclear third stage, as shown in Fig. 3. Vehicle performance is shown in Fig. 4. The nuclear stage is started at an altitude of 80 kilometers, 490 kilometers downrange.
- (3) Orbital startup mission--In the orbital startup mission the nuclear stage is injected into a 300-nautical mile parking orbit, started after the orbit is achieved and fired to escape. This is accomplished with a three-stage Saturn vehicle and a nuclear fourth stage. The performance of this vehicle is shown in Fig. 5.

The tests will be conducted over the Atlantic Missile Range that has its point of origin at Cape Canaveral, Florida. All successful and aborted trajectories are superimposed on this range, and its oceanographic features are employed for evaluating nuclear stage impact cases.

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Fig. 1. Saturn C-1 Nuclear Test Vehicle Configuration

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Fig. 2. Vehicle Performance--Ballistic Mission

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Fig. 3. Saturn D-2 Vehicle Nuclear Third-Stage Escape Payload or Orbital Injection Payload

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Fig. 4. Vehicle Performance Orbital Injection Mission (100 Mile Orbit)

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Fig. 5. Vehicle Performance--Orbital Startup Vehicle

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The KIWI-B engine configurations are used in the analysis. Initially the KIWI-B-1 configuration was used, because of the data immediately available. A typical fuel element for this configuration is shown in Fig. 6. A simplified drawing of the KIWI-B-1 is shown in Fig. 7 and Table 1 lists the known parameters. Since the flight configuration of the KIWI-B will be selected from the KIWI-B-1, 2, or 3 designs late in Fiscal 1962, the final safety tests of the engine will utilize the design chosen. However, the three designs have many similarities, which allow the study and testing to proceed with reasonable validity.

This report is of an interim nature and does not present final solutions to the various safety problems which have been defined. However, it does present the basic information that is necessary to attack the problems. Several areas of testing have been clearly delineated by the analysis including aerothermodynamic experiments and anticriticality destruct system development.

TABLE 1

Parameters of KIWI-B-1

Core (in.)	
Diameter	35
Length	52
Thickness of graphite cylinder around core (in.)	2.0
Thickness of Be reflector (in.)	5.25
Core	
Void fraction (%)	20
Fuel fraction (%)	35
Structure fraction (%)	45
Outlet temperature (°R)	4090
Outlet pressure (psi)	550
Density (gm/cc)	
Structure	1.88
Fuel	2.15
Weight of core (lb)	2888
Cold, clean critical mass (kg)	120
Be reflector density (gm/cc)	1.84
Reflector void fraction (%)	7
Core coolant hole diameter--average (in.)	0.170

~~SECRET~~TABLE 1 (continued)

Reference coolant hole diameter--average (in.)	0.1875
Fuel pin diameter (in.)	0.75
Structure dimensions, hexagonal design (in.)	0.95 across flats
Hydrogen flow rate through core (lb/sec)	70
Weight (lb)	
Nozzle	500
Reflector	2000
Graphite ring	820
Power generated in (%)	
Core	93
Reflector	3
Structure	4
Total power generated (mw)	1180
Reflector void fraction (%)	7
Pump turbine speed (rpm)	22,922
Pump outlet pressure (psi)	800
Tank pressure (psi)	30
Reflector inlet ($^{\circ}$ R)	160
(psi)	700
Reactor inlet ($^{\circ}$ R)	245
(psi)	650
Coolant velocity in nozzle (hot gas) (fps)	375
Core flow area (ft ²)	1.33
Reflector flow area (ft ²)	0.35
Volume of core (ft ³)	28.95
Pressure vessel (in.)	
Inside diameter	49.5
Length	71
Thickness	0.75

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Fig. 6. KIWI-B Fuel Module

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Fig. 7. KIWI-B-1

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II. OPERATIONS ANALYSIS

An operations analysis has been performed to isolate and define any areas of potentially unsafe operation in the three missions described in Chapter I. The results of this analysis are presented in Tables 2 and 3. A safety index with values ranging from 1 to 4 is used to evaluate the safety of each portion of the trajectory. A value of 1 denotes a completely safe condition, 2 safe with restrictions, 3 condition that is unsafe but tolerable and 4 denotes an unsafe, unacceptable condition. Both successful and unsuccessful missions are treated and the effects of countermeasures are appraised.

A. SUCCESSFUL MISSION

The successful mission is one in which the test objective is accomplished. Table 2 treats the successful mission.

1. Ballistic Mission

The ballistic mission is entirely safe during chemical and nuclear stage operation until the spent nuclear stage re-enters the atmosphere. However, the nuclear engine will impact downrange where the water depth is 15,000 feet. Aside from the normal fission product inventory within the engine there is the possibility of increasing the inventory with an excursion on impact. Three unknown factors are present here. First, the engine will be thermally damaged by uncooled shutdown and aerodynamic heating and mechanically damaged by impact so that it may not represent a critical configuration. Second, a nominal excursion (10,000 mw-sec) will only add a small fraction of fission products to the normal inventory after a short decay time, but a much larger excursion could conceivably occur in water where the pressures are 7000 psi* or greater.

Countermeasures can be postulated to enhance the safety of the ballistic mission. The first is to resolve the engine into aerosols above 100,000 feet to inject the fission products into the stratosphere where they decay and dilute. The second and simpler method is to assure the loss of critical geometry at shutdown to preclude criticality on impact. Use of these countermeasures reduces the safety index from 3 to 2.

2. Orbital Injection Mission

The orbital injection mission shows a similar safe pattern for chemical and nuclear stage operation. Post-mission re-entry is unsafe and unacceptable since it results in random impact of the engine on the earth's surface. Statistically one out of four will impact on a land mass with the remaining impacting at sea.

*The critical point of water occurs at 3206.4 psia.

Operational Safety Analysis--Successful Missions

* 1	Safe	3	Unsafe but tolerable
2	Safe with restrictions	4	Unsafe and unacceptable

TABLE 3

Operational Safety Analysis--Unsuccessful Missions

Mission Stage	Safety Problems	Countermeasure Device	Fate of Reactor	Safety Index*
Saturn C-1 (Ballistic)	Chemical	Excursion and GFP release at AFMTC Direct radiation from incident Excursion and GFP release in shallow water	Destroy critical geometry with destruct system	Without CM Excursion on pad or in water with release of GFP With CM Fragmentation of engine, dispersal of U-235 at AFMTC or in water 4 becomes with CM 2
	Nuclear	Excursion and GFP release to atmosphere Possible criticality and excursion in deep water	Destroy critical geometry with destruct system	Without CM Possible excursion in deep water with release of GFP With CM Dispersal of fragments with U-235 and GFP in deep water 3 becomes with CM 2
Saturn D-1 (Orbital Injection)	Chemical	Same as Saturn C-1	Same as Saturn C-1	Same as Saturn C-1 4 becomes with CM 2
	Nuclear	Excursion and GFP release to atmosphere Random re-entry from orbit with possible criticality on impact, high direct radiation and release of GFP at impact site	Destroy critical geometry with destruct system Resolve into aerosols thermochemically Combined thermochemical and mechanical destruct	Without CM Engine will impact at random location with release of GFP With CM Engine dispersal above 10 ⁵ feet 4 becomes with CM 2
Saturn C-2 (Orbital Start)	Chemical	Same as Saturn C-1	Same as Saturn C-1	Same as Saturn C-1 4 becomes with CM 2
	Nuclear	Same as Saturn D-1	Same as Saturn D-1	Same as Saturn D-1 4 becomes with with 2

* 1 Safe
 2 Safe with restrictions
 3 Unsafe but tolerable
 4 Unsafe and unacceptable

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The only known countermeasure is to resolve the engine into aerosols above 100,000 feet.

3. Orbital Startup Mission

The orbital startup of the nuclear stage and its placement into an escape trajectory does not present any safety problem.

B. UNSUCCESSFUL MISSION

The unsuccessful mission is defined as one in which chemical or nuclear stage malfunctions occur. This is the limiting criterion on nuclear rocket safety. Table 3 describes the safety aspects of aborted missions.

1. Ballistic Mission

The safety problems affixed to the ballistic mission are launch pad excursions, shallow water excursions and post-mission impact.

Should a major vehicle abort occur on the launch pad, there is a possibility of a 10,000 mw-sec excursion and a release of fission products in the incident cloud. However, this is admittedly undesirable but is tolerable in terms of direct, internal and fallout radiation doses to individuals downwind from the event. The cloud concentration is $1.08 (10^{-3}) \mu\text{c/cc}$ (Ref. 2) and the greatest exposure is $0.172 \text{ curie-sec/cm}^3$. This results in a maximum exposure to a receptor on the centerline of the cloud passage of 27 milliroentgens from gamma radiation and 6 mrem from beta radiation. Receptors on the centerline could receive lifetime doses, due to inhalation, of about 0.07 mrem from Sr-89, 0.1 mrem from Sr-90 and 0.8 mrem from I-131. The maximum dose rate from the ground deposition one hour after the excursion is 25 mr/hr.

The results of a 10^4 mw-sec excursion in shallow water just off-shore from Cape Canaveral are more serious. If it is assumed that 15% of the fuel is volatilized (Ref. 1 and 2) with the release of 15% of undifferentiated fission products plus an additional 15% of the more diffusable nuclides, a volume of water $4 \times 10^{10} \text{ m}^3$ would have a concentration of $10^{-8} \mu\text{c/cc}$ (equivalent to $10^{-8} \text{ curies/m}^3$) after 10 days. If this quantity of water occupies a region where the average depth is 100 meters, the area covered would be $4 \times 10^8 \text{ m}^2$. This would represent a circular area with a radius of 11.24 kilometers or about seven miles. The 100-meter line is at a distance of about 30 miles from Cape Canaveral.

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Both of these situations can be prevented by anticriticality destruct system. This system would physically fragment the core into sections small enough that one piece would not achieve criticality by immersion into water, hydrogen or the Saturn chemical fuel RP-1. This system is described in detail in Chapter V.

2. Orbital Injection Mission

The aborted orbital injection mission has the same problems as previously described for the ballistic mission and the random orbital re-entry problem. However, the latter is more serious because of the possibility of prompt random re-entry, without decay of the engine inventory, induced by propulsion or guidance failures occurring during orbital injection.

The most effective countermeasure is to resolve the engine into aerosols above 100,000 feet altitude by thermochemical, mechanical and aerothermochemical means as described in Chapter V.

3. Orbital Startup Mission

The aborted orbital startup mission is similar to the orbital injection mission. However, failures occurring after orbital startup are less serious. Thrust cutoffs will not yield prompt re-entry without decay of the fission product inventory. Only extreme guidance failures will yield prompt re-entry. However, if escape velocity is not attained, orbits with reasonable decay lifetimes will result in reducing the source strength of the engine. The guidance and thrust failures associated with orbital startup are described in Chapter IX.

C. SUMMARY

It is concluded that the three basic safety problems generally associated with nuclear rockets are:

- (1) Launch pad excursions.
- (2) Shallow water impact.
- (3) Random re-entry from orbit.

The ballistic mission has Problems 1 and 2 associated with it. The orbital injection and orbital startup missions have all three.

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III. AEROTHERMODYNAMICS*

A nuclear reactor re-entering the earth's atmosphere (at random) poses a major safety problem. Consequently, methods of disposing of this vehicle which do not compromise the nuclear rocket propulsion system performance and also ensure the greatest possible reliability must be found.

Two basic methods of destruction are available to the designer, the first is a passive form composed of re-entry heating and atmospheric oxidation; the second is an active destruction category, composed of pre-oxidation of the reactor before re-entry by the injection of fluorine, water, steam or oxygen, the addition of chemical additives to speed up oxidation or erosion and the physical breakup of the reactor with the use of explosive charges at re-entry. Passive methods may also be supplemented by active methods such as additives and the reduction in physical size of the re-entry body by a planned core breakup or by a destruct system. Since stagnation point heating ($q_s \propto \frac{1}{\sqrt{R_B}}$) is inversely proportional to the square root of the body nose radius, reduction in physical size, to as great a degree as possible is desirable.

To determine the nature or necessity of any active destruction systems, the amount of destruction which can be passively achieved must be determined. To achieve this, the amount of available re-entry energy transferred to a typical re-entry configuration in the form of heat energy and chemical energy must be computed. Consequently, analytical models have been set up to represent configurations of interest. The basic choice of configurations is the reactor debris, simulating the result of an orbit destruct system operation, re-entering the earth's atmosphere from a 300-nautical mile orbit. If it can be shown that the reactor debris cannot be destroyed by passive means; then the complete reactor re-entering whole or within the complete nuclear stage certainly will not be destroyed. The debris represent an optimum re-entry configuration for destruction as each piece is smaller than the total reactor and is exposed to oxidation and heating throughout the total re-entry time.

This philosophy leads to the choice of three re-entry configurations to be investigated:

*R. Weiner

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- (1) The reactor is fractured into small pieces. The debris is represented by spheres of various diameters and materials. The choice of the sphere is felt to be conservative in that the sphere has the smallest surface area-to-volume ratio of any shape resulting from destruction of the reactor using an explosive type of device. Figure 8 indicates the effects of geometry on surface area-to-volume ratios.
- (2) A cylindrical fuel element re-entering whole or with various length-to-diameter ratios.
- (3) Reactor re-entering as a unit without the pressure vessel. The pressure vessel is assumed destroyed by afterheat and the reflectors mechanically separated from the core body.

Each of these then will be investigated for:

- (1) Re-entry at different velocities and flight path angles to simulate various abort and orbital decay situations. This is especially important for the exploded configurations since many re-entry angles could result.
- (2) For configurations other than spherical, the effect of re-entry with different orientations to the flight path as well as spinning and tumbling will be investigated.

If any of these configurations show signs of being destroyed before reaching 100,000 feet, where destruction is defined by particles of 25 microns in size at that altitude to negate prompt fallout, they will be factored back into the full propulsion system configuration and re-investigated for re-entry destruction, along the trajectories that indicated particle burnup. Finally, if it can be achieved here the full stage will be assumed to re-enter and a final test for destruction of the complete configuration will be applied. This analytical approach is designed to answer the basic questions:

- (1) Can the reactor and its highly radioactive components be destroyed by purely passive techniques?
- (2) What configurations and trajectories must be present for destruction?
- (3) Can the complete or partial nuclear stage also be destroyed?

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Sphere

$$\left(\frac{S}{v_o}\right) = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{3}{r}$$

Cylinder

$$\left(\frac{S}{v_o}\right)_{\text{cyl}} = \frac{2\pi r l + 2\pi r^2}{\pi r^2 l} = \frac{2}{r} + \frac{2}{l} \quad \text{including ends}$$

$$\text{for equivalent weight sphere } \pi r^2 l = \frac{4}{3}\pi r^3 \therefore l = \frac{4}{3}r$$

$$\therefore \left(\frac{S}{v_o}\right)_{\text{cyl}} = \frac{2}{r} + \frac{3/2}{r} = \frac{3.5}{r}$$

Cone

$$\left(\frac{S}{v_o}\right)_c = \frac{\pi r c}{\frac{1}{3}\pi r^2 h} = \frac{3c}{rh} \quad \text{where } \frac{h}{c} = \cos \theta$$

$$\therefore \left(\frac{S}{v_o}\right)_c = \frac{3}{\cos \theta r} \quad \text{since } 0 < \cos \theta < 1$$

$$\left(\frac{S}{v_o}\right)_c > \left(\frac{S}{v_o}\right)_s$$

Cube

$$\left(\frac{S}{v_o}\right)_{\text{cube}} = \frac{6a^2}{a^3} = \frac{6}{a} \quad \text{for equivalent weights}$$

$$\frac{4}{3}\pi r^3 = a^3; \therefore r = 1.33a$$

$$\text{Then } \left(\frac{S}{v_o}\right)_{\text{cube}} = \frac{7.98}{r} > \left(\frac{S}{v_o}\right)_s$$

Flat Plate

$$\left(\frac{S}{v_o}\right)_P = \frac{2l^2 + 4lt}{l^2 t} = \frac{2}{t} + \frac{4}{l} \quad \text{for equivalent weights}$$

$$\frac{4}{3}\pi r^3 = l^2 t \quad \therefore l \approx \frac{2r^{3/2}}{t^{1/2}}$$

$$\therefore \left(\frac{S}{v_o}\right)_P = \frac{2}{t} + \frac{2t^{1/2}}{r^{3/2}} \quad \text{where } t \ll r$$

$$\therefore \left(\frac{S}{v_o}\right)_P \sim \frac{2}{t} > \left(\frac{S}{v_o}\right)_s$$

Fig. 8. Determination of Surface Area/Volume Ratios of Expected Debris

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A. GENERAL ANALYTIC PROCEDURES

The general solution for determining the fate of a re-entry body can be schematically represented as shown in Fig. 9. Most of the previous analyses of re-entry heating on nose cones have been done assuming constant mass because only a small amount of mass is lost compared to the total system mass. In other words, methods of minimizing heat input were stressed. Here the opposite problem is considered and methods of maximizing the mass lost due to ablation, erosion, oxidation, additives etc., are stressed. Consequently for each step change in altitude a corresponding change in mass of the re-entry body occurs and this in turn has a significant affect on the re-entry velocity profile by changing the drag and orientation of the body. Hence, the step-by-step solution of the problem must be attempted as outlined in Fig. 9.

Because of the complexity of the computations and the dependence of the solution upon various inputs available only as experimental data, a digital machine program will be written to incorporate these procedures and the results of the experimental program factored into the main solution. It is obvious, therefore, that no really exact solution can be completed before an experimental program is at least partially complete and yielding the data necessary to supplement the analyses. However, an approximation of the solution can be undertaken which will yield results sufficiently accurate to answer the main question of whether re-actor debris can be passively destroyed by aerodynamic heating and atmospheric oxidation alone. This solution is outlined in the following discussion.

B. APPROXIMATIONS TO THE GENERAL SOLUTION

1. Trajectory Predictions

The initial step in any analysis of re-entry heating is to determine the amount of energy being absorbed by the re-entering body at any point on its re-entry trajectory. To do this, the available kinetic energy at any altitude can be obtained from the basic equations of motion,

$$-\frac{dr}{dt} = g + \frac{D \sin \phi}{m} - \frac{L \cos \phi}{m} - \frac{u^2}{r} \approx -\frac{d^2y}{dt^2} \quad (1)$$

and

$$\frac{du}{dt} - \frac{D}{m} \left[\cos \phi + \frac{L}{D} \sin \phi \right] \approx \frac{d^2x}{dt^2} \quad (2)$$

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Fig. 9. Formulation of the General Solution of Destruction by Re-Entry Phenomena

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The exact solution of these parametric equations present a very formidable problem which has been successfully attacked by Chapman (Ref. 3) and approximated for steep re-entry angles by Allen and Eggers (Ref. 4). However, to reduce the pair of motion equations to a single equation Chapman introduces a transform Z which is essentially an index for different types of re-entry, ballistic, lifting etc., and all re-entry parameters are expressed relative to the transform index. This gives an excellent picture of the comparison of re-entry of a vehicle of arbitrary weight, size and shape in different planetary atmosphere but is still bulky when the actual values of velocity, altitude deceleration etc., versus time are required. Hence Eqs. (1) and (2) were written in finite difference form, assuming a fixed geometry and solved numerically on an IBM-709 computer for spheres of graphite, beryllium and aluminum having various re-entry angles from $\phi = -1^\circ$ to $\phi = -90^\circ$ and diameters of one foot to $1/32$ inch. Figures 10 and 11 show the typical variations of velocity versus time and altitude versus time with sphere diameter and re-entry angle. The re-entry velocity for these computations was assumed as approximately 25,000 fps for all angles. The motion of the entire body is assumed to be that of a point mass under the influence of a central inverse square gravity field. This assumption permits the moments due to vehicle dynamics to be neglected. The earth is assumed to be a nonrotating sphere of radius $= 2.09029 \times 10^7$ feet; since the regime where drag is important is less than one percent of the radius of the earth, (the rectilinear treatment shown here) seems a permissible approximation. The variation of atmospheric density with altitude is approximated by the ARDC standard atmosphere 1956 from which:

$$\rho = \rho_0 e^{-\beta y} \quad (3)$$

consistent with the assumption of an isothermal atmosphere.

In addition, certain other assumptions must be introduced to obtain the desired degree of simplification necessary for an approximate solution. They are:

- (1) The drag coefficient is constant and hence the body shape is constant (but its actual dimensions may vary). Although the drag coefficient varies with Mach number and Reynold's number, this assumption is generally of good accuracy at the high Mach numbers under consideration as long as the total drag is largely pressure drag.
- (2) The acceleration of gravity is constant since the decrease in the acceleration of gravity is only one percent for every 100,000 feet increase in altitude.

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Fig. 10. Typical Velocity Profiles of Various Graphite Spheres Re-Entering Earth's Atmosphere

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Fig. 11. Typical Altitude Profiles for Graphite Spheres Re-Entering at $V_E = 25,000$ fps and $\phi_E = -1^\circ, -10^\circ$ and -90°

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2. Heat Generation During Re-Entry

Any body re-entering the earth's atmosphere passes through three distinct regimes which effect the heat entering the body due to various aerodynamic phenomena. When the body first re-enters the atmosphere, it is in a region of free molecule flow where the stagnation point heat transfer may be described by Ref. 5 as:

$$q_S \cong 2.69 \times 10^7 \eta \left(\frac{\rho}{\rho_0} \right) \left(\frac{v}{v_E} \right)^3 \frac{\text{Btu}}{\text{ft}^2\text{-sec}} \quad (4)$$

where η is the accommodation coefficient based on energy transfer. The accommodation coefficient is not known in general but definitely has an upper limit of $\eta = 1$, i.e., all the kinetic energy of the incident molecules is transferred to the body. As the re-entering body descends lower into the atmosphere, the molecular mean free path decreases and the flow eventually becomes the continuum type having the simple equation for approximating the stagnation point heat flux of:

$$q_S = \frac{17,600}{\sqrt{R_B}} \sqrt{\frac{\rho}{\rho_0}} \left(\frac{v}{v_E} \right)^{3.25} \left(1 - \frac{h_{sw}}{h_{sl}} \right) \frac{\text{Btu}}{\text{ft}^2\text{-sec}} \quad (5)$$

from Ref. 5.

The transition region, between free molecule flow and continuum flow, is known as the slip flow regime. The effect of the slip flow regime is to cause a gradual transition from the continuum to the free molecule heat transfer rate.

For the purposes of this approximation, the slip flow regime and the free molecule regime will be assumed to add little to the total heat input to the body as shown in Fig. 12 and although the re-entry regime is assumed to begin at approximately 400,000 feet where free molecule heating is prevalent, continuum flow is assumed fully developed at approximately 310,000 feet.

Since the equilibrium wall temperatures of the re-entry bodies considered change with altitude the term $\left(1 - \frac{h_{sw}}{h_{sl}} \right)$ in Eq. (5) has a pronounced effect on the stagnation point heat transfer rates as the re-entry progresses. For example, as the wall temperature increases with exposure time during re-entry the temperature differential between the gas and the wall decreases and hence the heat flux diminishes. The exact change of the wall enthalpy with altitude is difficult to determine especially when chemical reactions on the surface and conduction

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Fig. 12. Heat Transfer Rate $\dot{q}_s$ at the Stagnation Point of a Blunt Body of 1 Foot Nose Radius Traveling at 26,000 fps as a Function of Air Density Ratio ρ/ρ_0 (from Ref. 5)

of heat from the surface to the interior of the body is taking place. However Lees (Ref. 6) and Cohn (Ref. 7) both assume that good approximations to the real case can be obtained by the cold wall approximation, i.e., $h_{sw} \ll h_{sl}$, throughout most of the re-entry regime except at the low altitudes where velocity is low and wall temperatures high. Figure 13 shows the difference between the total aerodynamic heat inputs assuming hot or cold wall conditions. The hot wall total heat input is approximately 20% lower than the cold wall. However, when conduction and the true radiation balance is taken into consideration, it is expected that this difference will be substantially decreased. Consequently Eq. (5) was modified to

$$q_s = \frac{17,600}{\sqrt{R_B}} \left(\frac{\rho}{\rho_0} \right)^{1/2} \left(\frac{v}{v_E} \right)^{3.25} \quad (6)$$

3. Radiation Heat Inputs

In addition to the convective heat transfer rates at the stagnation point, radiation from the dissociated gases behind the bow shock wave (Fig. 14) constitute another heat input which must be approximated in this solution. Lee's (Ref. 6) and Kivel (Ref. 8) both concur that radiation heat transfer at the stagnation point is important only for vehicles with re-entry velocities $v_E \geq 30,000$ fps at altitudes $y \leq 25$ miles.

In addition, Kivel points out that ($q_{rad} \propto R_B$) therefore, small bodies at low velocities and high altitudes have negligible radiation heat inputs. Since the preliminary analysis is for debris of a nuclear stage after an explosive destruct, radiation can safely be neglected as a significant portion of the total heat input.

4. Effect of Body Shape on Average Heat Flux

Because of the dependence of convective heat flux on the velocity gradient at every point on the re-entry body, as demonstrated by Fay and Riddell, (Ref. 9), the heat flux at any local point "l" on the surface of the body in question may be related to the known stagnation heat flux if the variation of velocity gradient $\left(\frac{du}{dx} \right) l$ is also known. Since the variation of the velocity gradient is a direct function of the physical shape of the re-entry body, which is known, the ratio of local to stagnation point heating rates, assuming laminar flow in the boundary layer, can be determined. R. Oehrli in Ref. 10 develops these functions for both a hemispherical nose and a circular cylinder and both are shown in Fig. 15. Assuming both the sphere and the cylinder are spinning upon re-entry, a conservative estimate of the average heat flux over the whole surface of each body is $(q_l / q_s) \cong 0.23$ for a spinning sphere and

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*NOTE: When conduction is considered

$$\sum q = q_{\text{aero}} + q_{\text{rad}} - K \frac{dT}{dr}$$

The hot wall valves
move closer to the
cold wall tending to
further validate

$$\left(1 - \frac{h_{\text{sw}}}{h_{\text{sl}}}\right) \sim 1 \text{ in Eq (6)}$$

Fig. 13. Effect of Cold Wall Assumption $h_{\text{sw}} \ll h_{\text{sl}}$ on Average Heating Profile of a 1 Inch Spinning Sphere of Graphite

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Fig. 14. Hypersonic Flow Over a Blunt-Nosed Body

Fig. 15. Ratio of Local to Stagnation Point Heating Rate Laminar Flow

$(q_\ell/q_s) \approx 0.323$ for a spinning cylinder. Therefore the average heat flux to any point on the body can be represented as a function of the calculated stagnation heat flux at any time during the descent.

5. Latent Energy of Debris

If it is assumed that the nuclear stage is exploded in orbit just after a startup abort, the debris might contain significant latent energy at an altitude where aerodynamic heating begins. Consequently this heat must be estimated as part of the total heat inventory available to destroy the particle. The mechanism of energy loss when the particle falls from orbit to approximately 400,000 feet is radiation, therefore:

$$w C_P \frac{dT}{dt} = - S \sigma \epsilon T^4 \quad (7)$$

lumping the parameters w , C_P , S , σ and ϵ into one constant β we have,

$\beta = \frac{S \sigma \epsilon}{w C_P}$, although $C_P = f(T)$ to forego the complexities of fitting approximate curves to the experimental specific heat versus temperature curves of graphite, aluminum and beryllium the assumption $C_P \approx C_{P_{av}}$ was introduced where $C_{P_{av}} = \frac{1}{\Delta T} \int_T^{T_0} C_P dT$ and is numerically determined.

The resulting value of T can be used to interate on $C_{P_{av}}$ from the given experimental curve. However, this preliminary assumption $C_P \approx C_{P_{av}}$ will certainly give good order of magnitude results, therefore

$$\beta = \frac{S \sigma \epsilon}{w C_{P_{av}}}$$

then

$$\frac{dT}{dt} \approx - \beta T^4 \quad \therefore \quad \int_{T_0}^T \frac{T}{T^4} = - \beta \int_0^t dt$$

and

$$T = T_0 (1 + \beta T_0^3 t)^{-1/3} \quad (8)$$

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Since the debris can be considered spheres

$$w = \frac{4}{3} \pi R_B^3 \rho_B, S = 4 \pi R_B^2$$

$$\therefore \frac{3 \sigma \epsilon}{R_B \rho_B C_{P_{av}}} \quad (9)$$

and the time to fall from an initial altitude y_o to the re-entry altitude 400,000 feet in the absence of drag would just be

$$t = \frac{y_o - 400,000}{v_E \sin \phi_E} \quad (10)$$

then

$$T_{4 \times 10^5 \text{ ft}} \cong T_o \left[1 + \left(\frac{3 \sigma \epsilon}{R_B \rho_B C_{P_{av}}} \right) T_o^3 \left(\frac{y_o - 400,000}{v_E \sin \phi_E} \right)^{-1/3} \right] \quad (11)$$

Then the latent heat, at 400,000 feet, of any particle of radius R_B and material ρ_B having an initial temperature T_o is

$$\left(Q_L \right)_{4 \times 10^5} = \left(C_P \right)_T (T) w \text{ Btu} \quad (12)$$

6. Heat Required for Destruction

For the preliminary analysis presented here destruction of aluminum and beryllium debris will be considered as complete meltdown and complete vaporization for the graphite. No oxidation or ablation will be considered initially, consequently fixing the radius of each piece of debris considered. If the radius changes, as it will with ablation of successive layers of material from the aluminum and beryllium and the loss of mass by oxidation of the surface of the graphite, the aerodynamic heat flux increases with decreasing radius and the heat required to destroy the object decreases with decreasing mass. However, this neglects mass transfer blocking effects which may be significant, especially on graphite as is shown in Section 7.

ΣQ_{req} = heat to raise mass from ambient temperature to the melt temperature, T_M + the heat of fusion, L_H

$$\therefore \left[\Sigma Q_{\text{req}} \right]_{\text{metals}} \approx \left[C_{P_{\text{av}}} (T_M - T_o) + L_H \right] m_o \text{ Btu} \quad (13)$$

for the graphite

ΣQ_{req} = heat to raise mass from ambient temperature, T_o , to the vaporization temperature, T_v , + the heat of vaporization

$$\therefore \left[\Sigma Q_{\text{req}} \right]_{\text{graphite}} \approx \left[C_{P_{\text{av}}} (T_v - T_o) + v_H \right] m_o \text{ Btu} \quad (14)$$

The ratio $K = \frac{\Sigma Q_{\text{available}}}{\Sigma Q_{\text{required}}}$ can be computed for each body for all its various re-entry angles and orientations, where

$$\Sigma Q_{\text{available}} = \int_{t_o}^t \dot{q}_{\text{av}} S \, dt + Q_L \quad (15)$$

This has been done as an example for graphite. Cold wall heat rates are assumed giving optimistic values of $\Sigma Q_{\text{available}}$. However, burnup is far from being achieved even with optimistic heat inputs. Considering the maximum available kinetic energy of a body re-entering at 25,000 fps as 12,500 Btu/lb and comparing this to the heat of vaporization of graphite, 26,000 Btu/lb; total destruction from aerodynamic heating alone is impossible.

A more complete study of ablation and blocking phenomena will be undertaken in the final solution for the predictions of the burnup of the complete nuclear stage and propulsion module. This study will indicate altitudes where components are destroyed and engine fragments, fuel elements, etc., are fully exposed to re-entry heating and oxidation, assuming the destruct package does not fire on abort of the nuclear stage.

7. Oxidation

"It has been determined that the recovered fragments of metallic meteorites represent only a small fraction of the original size of the meteor. This is due to the fact that when a metallic material is subjected to severe heating, it undergoes severe failure by melting, in which only a negligible quantity of material vaporizes" (Ref. 11). This type of failure occurs because the liquid phase viscosity of a metal is very low, and hence the molten metal will be driven away from the stagnation region before appreciable vaporization can begin. This is espe-

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cially true for spinning bodies where there is a centrifugal force component acting as well. Therefore it will be assumed for the purposes of this analysis that negligible vaporization or surface combustion occurs on the aluminum and beryllium debris. Consequently, our attention will be given solely to surface combustion of the graphite fuel element debris, since it was shown that if appreciable weight losses do occur for the graphite they will be due to a mechanism other than pure aerodynamic heating which is inadequate to vaporize specimens.

Scala (Ref. 11) has attacked the problem of surface combustion of graphite and carbon and has developed a unified theory relating the mass loss rates due to chemical combustion at the stagnation point to the aerothermodynamic inputs to the surface at every point on its re-entry trajectory. The results of this work are shown in Fig. 16 which indicates that although flight speed (stagnation enthalpy) and surface temperature (shifting chemical equilibrium) effects do exist in a hypersonic environment, the most important single independent variable is the stagnation pressure. This result is evident from

$$\dot{m}_w \cong 0.1 \sqrt{2 \rho_w \mu_w \left(\frac{du}{dx} \right)_s} \quad (16)$$

and since

$$\left(\frac{du}{dx} \right)_s = \frac{1}{R_B} \sqrt{\frac{2(P_s - P_\infty)}{\rho_s}} \quad (17)$$

as well as assuming

$$\mu_w \sim T_w$$

then

$$\dot{m}_w \sqrt{R_B} \cong 5 \times 10^{-6} \left(\frac{P_s}{\rho_s} \right)^{\frac{1}{4}} \frac{\text{lb}}{\text{ft}^{3/2} \text{-sec}} \quad (18)$$

This equation clearly shows the dependence of the combustion rate on the stagnation pressure Fig. 16 was plotted from the general equation:

$$\dot{m}_w \sqrt{R_B} \cong C (10)^a (v_\infty)^b \frac{\text{lb}}{\text{ft}^{3/2} \text{-sec}} \quad (19)$$

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Fig. 16. Mass Transfer for Carbon Combustion at the Stagnation Point of a Blunt Body

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where

$$a = -(4.6759 + 9.16 \times 10^{-6} y)$$

$$b = 0.875$$

and

$$c = 0.508 + 1.4725 \times 10^{-6} T_w \text{ when } 1000^\circ \text{ R} < T_w < 3000^\circ \text{ R}$$

and when $T_w > 3000^\circ \text{ R}$

$$c = 1.17 - 1.045 \times 10^{-6} y - (7.41 \times 10^{-5} - 2.85 \times 10^{-10} y) T_w$$

In order to apply the results of Fig. 16 to points other than the stagnation point of the body, a method must be devised to determine the dependence of the mass flux parameter $(\dot{m}_w \sqrt{R_B})_S$ on other thermal properties whose variations at some other point, p, away from the stagnation point are known. Therefore,

since

$$(\dot{m}_w \sqrt{R_B})_S \sim \sqrt{2 \rho_{wS} \mu_{wS} \left(\frac{du}{dx} \right)_S} \quad \text{Ref. 11} \quad (20)$$

the ratio of stagnation point mass flux to the mass flux at any other point on the surface is

$$\frac{(\dot{m}_w \sqrt{R_B})_S}{(\dot{m}_w \sqrt{R_B})_p} \sim \sqrt{\left(\frac{\rho_{wS}}{\rho_{wp}} \right) \left(\frac{\mu_{wS}}{\mu_{wp}} \right) \frac{(du/dx)_S}{(du/dx)_p}} \quad (21)$$

Now from Ref. 12, Sibulkin, describes the general relation of stagnation point heating as:

$$q_S \cong G \sqrt{\rho_{S\ell} \mu_{S\ell} \left(\frac{du}{dx} \right)_S}; T_{wS} \ll T_{S\ell} \quad (22)$$

where $G = \text{constant}$ and ℓ refers to parameters at the edge of the boundary layer

therefore:

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$$\frac{q_S}{q_P} \sim \sqrt{\frac{\rho_{Sl} \mu_{Sl}}{\rho_{Pl} \mu_{Pl}} \frac{(du/dx)_S}{(du/dx)_P}} \sim \sqrt{\frac{(du/dx)_S}{(du/dx)_P}} \quad (23)$$

Then from Eq. (21):

$$\frac{(\dot{m}_w \sqrt{R_B})_S}{(\dot{m}_w \sqrt{R_B})_P} \sim \left(\sqrt{\frac{(\rho_{wS} \mu_{wS})}{(\rho_{wP} \mu_{wP})}} \right) \left(\frac{q_S}{q_P} \right) \quad (24)$$

therefore, the mass flux rate at any point away from the stagnation point is

$$(\dot{m}_w \sqrt{R_B})_P \sim \frac{q_P}{q_S} \sqrt{\frac{\rho_{wP} \mu_{wP}}{\rho_{wS} \mu_{wS}}} (\dot{m}_w \sqrt{R_B})_S \quad (25)$$

Now considering $\frac{\mu_w}{\mu_\ell} \sim \left(\frac{T_w}{T_\ell} \right)^n$ for a gas boundary layer Ref. 13 P-1049

where $n \sim 0.75$ from experiment and $\left(\frac{\rho_{wP}}{\rho_{wS}} \right) = \left(\frac{T_{wP}}{T_{wS}} \right)^{\frac{1}{\gamma-1}}$ from perfect gas relationships

$$\begin{aligned} \therefore \sqrt{\left(\frac{\rho_{wP}}{\rho_{wS}} \right) \left(\frac{\mu_{wP}}{\mu_{wS}} \right)} &= \left[\left(\frac{T_{wP}}{T_{wS}} \right)^{\frac{1}{\gamma-1}} \times \left(\frac{T_{wP}}{T_{wS}} \right)^{3/4} \right]^{\frac{1}{2}} \\ &= \left(\frac{T_{wP}}{T_{wS}} \right)^{\frac{3\gamma+1}{8(\gamma-1)}} \end{aligned} \quad (26)$$

Now $\frac{T_{wP}}{T_{wS}} \sim \left(\frac{q_{wP}}{q_{wS}} \right)^{\frac{1}{4}}$ from radiation considerations

Therefore

$$\sqrt{\frac{\rho_{wP} \mu_{wP}}{\rho_{wS} \mu_{wS}}} \sim \left(\frac{q_{wP}}{q_{wS}} \right)^{\frac{3\gamma+1}{32(\gamma-1)}} \quad (27)$$

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for air at 2000° R as an average temperature in the boundary layer
 $\delta \approx 1.33$

Therefore

$$\sqrt{\frac{\rho_{wp}}{\rho_{ws}} \cdot \frac{\mu_p}{\mu_s}} \sim \left(\frac{q_{wp}}{q_{ws}} \right)^{0.473}$$

finally then Eq. (25) becomes;

$$(\dot{m}_w \sqrt{R_B})_p \sim \left(\frac{q_{wp}}{q_{ws}} \right)^{1.473} (\dot{m}_w \sqrt{R_B})_s \quad (28)$$

If $\left(\frac{q_{wp}}{q_{ws}} \right)$ is considered as the average value for a sphere spinning then:

$$(\dot{m}_w \sqrt{R_B})_{av} \approx 0.130 (\dot{m}_w \sqrt{R_B})_s \quad (29)$$

Assuming step changes in radius and that the body retains its spherical shape as it oxidizes, it is possible using finite difference techniques applied to the variations in velocity, altitude and surface temperature to approximate the total mass lost throughout the entire re-entry period and to predict burnup altitude.

The results of some preliminary computations using this method are presented in Figs. 17 and 18 for various size graphite spheres re-entering at different angles. They indicate the maximum sizes which will burn up in different re-entry trajectories and the altitudes at which this happens.

C. CONCLUSIONS

It is quite obvious from the results of Figs. 17 and 18, that the maximum sizes of core debris which will be destroyed by the combined effects of aerodynamic heating and oxidation, before reaching 100,000 feet are quite small.

Particles between (1/32) and (1/16) inch seem to show positive signs of destruction. Consequently the passive destruction of the whole reactor without any means of fragmenting the core seems very unlikely. This is especially true when the reactor is assumed to re-enter within the complete nuclear stage where a large portion of the total re-entry energy is absorbed in burning away the space frame and attending structure before the core is fully exposed.

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Fig. 17. Percentage of Graphite Oxidized from Spheres of Various Diameters
Re-Entering at $\phi_E = -1^\circ$ and $v_E = 25,000$ fps

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Fig. 18. Typical Effect of Re-Entry Angle on the Oxidation of a $\frac{1}{16}$ -Inch Diameter Sphere
 $v_E = 25,000$ fps

An experimental program is postulated to varify these initial findings and is outlined in Chapter VIII.

LIST OF SYMBOLS

S	-	Surface area (ft^2)
v_o	-	Volume (ft^3)
v	-	Normal component of velocity (fps)
u	-	Tangential component of velocity (fps)
D	-	Drag (lb)
C_D	-	Drag coefficient
t	-	Time (sec)
ϕ	-	Angle tangent to the flight path makes with local horizontal
L	-	Lift (lb)
w	-	Weight (lb)
m	-	Mass $\left(\frac{\text{lb-sec}^2}{\text{ft}}\right)$
ρ	-	Density (lb/ft^3)
y	-	Altitude (ft)
R_B	-	Body radius (ft)
ρ_B	-	Body density (lb/ft^3)
h	-	Enthalphy $\left(\frac{\text{Btu}}{\text{lb}}\right)$
q	-	Heat flux $\left(\frac{\text{Btu}}{\text{ft}^2\text{-sec}}\right)$
C_P	-	Specific heat $\left(\frac{\text{Btu}}{\text{lb } ^\circ\text{R}}\right)$
T	-	Temperature ($^\circ\text{R}$)
ϵ	-	Surface emissivity

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- σ - Stephan-Boltzman constant
- $\dot{m}$ - Oxidation rate $\left(\frac{\text{lb}}{\text{ft}^2 \text{-sec}}\right)$
- μ - Viscosity (centpoises)
- P - Total pressure (psi or psf)
- $\left(\frac{du}{dx}\right)$ - Velocity gradient along a flow stream line
- A - Cross sectional area (ft^2)

Subscripts

- S - Stagnation point
- B - Body
- O - Initial
- A - After heat
- E - At re-entry
- W - Wall
- l - Edge of boundary layer
- p - Point on surface other than stagnation point
- M - Melting
- V - Vaporization
- L - Latent
- ∞ - Free stream conditions
- R - Radiation
- x, r - Body coordinates

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IV. REACTOR ANALYSIS*

The reactor analysis conducted during this report period falls into two general classifications, reactivity calculations and core shutdown power determination. The reactivity calculations were made to determine the reactivity of the total core and sections of the core, under a variety of conditions. The core shutdown power study, which was conducted on an electronic analog computer, was made to determine the amount of heat available to aid in core destruction.

A. REACTIVITY CALCULATIONS

The series of reactivity calculations were made using APWRC-SYNFAR, an improved C_3-F_3 program developed by Martin that makes a homogeneous, one-dimensional, three-group calculation. The six following separate groups of calculations were made:

- (1) Reactivity of the core when immersed in water with the reflector removed and the reactivity as a function of percent of fuel element lost (eroded, corroded or volatilized) when the core is immersed in water.
- (2) Reactivity of the core when immersed in liquid oxygen and the Saturn first stage fuel, RP-1, with the beryllium reflector intact.
- (3) Reactivity change involved when the reactor control cylinders are removed from the system.
- (4) Reactivity change when the beryllium reflector is replaced by a water reflector.
- (5) Reactivity as a function of fragment size for pieces of the core immersed in water.
- (6) Reactivity as a function of percent of fuel element lost with the core in air, for various core temperatures.

1. Core Immersed in Water

The reactivity of the core when immersed in water with the reflector removed was determined. In the calculation the core was immersed in an effectively infinite body of water. The infinite water reflector and

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water moderator in the core, due to filling of the void channels, converts the normally intermediate spectrum (epithermal) reactor to a thermal reactor with an excessive amount of fuel. It was assumed that the water in its liquid state would completely fill the resulting void. The result, $K_{eff} = 1.50$, reveals that completely filling the voids with water is impossible. In the sequence the voids would partially fill with water until a sufficient amount of reactivity was obtained to cause the reactor to experience an excursion. The generation of steam would then cause an expulsion of the water what would result in a decrease in reactivity and termination of the excursion. This cycle would then repeat itself until a sufficient amount of fuel had been removed by sublimation, or erosion or fission to render the core subcritical.

To determine the amount of fuel that must be removed to render the core subcritical, a study of reactivity versus percent of fuel element eroded was conducted. The conditions were the same as outlined, however, as the fuel matrix erodes, more water enters the resulting void. The introduction of more water more than offsets the reduction in fuel and increases the reactivity (Fig. 19) up to a point where approximately 33% of the fuel matrix has been eroded and where the atomic H/O ratio is 40:1 and about 80% of the power is in the thermal range. An increase in the moderation fraction beyond this peak (or reduction in fuel) results in an overmoderated core and the reactivity begins decreasing. When 89% of the fuel matrix has eroded the reactor becomes just critical and any further reduction in fuel renders it incapable of achieving criticality. This study did not include effects of neutron streaming (Behren's correction) and self-shielding (cell corrections) and therefore represents the worst possible situation that can exist in the core.

2. Core Immersed in Liquid Oxygen or RP-1

The reactivity resulting from immersing the core in liquid oxygen and the fuel of the Saturn first stage, RP-1, was calculated using the same conditions as listed prior except the beryllium reflector was not removed. The results show that while immersion in liquid oxygen ($\Delta K_{eff} = 0.0593$) is not a serious problem, immersion in RP-1 ($\Delta K_{eff} = 0.522$) could be. The immersion in liquid oxygen would not introduce sufficient reactivity to achieve prompt criticality even assuming the reactor was delayed critical before it was immersed. Immersion in RP-1 fuel would introduce sufficient reactivity to cause an excursion even assuming that the control drums are in their least reactive position.

3. Loss of Control Drums

The reactivity change involved when the reactor control drums are removed was studied. This was done to examine the case where an explosion of vehicle propellants resulted in physical ejection of the control drums. This is an unlikely case, but one that should be examined. The results are as follows:

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Fig. 19. K_{eff} Versus Percent of Fuel Matrix Eroded

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Drums at minimum control $K_{\text{eff}} = 1.04169$

Drums removed $K_{\text{eff}} = 0.99528$

Drums at maximum control $K_{\text{eff}} = 0.99373$

The results indicate that removal of the control drums will either increase or decrease the reactivity depending on the position of the drums at the time of the accident. Two possibilities can be examined, one where the drums were at their least reactive position ($K_{\text{eff}} = 0.99373$)

at the time of the accident and where they were at a critical position ($K_{\text{eff}} = 1.000$). In the first incident, the reactivity would increase but would need an additional source of reactivity, i.e., immersion into liquid oxygen or RP-1, to achieve criticality. In the second case the same situation prevails, the core would become subcritical unless an additional source of reactivity is present. The conclusion that complete loss of the control drums will not present a dangerous condition, can be drawn.

4. Water Reflector

One of the countermeasures under consideration is the insertion of water, or some other liquid, into the core after the hydrogen propellant is exhausted to aid in the destruction of the core. This liquid would not only physically erode the core but remove uranium and graphite by chemical reactions. One problem that exists with this concept is the added weight that must be carried along (a calculation indicates as much as three tons of water would be required). However, if the shield and reflector materials were replaced with water the weight penalty would be reduced or eliminated. The reactivity calculation indicates, however, that about 10.5% in reactivity would be lost and must be made up by higher fuel loadings. This is not considered feasible at this time, especially with the KIWI-B-1 configuration.

5. Reactivity as Function of Fragment Size

The countermeasure that is proposed to eliminate the possibility of a reactor excursion in shallow water off-shore of the launching pad is physically destroying the core. This will be accomplished by either firing a number of shaped charges through the core to set up a series of fracture patterns or by firing a charge of high explosive into the center of the core where it will be detonated. However, to properly design this destruct system, the fragment size necessary to prevent criticality when immersed in water must be determined both analytically and experimentally. A preliminary examination of the problem using the SYN FAR code produced the results illustrated in Fig. 20. This graph

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Fig. 20. Fragment Size Versus Total Core Volume

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shows that the fragment size must not be greater than approximately seven percent of the total core volume. This calculation assumed that the fragment cylinders have the same L/D ratio as the original core and also have the same volume fraction of fuel, graphite and void.

6. Effects of Erosion

The last reactivity study, shown graphically in Fig. 21, treated the reactivity effects due to the erosion of up to 20% of the fuel matrix. The reactor studied contained no hydrogen gas, or no local control drums in the reflector and was not assumed to be immersed in any liquid. Therefore the results (Fig. 21) are only for comparison purposes. Temperature effects are included to indicate operation at elevated temperature. Subcriticality is obtained after approximately 19% of the fuel matrix is eroded for an average operating temperature of 2200° F and after 17.5% erosion at 3000° F. Cores operating below 1200° F are still critical with 20% of the fuel matrix removed.

B. SHUTDOWN ANALOG STUDY

An analog study was conducted primarily to observe the shutdown power. Various temperatures throughout a typical fuel module were calculated to gain knowledge of the extent of fuel vaporization during the shutdown transient. Effects of simultaneously inserting various rates of positive reactivity associated with reflector control drum motion were investigated. These control drum motions could be used in the physical system in an attempt to maintain core reactivity (and power) after propellant exhaustion. The effects of temperature coefficient were also studied.

1. Procedure

A mathematical model was developed from system data and programmed on the computer. To obtain the desired results, a series of runs were set up to achieve the goals specified.

To determine the operating temperature of each section of the radially sectionalized typical fuel element at seven axial core positions, seven runs were made. Input to the temperature system consisted of a wall temperature as calculated by a digital computer code. The computer then was allowed to compute the radial temperature profile at the respective positions.

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Fig. 21. Reactivity Versus Percent of Fuel Matrix Eroded

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<u>Run</u>	<u>T1 (Input) (°R)</u>	<u>Axial Core Position</u>
1	635	Core inlet
2	2443	1/6
3	3174	2/3
4	4000	1/2
5	4511	2/3
6	4720	5/6
7	4412	Core outlet

The resulting temperatures were then used as initial conditions for the remainder of the program.

The next goal was to observe the shutdown power and temperature transients radially across the typical fuel section at seven axial positions. The power drop transient was governed by the negative reactivity associated with the hydrogen worth and fission product decay power. The temperature coefficient held constant at $-3 \times 10^{-6} \Delta k/^{\circ}R$

<u>Run</u>	<u>Axial Core Position</u>	<u>K (Input) (Step)</u>
8	Inlet	-0.03
9	1/6	-0.03
10	1/3	-0.03
11	1/2	-0.03
12	2/3	-0.03
13	5/6	-0.03
14	Outlet	-0.03

The next set of runs were designed to compare core temperature transients and power when positive reactivity was inserted simultaneously with shutdown. Temperatures were monitored at the axial position of Run 9 (1/6 of the total distance through the core) so the temperatures

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recorded would remain within the scaling limits of the program which in turn were above the sublimation temperature of the core material. In this way, temperature could be easily compared from one run to the next.

<u>Run</u>	<u>K (Hydrogen) (Step)</u>	<u>K (Reflector) (per sec)</u>	<u>K (Reflector) Maximum</u>
15	-0.03	0.0075	0.03
16	-0.03	0.0150	0.03
17	-0.03	0.0220	0.03
18	-0.03	0.0300	0.03

A radial temperature profile was again taken for conditions of Run 16 to determine any difference in temperature transients under these conditions.

<u>Run</u>	<u>Core Axial Position</u>	<u>K (Hydrogen) (Step)</u>	<u>K (Reflector) (per sec)</u>
19	Inlet	-0.03	0.015
20	1/6 (use Run 16)	-0.03	0.015
21	1/3	-0.03	0.015
22	1/2	-0.03	0.015
23	2/3	-0.03	0.015
24	5/6	-0.03	0.015
25	Outlet	-0.03	0.015

The maximum reactivity in all cases was $0.03 \Delta k$.

The effects of temperature coefficient variations were investigated at the 1/6 axial core position. The typical case used is specified in Run 16.

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<u>Run</u>	<u>Temperature (k/°R)</u>	<u>K (Hydrogen) (Step)</u>	<u>K (Reflector) (per sec)</u>
26	-1×10^{-6}	-0.03	0.015
27	-2×10^{-6}	-0.03	0.015
28	-3×10^{-6}	-0.03	0.015
29	-4×10^{-6}	-0.03	0.015
30	-5×10^{-6}	-0.03	0.015

The maximum reactivity in all cases was $0.03 \Delta k$.

Not recorded, but of academic interest, was the magnitude of the integrated power represented from the initiation of shutdown through the duration of the run. The maximum value obtained was 10,000 megawatt-seconds. This was obtained in Run 26 where the lowest value of temperature coefficient was used. By comparison, Run 30 resulted in less than 3000 megawatt-seconds of integrated power.

2. Results

The results of the analog study can be seen in a series of graphs. Figure 22 shows the power as a function of time after shutdown for the normal case and for the case where reactivity was inserted (with the reflector control drums) at rates of $0.0075 \Delta k/\text{sec}$, $0.0150 \Delta k/\text{sec}$ and $0.030 \Delta k/\text{sec}$ with a maximum of $0.030 \Delta k$ for all cases. This graph shows the amount of power that can be obtained by utilizing the reactivity available in the control drums. Figure 23 represents a temperature profile (see Fig. 42 for the physical profile represented by Fig. 23) through the typical fuel module for steady state operation as calculated by the analog computer. Figures 24 through 30 represent the fuel module temperatures as a function of time after shutdown for the normal case, i.e., no control drum motion. Figures 31 through 34 reveal the effects of positive reactivity insertions for a typical axial position, $1/6$ the total distance through the core. Figures 35 through 41 show the temperature distribution through an average module in the axial and radial direction for a typical positive reactivity insertion, $0.0150 \Delta k/\text{sec}$ with a maximum of $0.030 \Delta k$.

The results in general show that while a portion of the core will be vaporized in this type of operation, some other means of utilizing the shutdown power or increasing it must be found. The power trace and temperature distribution obtained in this study will be used in a future study to determine the fate of the reflector and pressure vessel.

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Fig. 22. Shutdown Power Curve--Hydrogen Worth 0.03 \$k, Total Rod Motion 0.03 \$k

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Fig. 23. Radial Position in Fuel Module Versus Time

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Fig. 24. Fuel Module Temperature Distribution, Core Inlet, No Positive Reactivity Insertion

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Fig. 25. Fuel Module Temperature Distribution, 1/6 Axial Distance, No Positive Reactivity Insertion

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Fig. 26. Fuel Module Temperature Distribution, 1/3 Axial Distance, No Positive Reactivity Insertion

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MND-2516Fig. 27. Fuel Module Temperature Distribution, $1/2$ Axial Distance, No Positive Reactivity Insertion

Fig. 28. Fuel Module Temperature Distribution, 2/3 Axial Distance, No Positive Reactivity Insertion

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Fig. 29. Fuel Module Temperature Distribution, 5/6 Axial Distance, No Positive Reactivity Insertion

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Fig. 30. Fuel Module Temperature Distribution, Core Outlet, No Positive Reactivity Insertion

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Fig. 31. Fuel Module Temperature Distribution, 1/6 Axial Distance,
 $\pm 0.03 \Delta k$ at $0.0075 \Delta k/\text{sec}$

Fig. 32. Fuel Module Temperature Distribution, 1/6 Axial Distance, $\pm 0.03 \Delta k$ at $0.0150 \Delta k/sec$

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Fig. 33. Fuel Module Temperature Distribution, 1/6 Axial Distance,
 $\dagger 0.03 \Delta k$ at $0.0220 \Delta k/\text{sec}$

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Fig. 34. Fuel Module Temperature Distribution, 1/6 Axial Distance,
 $\pm 0.03 \Delta k$ at $0.03 \Delta k/\text{sec}$

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Fig. 35. Fuel Module Temperature Distribution, Core Inlet, $+ 0.03 \Delta k$ at $0.015 \Delta k/\text{sec}$

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Fig. 36. Fuel Module Temperature Distribution, 1/6 Axial Distance, + 0.03 Δk at 0.0150 $\Delta k/\text{sec}$

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Fig. 37. Fuel Module Temperature Distribution, 1/3 Axial Distance,
 $+0.03 \Delta k$ at $0.015 \Delta k/\text{sec}$

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Fig. 38. Fuel Module Temperature Distribution, 1/2 Axial Distance, $+0.03 \Delta k$ at $0.015 \Delta k/\text{sec}$

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Fig. 39. Fuel Module Temperature Distribution, 2/3 Axial Distance,
 $\pm 0.03 \Delta k$ at $0.015 \Delta k/\text{sec}$

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Fig. 40. Fuel Module Temperature Distribution, 5/6 Axial Distance,
 $+0.03 \Delta k$ at $0.015 \Delta k/\text{sec}$

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Fig. 41. Fuel Module Temperature Distribution, Core Outlet, $+0.03 \Delta k$ at $0.015 \Delta k/\text{sec}$

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3. Mathematical Model

A two-delay group reactor kinetics model was used to free more integrators for use in a sectionalized reactor core and fuel element analysis.

$$\dot{N} = \frac{\delta K}{\ell^*} N - \beta N + \lambda_1 c_1 + \lambda_2 c_2 *$$

$$\dot{c}_1 = \frac{\beta_1}{\ell^*} N - \lambda_1 c_1$$

$$\dot{c}_2 = \frac{\beta_2}{\ell^*} N - \lambda_2 c_2$$

$$K = \mathcal{S} K_e + \alpha_T \Delta T$$

$$\Delta T = \bar{T}_F - \bar{T}_{F0}$$

$$Q = K_p N$$

$$\bar{T}_F = 1/3 (T_{F1} + T_{F2} + T_{F3})$$

Heat transferred from reactor to fuel in each of the three core sections is represented by

$$M_{F1} C_{pF} \dot{\bar{T}}_{F1} = Q_{F1} - h_{F1} A (\bar{T}_{Fu} - T_{Gci.}) - \frac{k}{t} A_s (\bar{T}_{F1} - \bar{T}_{S1}) \quad i = 1, 2, 3$$

Heat transferred from structure to fuel in each section

$$M_{S1} C_{pS} \dot{\bar{T}}_{S1} = \frac{k A_s}{t} (\bar{T}_{F1} - \bar{T}_{S1}) + Q_{S1} \quad i = 1, 2, 3$$

Heat generated in the core is proportioned in each section as follows:

$$Q_{F1} = K_{F1} Q \quad i = 1, 2, 3$$

$$Q_{S1} = K_{S1} Q \quad i = 1, 2, 3$$

A typical fuel element was divided into five hollow cylindrical sections and finite difference equations written for the series of cylinders around the coolant hole (see Fig. 42). Three cylinders were taken in the fuel region and two in the structural region. Heat flows are equated across each interface and the following equations result:

*Symbols are listed at end of chapter.

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Fig. 42. Finite Difference Approximation of Temperature Distribution

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First cylindrical section surrounding the coolant hole

$$\begin{aligned}
 \dot{t}_1 &= \frac{q_F}{\rho_F C_{pF}} - \frac{2h}{\rho_F C_{pF}} \left[\frac{\left(r_1 - \frac{\Delta r_f}{2}\right)}{\left(\left[r_1 + \frac{\Delta r_f}{2}\right]^2 - \left[r_1 - \frac{\Delta r_f}{2}\right]^2\right)} \right] (T_1 - T_G) \\
 &+ \frac{2k}{\rho_F C_{pF}} \left[\frac{\left(r_1 + \frac{\Delta r_f}{2}\right)}{\Delta r_f \left(\left[r_1 + \frac{\Delta r_f}{2}\right]^2 - \left[r_1 - \frac{\Delta r_f}{2}\right]^2\right)} \right] (T_2 - T_1) \\
 \dot{t}_2 &= \frac{q_F}{\rho_F C_{pF}} + \frac{2k}{\rho_F C_{pF}} \left[\frac{\left(r_2 + \frac{\Delta r_f}{2}\right)}{\Delta r_f \left(\left[r_2 + \frac{\Delta r_f}{2}\right]^2 - \left[r_2 - \frac{\Delta r_f}{2}\right]^2\right)} \right] (T_3 - T_2) \\
 &- \frac{2k}{\rho_F C_{pF}} \left[\frac{\left(r_2 - \frac{\Delta r_f}{2}\right)}{\Delta r_f \left(\left[r_2 + \frac{\Delta r_f}{2}\right]^2 - \left[r_2 - \frac{\Delta r_f}{2}\right]^2\right)} \right] (T_2 - T_1) \\
 \dot{t}_3 &= \frac{q_F}{\rho_F C_{pF}} + \frac{2k}{\rho_F C_{pF}} \left[\frac{\left(r_3 + \frac{\Delta r_f}{2}\right)}{\Delta r_f \left(\left[r_3 + \frac{\Delta r_f}{2}\right]^2 - \left[r_3 - \frac{\Delta r_f}{2}\right]^2\right)} \right] (T_4 - T_3) \\
 &- \frac{2k}{\rho_F C_{pF}} \left[\frac{\left(r_3 - \frac{\Delta r_f}{2}\right)}{\Delta r_f \left(\left[r_3 + \frac{\Delta r_f}{2}\right]^2 - \left[r_3 - \frac{\Delta r_f}{2}\right]^2\right)} \right] (T_3 - T_2) \\
 \dot{t}_4 &= \frac{2k}{\rho_S C_{pS}} \left[\frac{\left(r_4 + \frac{\Delta r_s}{2}\right)}{\Delta r_s \left(\left[r_4 + \frac{\Delta r_s}{2}\right]^2 - \left[r_4 - \frac{\Delta r_s}{2}\right]^2\right)} \right] (T_5 - T_4)
 \end{aligned}$$

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$$\begin{aligned}
& + \frac{q_s}{\rho_f c_{ps}} - \frac{2k}{\rho_s c_{ps}} \left[\frac{\left(r_4 + \frac{\Delta r_s}{2}\right)}{\Delta r_s \left[\left(r_4 + \frac{\Delta r_s}{2}\right)^2 - \left(r_4 - \frac{\Delta r_s}{2}\right)^2\right]} \right] (T_4 - T_3) \\
& \dot{T}_5 = \frac{-2k}{\rho_s c_{ps}} \left[\frac{\left(r_5 - \frac{\Delta r_s}{2}\right)}{\Delta r_s \left[\left(r_5 + \frac{\Delta r_s}{2}\right)^2 - \left(r_5 - \frac{\Delta r_s}{2}\right)^2\right]} \right] (T_5 - T_4) \\
& + \frac{q_s}{\rho_s c_{ps}}
\end{aligned}$$

Fission product power, Fig. 43 was approximated by two time constants:

$$P_D = \frac{5}{s(1 + 3.57 s)} \quad \text{For } 0 < t < 2.25 \text{ seconds after shutdown}$$

and

$$P_D = \frac{2.335}{s(1 + 14.28 s)} \quad \text{For } 2.25 < t < \infty \text{ after shutdown}$$

The computer diagram for this set of equations is shown as Fig. 44. The runs outlined under Procedure are included in the Appendix.

Constants

$$\ell^* = 1.44 \times 10^{-5} \text{ second}$$

$$\beta = 0.006995$$

$$\lambda_1 = 0.025 \text{ sec}^{-1}$$

$$\lambda_2 = 0.272 \text{ sec}^{-1}$$

$$\beta_1 = 0.00182$$

$$\beta_2 = 0.005174$$

$$K_p = 1.002772 \times 10^4 \text{ Btu/sec-}\%$$

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Fig. 43. Fission Product Decay Power

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Fig. 44. Nuclear Rocket Shutdown Analysis--Analog Program

$$\begin{aligned}M_{F1} &= 453 \text{ pounds} \\C_{PF} &= 0.52 \text{ Btu/lb-}^{\circ}\text{R} \\h_{F1} &= 0.285 \text{ Btu/ft}^2\text{-sec-}^{\circ}\text{R} \\T_{GC1_o} &= 821^{\circ}\text{R} \\k_{F2} &= 0.534 \text{ Btu/ft}^2\text{-sec-}^{\circ}\text{R} \\T_{GC2_o} &= 2283^{\circ}\text{R} \\h_{F3} &= 0.714 \text{ Btu/ft}^2\text{-sec-}^{\circ}\text{R} \\T_{GC3_o} &= 3628.75^{\circ}\text{R} \\A &= 545 \text{ ft}^2 \\k &= 0.01388 \text{ Btu-ft/ft}^2\text{-sec-}^{\circ}\text{R} \\A_s &= 343.4 \text{ ft}^2 \\M_{s1} &= 510 \text{ pounds} \\C_{ps} &= 0.52 \text{ Btu/lb-}^{\circ}\text{R} \\t &= 0.01244 \text{ foot} \\K_{F1} &= 0.2543 \\K_{F2} &= 0.4311 \\K_{F3} &= 0.2445 \\K_{S1} &= 0.01094 \\K_{S2} &= 0.01854 \\K_{S3} &= 0.01052 \\\rho_F &= 134.2 \text{ lb/ft}^3 \\r_1 &= 0.00767 \text{ foot} \\r_2 &= 0.009509 \text{ foot}\end{aligned}$$

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$$r_3 = 0.01134 \text{ foot}$$

$$r_4 = 0.015487 \text{ foot}$$

$$r_5 = 0.021945 \text{ foot}$$

$$r_f = 0.001833 \text{ foot}$$

$$r_s = 0.006458 \text{ foot}$$

$$\rho_s = 109 \text{ lb/ft}^3$$

Variables

$$N = \text{reactor power (\%)}$$

$$\delta K = \text{excess core reactivity}$$

$$C_1 = \text{precursor concentration of first delay group (neutrons/cm}^3\text{)}$$

$$\alpha T = \text{negative temperature coefficient } (\delta K/^{\circ}\text{R})$$

$$T = (\bar{T}_F - \bar{T}_{F_0})$$

$$\bar{T}_{F1} = \text{average fuel temperature in 1}^{\text{th}} \text{ core section } (^{\circ}\text{R})$$

$$Q_{F1} = \text{heat generated in 1}^{\text{th}} \text{ core section fuel (Btu/sec)}$$

$$Q_{S1} = \text{heat generated in 1}^{\text{th}} \text{ core section structure (Btu/sec)}$$

$$Q = \text{total heat produced in fuel and structure (Btu/sec)}$$

$$\bar{T}_{S1} = \text{average structure temperature } (^{\circ}\text{R})$$

$$T_1 = \text{average temperature of first cylindrical fuel section (radial) } (^{\circ}\text{R})$$

$$T_2 = \text{average temperature of second cylindrical fuel section (radial) } (^{\circ}\text{R})$$

$$T_3 = \text{average temperature of third cylindrical fuel section (radial) } (^{\circ}\text{R})$$

$$T_4 = \text{average temperature of first cylindrical structure section (radial) } (^{\circ}\text{R})$$

$$T_5 = \text{average temperature of second cylindrical structure section (radial) } (^{\circ}\text{R})$$

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T_G = gas temperature at the axial core position at which temperature distribution is being taken ($^{\circ}\text{R}$)

q = volumetric heat production rate in radial cylindrical fuel sections (Btu/sec-ft^3)

$\bar{T}_F$ = average fuel temperature of three axial core sections ($^{\circ}\text{R}$)

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V. COUNTERMEASURES*

The major nuclear rocket safety problems are:

- (1) Inadvertent criticality in the launch area.
- (2) Excursions induced by shallow water impact.
- (3) Postorbital random re-entry.

Three countermeasure methods are being investigated to attack these problems including an anticriticality destruct system, chemical sensitive additives and thermochemical reactions.

A. ANTICRITICALITY DESTRUCT SYSTEM

The requirement for this countermeasure is clearly defined by Problems 1 and 2, that is, to preclude criticality events resulting from early launch failures. The use of this device as a universal destruct system (i.e., applied to Problems 1, 2, and 3) is also attractive although its applicability to postorbital destruct is not yet established.

1. Destruct System

The function of the anticriticality device is to render the reactor subcritical by destroying its geometry and dispersing its mass with the directed mechanical energy yield of high explosives. The device would be activated when a vehicle malfunction occurs and would merely fragment the core. A conservative reactivity calculation indicates that the core must be fragmented into sections, each of which is less than seven percent of the total core, to preclude criticality when immersed in water. It is apparent that this is not a stringent requirement to impose upon the destruct system.

The anticriticality system is a logical outgrowth of the conventional missile safety subsystem currently employed on all major launchings. The adaptation of the conventional system to a nuclear stage is facilitated by integrating its redundant command receivers and relay circuitry with a high explosive component directed at the reactor core.** The design philosophy is to develop a single destruct package located

*C. Riggs

**The existing systems are attached to primacord to rupture tankage, thereby terminating thrust.

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apart from the engine which could be initiated either by a ground command signal or by selfcontained malfunction sensors within the vehicle. The engine destruct component could be either a mortar injection device or an array of shaped charges.

The mortar-type device shown in Fig. 45, fires a high explosive charge which comes to rest in the center of the core and detonates at that point. It has been estimated that a HE M-56 shell (weighing 10.9 pounds) impacted on brick graphite at a velocity of 1090 fps would penetrate the graphite approximately 38 inches. It is also estimated that a five-pound charge within the shell would resolve the core into subcritical fragments. The penetration of the mortar shell would be particularly sensitive to passage through nuclear stage component supports. The shell should have more or less free access to the top of the engine through a tubular channel if it is to be located at a large distance from the engine.

The second high explosive component, shown in Fig. 46, is an array of 13 shaped charges which fire vertically into the top of the engine focusing on the core. The total weight of this array would be about 100 pounds. This system would set up local fracture patterns which would be propagated throughout the core to reduce it to subcritical fragments.

The high explosive component of this system has been formulated by the U.S. Army Ordnance Corps, Aberdeen Proving Ground, Maryland. Los Alamos Scientific Laboratory has performed some preliminary tests on the effects of high explosives on graphite. A test program for the development of the anticriticality destruct system is found in MND-2515, "Safety Test Program Report, Volume I."

2. Postorbital Destruct

The adaptation of the anticriticality destruct system for post-orbital destruct is feasible only if reasonable amounts of high explosives, when properly directed, can pulverize the core. However, the resultant fragments, when re-entering at orbital velocity, must be reduced into aerosols by aerothermochemical forces above 100,000 feet altitude. Present indications are that graphite particles one-eighth inch in diameter can be consumed on orbital re-entry. However, the reliability of this system is dependent upon radiation damage of the circuitry, fuses and explosives of the destruct system.

B. ADDITIVES

Since graphite is both a high temperature material and a heat sink, it must be attacked by thermochemical means to reduce it to aerosols on postorbital re-entry. It has been proposed that chemical sensitive ad-

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Fig. 45. Conceptual Design--Mortar and High Explosive Charge Destruct System

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Fig. 46. Conceptual Design--Shaped Charge Destruct System

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ditives be placed in the matrices of the core materials to accelerate the thermochemical reactions of graphite with air, steam, oxygen, fluorine, hydrogen peroxide or other chemical agents. The additive development program would be a backup program to facilitate the destruction of the engine on postorbital re-entry situations. The additive, to be compatible with the engine and be effective in its function, must have the following attributes:

- (1) It must be chemically compatible with the graphite-uranium core at elevated temperatures in atmospheres encountered in manufacturing and during reactor operation.
- (2) It should not have a marked adverse effect on the mechanical and heat transfer properties of the core materials (implies a high melting point).
- (3) It should not have a marked adverse effect upon the structural and nuclear properties of the reactor.
- (4) It must contribute to the thermochemical destruction of the core.

Graphite will react with a number of agents to form gaseous reaction products which are readily dispersed at high altitudes. The rate of reaction between graphite and oxidizing agents depends upon reaction temperature, concentration of reactants, surface area and the rate of removal of reaction products.

Additives in the core of the engine might be particularly effective in increasing the surface area of the graphite by:

- (1) Reacting rapidly with the oxidizer and leaving irregular pitted surfaces, resulting in an increase of the surface area.
- (2) Reacting in such a manner as to produce a solid reaction product with a much greater volume than the graphite. This product would expand within the structure and cause mechanical damage to increase the surface area.

Additives could also serve a useful function by absorbing reaction products to prevent any approach to chemical equilibrium which would tend to decrease the reaction rate.

The selection of particular materials for use as additives is difficult because of the limited information on high temperature chemical reactions. However, it is possible to restrict the materials considered to those with a melting point above the maximum operating temperature of

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the reactor since it is probable that materials with lower melting points would be lost and would adversely affect the mechanical properties of the fuel elements. For preliminary screening purposes the minimum melting point of an acceptable additive was set at 4000° F. Table 4 shows possible additives, their melting points and the maximum loading in gm/cc of fuel. The maximum loading was calculated as:

$$\rho_{\max} = \frac{(0.062) (\text{atomic weight})}{(\text{thermal neutron capture cross section})}$$

The constant, 0.062, is based upon amounts of additives which will produce no more than a five percent loss in the reactivity of the core. Additional screening from the 52 materials shown in Table 4 will eliminate materials which are not compatible with graphite, those which do not make significant contributions and those which act to decrease reactivity the most. On the basis of such evaluations, it should be possible to select several of the most favorable additives for future study.

C. THERMOCHEMICAL DESTRUCT SYSTEM

The problem of postorbital random re-entry is a difficult one since the nuclear rocket will not completely vaporize on re-entry, and its radioactive fragments will survive to impact at a random location. The engine is a very large heat sink and will absorb about 120,000 megawatt-seconds of energy in raising it from its operating temperature to its sublimation temperature and providing its heat of sublimation. Since it cannot be effectively destroyed by purely thermal means by the sources of heat available including afterheat, heat generated by running the engine without a coolant, excursions or aerodynamic heating, other means must be investigated. Thermochemical methods appear very promising in accomplishing this end because enough heat is available to trigger thermochemical reactions and because graphite is a material which will react with a number of chemicals at elevated temperatures.

Any chemical reaction that may be effective in destroying the reactor is likely to require an initially hot reactor. During normal operation the surface temperature of the fuel elements at the core exit reaches 2450° K. If the core is not cooled at shutdown, the afterheat would raise its average temperature to 3330° K in the first nine seconds. This temperature falls short of the vaporization temperature (~4700° K) but will initiate thermochemical reactions. This effect can be further enhanced by either running the engine without a coolant or by inducing an excursion. However, since the engine will shut itself down after some portion of the core has been vaporized, it is not possible to vaporize 100% by this method.

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TABLE 4

Materials of Interest in the Additive Program

<u>Material</u>	<u>Reported Melting Point (°F)</u>	<u>Maximum Permitted Loading* (metallic construction gm/cc fuel)</u>
W	6170	0.594
Re	5756	0.134
Os	5432	0.771
Ta	5425	0.534
Mo	4732	2.203
Nb	4379	5.009
Ir	4430	0.027
Ru	4082	2.449
HfC	7030	0.105
TaC	7010	0.534
Ta ₂ C	6152	0.534
ZrC	6380	31.42
NbC	6330, 6800	5.009
Nb ₂ C	5900, 4650	5.009
TiC	5700, 5882	0.512
VC	5120	0.634
Al ₄ C ₃	5072	7.273
WC	4766, 5190	0.594
W ₂ C	4946, 5178	0.594
MoC	4877	2.203
Mo ₂ C	4870, 4650	2.203
Th ₂ C	4811	1.903
ThC	4757	1.903
SiC	4710, 5126 (decomposes)	10.88
HfN	5990	0.105
TaN	5600	0.534

TABLE 4 (continued)

<u>Material</u>	<u>Reported Melting Point (°F)</u>	<u>Maximum Permitted Loading* (metallic construction gm/cc fuel)</u>
ZrN	5400	31.42
TiN	5342, 5800	0.512
ScN	4800	0.116
ThN	4766	1.903
Th ₃ N ₄	4280	1.903
AlN	4060, 4352 (sublimes)	7.273
VN	4280	0.634
Be ₃ N ₂	4000	55.88
ThO ₂	5522, 5970	1.903
MgO	5070	23.93
SrO . ZrO ₂	5070	4.490 (Sr)
ZrO ₂	4622, 4920	31.42
CeO ₂	4712	11.90
CaO	4660, 4712	5.648
ZrO ₂ . SiO ₂	4622	10.88 (Si)
BeO	4570, 4658	55.88
3 BeO . 2 ZrO ₂	4590	31.42 (Zr)
SrO	4406	4.490
Y ₂ O ₃	4380	4.556
CaO . ZrO ₂	4230	5.648 (Ca)
Cr ₂ O ₃	4127, 4410	1.040
CeS	4442	11.90
ThS	4000	1.903
BaS	4000	7.097
HfS	4000	0.105
Zr ₃ Si ₂ or Zr ₆ Si ₅	4010 to 4080	10.88 (Si)

Where two metallic constituents are present in a compound the value reported is for the element with lowest permitted loading.

*Permitted loading calculated as $\sigma_{\max} = \frac{0.062 \times \text{atomic weight}}{\sigma_A}$

1. Carbon-Oxygen Reactions

Hot carbon combines with oxygen in two possible reactions:

The masses of the elements required for the reactions are in the ratios determined by their respective molecular weights which are indicated with the equations. The mass of the core and graphite reflector is about 3800 pounds (1.74×10^6 gm, 1.45×10^5 moles). The mass of oxygen required for the first reaction is 10,134 pounds; for the second 5070 pounds.

The second reaction is favored at high temperatures and would prevail if oxygen is forced into the hot reactor. It is not to be expected that 100% efficiency of the reaction can be obtained, but the configuration of the reactor favors the achievement of a high efficiency.

Both reactions are exothermic, i.e., produce heat. The combustion of 3800 pounds of graphite by the second reaction will produce 3.89×10^9 cal (1.52×10^7 Btu, 1.60×10^4 mw-sec). The heat liberated maintains a condition that favors the second reaction and is available for melting the beryllium reflector and aluminum pressure vessel. The passage of oxygen through the system removes reaction products so that the reaction can proceed.

Irradiated graphite appears to be more susceptible to oxidation than does unirradiated graphite.

2. Carbon-Water Reactions

Hot carbon reacts with water (steam) in two ways:

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The mass of water required to react with 3800 pounds of graphite stoichiometrically according to Eq. (4) is 5700 pounds, a slight weight penalty compared to the use of oxygen. Both of the reactions are endothermic, i.e., require heat to be furnished if the reaction is to proceed to the right. The quantity of heat required for the reaction with 3800 pounds of graphite according to Eq. (4) is 4.58×10^9 cal (1.82×10^7 Btu, 1.92×10^4 mw-sec). The fact that the reaction is endothermic renders it more susceptible to control. The heat required for the reaction is supplied by the reactor which will be critical at a power level controllable by the rate of water flow.

Equation (4) is favored by high temperature; the effect is greater than the corresponding differentiation in the case of oxygen. Equation (4) represents the reaction that is applied in the universal and long established industrial production of water gas. There is extensive literature dealing with the control of equilibrium conditions, and temperature, pressure and flow rate for optimization of the reaction. In the production of water gas the operation has to be cycled. After a flow of steam over the hot carbon for a period of time the carbon temperature has fallen to a point, the reaction according to Eq. (3) is increasing. The steam is shut off and air is passed over the carbon until the exothermic reaction with oxygen (Eqs. (1) and (2)) raises the temperature. In the reactor the temperature is maintained by the fission process and the reaction can be continuous.

3. Carbide Reactions

In the preceding discussion of the use of steam, attention has been directed entirely toward its reactions with carbon, but there are other considerations which appear to indicate the desirability of water as the means of destroying the reactor. The carbides of uranium react with water with the formation of methane (CH_4), and perhaps acetylene (C_2H_2), even at moderate temperatures. Thus, steam passing through the coolant holes in the fuel elements will react rapidly with the fuel. This can be expected to expose and loosen grains of the associated graphite and allow it to be carried away mechanically without the necessity of chemical action. The combined effects of the carbide reaction and the carbon reaction expressed by Eq. (4) should be sufficient to remove the fuel from the reactor, perhaps with a lesser mass of water than is required to combine stoichiometrically with the corresponding mass of carbon. The exact behavior of the system and the optimum conditions can only be determined by tests carried out on a configuration closely simulating that of the reactor.

In a reactor core composed of fuel rods in a matrix of graphite modules it is conceivable that the reactor could be cleared of fuel and the associated fission products by the mechanism described in the

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preceding paragraph. The destruction of the graphite modules would then be dependent on Eq. (4), and the heat might be insufficient to do this. The radiological hazards of the nuclear engine re-entry would be removed, but the mechanical hazard of impact might remain. For a reactor core in which the core is homogeneous, i.e., in which all the graphite is loaded with fuel, the steam may be expected to corrode and erode the entire core.

Several other metallic carbides react with water with the production of methane, acetylene or other hydrocarbons. (A few are dangerously explosive.) Aluminum carbide reacts easily with water, and a complex carbide of aluminum and uranium is even more reactive than either of the simple carbides. Beryllium carbide reacts very easily with water; in fact the reaction takes place in moist air and the incorporation of the beryllium carbide in graphite might present production difficulties. However, since beryllium is a good moderator, its use would incur little penalty or might improve the moderating properties of the core.

The reactions of the various carbides with water are generally exothermic and would supply part of the heat required to maintain the endothermic reaction with carbon. If oxygen were injected along with steam, it is possible that additional heat to maintain the reaction would be produced by the combustion of the carbon monoxide and of the hydrocarbons.

4. Other Compounds

Various other compounds may be useful in promoting thermochemical reactions, such as UBe_{13} reacting with oxygen and with water. When there is a mixture of components, there may be formed solid solutions, inter-metallic compounds and eutectics. Such systems may be favorable or unfavorable for the construction of a reactor that is susceptible to destruction by thermochemical reactions. It is reported that it has been possible to prepare a U-Mo-C system with three percent graphite, such that the uranium present in the metallic state is alloyed with two percent molybdenum and surrounded by a carbide network. USi appears to have promise for burnup with oxygen but the U-Si-C system has not been extensively examined. The systems formed by iron or nickel with uranium and carbon have not been investigated.

5. Other Liquid Chemicals

Other fluids instead of, or in addition to, water and oxygen may be useful in thermochemical destruction of the reactor. Hydrogen peroxide may combine the effects of water and oxygen. Fluorine reacts with uranium and with hot carbon. It is reported to react explosively with uranium carbide. For a stoichiometric reaction fluorine suffers in comparison with oxygen since the masses required are in the ratio of 19 to 8. It may be helpful for removing the cladding of the coolant channels.

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6. Water Shield

In case it is found desirable to use water as the fluid for thermochemical reactions it can, in part, be carried usefully as the shielding for the instrumentation and propellant tanks. It can be carried for a longer time than the cryogenic liquids, hydrogen and oxygen.

7. Summary

It is probable that a well conceived test program can develop methods whereby the fuel elements and structural graphite of the nuclear engine can be reduced to aerosols by thermochemical reactions. It is possible that the effectiveness of such reactions can be enhanced by incorporation in the graphite of materials more reactive than the graphite alone.

Heat for vaporization of the reactor core can come from afterheat, operation without coolant, an excursion, and from aerodynamics heating. The heat available appears to be insufficient to completely vaporize the reactor. It can be used to promote chemical reactions with any fluid which may be injected into the reactor. Sources of heat that then become available are:

- (1) The heat of the reaction, if it is exothermic.
- (2) Maintenance of criticality, if the fluid is a moderator.
- (3) From combustion of the reaction products.

Chemical substances which may be injected as fluids into the reactor core are oxygen, water, hydrogen peroxide and fluorine.

Chemicals which may be incorporated in the structural graphite to enhance its destruction are the carbides of aluminum, beryllium and other metals, USi, and UBe₁₃, and perhaps many others which have not been studied.

The principal reactions which are being considered are the oxidation of graphite by oxygen, water, hydrogen peroxide and fluorine and the reaction of water with the carbides producing a hydrocarbon and probably bringing about a mechanical softening of the structure.

Water is attractive as the fluid to be used in the chemical destruction of the reactor for several reasons. It enters into various types of reactions. It can be carried more easily and for a longer time than cryogenic liquids. It can be carried in such a way as to provide shielding so that the weight penalty is reduced.

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VI. FISSION PRODUCT INVENTORY AND ACTIVATION ANALYSIS*

A. FISSION PRODUCT INVENTORY

The IBM computer program utilized to compute the fission product inventory assumes no depletion of U-235 fuel and no leakage of fission products from the nuclear engine. It does account for depletion of chain members by neutron capture.

The successful ballistic and preorbital startup missions have been run on the computer and their fission product histories obtained. The gross fission product inventory (GFPI) for both missions is reproduced in Fig. 47. The abscissa represents the time beginning at startup of the nuclear engine and extending to ~30 years of decay time. It should be pointed out that in view of the uncertainty in the startup procedure the computations were based on a linear startup, from zero to full power, over a 20-second period. The total gamma-beta decay power history for both missions is plotted in Fig. 48. These data represent the after-heat energy generated by fission product decay and, when combined with the energy generated by fission due to delayed neutrons, will constitute the afterheat energy input for analog studies to determine the post-shut-down temperature profiles of the engine.

The release of fission products from the nuclear engine can occur by a variety of mechanisms. That is, during normal operation of the engine, fission products will be released to the effluent stream by mechanical erosion and chemical corrosion, surface release induced by passage of recoils through open surfaces, and by their diffusion or diffusion of their precursors. During abnormal operation of the engine, such as an excursion, a portion of the core will be vaporized resulting primarily in an undifferentiated release. The mechanism of release will be influenced by the environmental conditions as well. In any case, an estimate of the rate of release by analytical methods is complex and will probably have to be measured during static testing of the engine. Once this is known, an estimate of the consequences can be obtained.

Table 5 lists some of the nuclides which might appear in fission product releases from the engine. The values are based on a total integrated power of 1.45×10^6 megawatts. Populations for the individual nuclides are shown for the start and termination of full power operation and for various decay times.

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Fig. 47. Gross Fission Product Inventory

Fig. 48. Total Gamma and Beta Power

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TABLE 5

Population of Various Nuclides as Function of Time for Preorbital Starting Mission

Isotope	T _{1/2}	Population 20 Seconds After Startup	Population at Shutdown	Population at Various Decay Times				
				15 sec	300 sec	8800 sec	99,000 sec	10 ⁸ sec
Halogens								
Sb-124	60d	6.465 x 10 ⁶	1.659 x 10 ¹¹	1.659 x 10 ¹¹	1.659 x 10 ¹¹	1.657 x 10 ¹¹	1.638 x 10 ¹¹	2.515 x 10 ⁵
-125	2y	6.668 x 10 ¹⁴	1.994 x 10 ¹⁸	2.046 x 10 ¹⁸	2.888 x 10 ¹⁸	4.990 x 10 ¹⁸	5.363 x 10 ¹⁸	4.610 x 10 ¹⁸
-127	3.7d	4.981 x 10 ¹⁶	1.068 x 10 ¹⁹	1.087 x 10 ¹⁹	1.444 x 10 ¹⁹	7.853 x 10 ¹⁹	9.306 x 10 ¹⁹	0
Te-125 ^m	58d	2.165 x 10 ¹¹	2.684 x 10 ¹²	2.718 x 10 ¹²	3.513 x 10 ¹²	4.973 x 10 ¹³	5.772 x 10 ¹⁴	4.047 x 10 ¹⁶
-127 ^m	105d	7.733 x 10 ¹⁶	7.201 x 10 ¹⁸	7.202 x 10 ¹⁸	7.202 x 10 ¹⁸	7.345 x 10 ¹⁸	1.023 x 10 ¹⁹	1.242 x 10 ¹⁶
-127	9.3h	1.031 x 10 ¹²	7.194 x 10 ¹⁵	7.472 x 10 ¹⁵	1.370 x 10 ¹⁶	7.342 x 10 ¹⁷	7.084 x 10 ¹⁸	4.602 x 10 ¹³
-129 ^m	33d	4.926 x 10 ¹⁴	2.068 x 10 ¹⁸	2.133 x 10 ¹⁸	3.360 x 10 ¹⁸	3.451 x 10 ¹⁹	1.040 x 10 ²⁰	3.029 x 10 ⁹
-129	1.1h	1.535 x 10 ¹⁵	6.262 x 10 ¹⁸	6.452 x 10 ¹⁸	9.988 x 10 ¹⁸	5.470 x 10 ¹⁹	2.068 x 10 ¹⁸	4.608 x 10 ⁶
-132	78h	1.443 x 10 ¹⁸	1.304 x 10 ²¹	1.328 x 10 ²¹	1.528 x 10 ²¹	1.540 x 10 ²¹	1.229 x 10 ²¹	0
I-129	1.6 x 10 ⁷ y	1.665 x 10 ¹²	3.159 x 10 ¹⁷	3.308 x 10 ¹⁷	6.998 x 10 ¹⁷	5.521 x 10 ¹⁹	3.368 x 10 ²⁰	4.500 x 10 ²⁰
-131	8.05d	3.780 x 10 ¹⁵	4.394 x 10 ¹⁹	4.567 x 10 ¹⁹	8.445 x 10 ¹⁹	1.048 x 10 ²¹	1.090 x 10 ²¹	0
-132	2.3h	2.843 x 10 ¹³	1.287 x 10 ¹⁸	1.334 x 10 ¹⁸	2.312 x 10 ¹⁸	2.510 x 10 ¹⁹	3.954 x 10 ¹⁹	0
Noble Gases								
Kr-85	10.4y	1.6096 x 10 ¹³	1.626 x 10 ¹⁸	1.689 x 10 ¹⁸	3.065 x 10 ¹⁸	4.421 x 10 ¹⁹	1.333 x 10 ²⁰	1.090 x 10 ²⁰
Xe-131 ^m	12d	1.650 x 10 ¹²	1.203 x 10 ¹⁴	1.268 x 10 ¹⁴	3.059 x 10 ¹⁴	6.051 x 10 ¹⁶	9.688 x 10 ¹⁷	0
-133 ^m	2.3d	6.343 x 10 ¹²	6.103 x 10 ¹⁶	6.335 x 10 ¹⁶	1.144 x 10 ¹⁷	3.597 x 10 ¹⁸	3.421 x 10 ¹⁹	0
-133	5.27d	2.613 x 10 ¹⁴	2.483 x 10 ¹⁸	2.578 x 10 ¹⁸	4.656 x 10 ¹⁸	1.475 x 10 ²⁰	1.550 x 10 ²¹	0
Alkali Earths								
Ru-86	18.6d	1.35 x 10 ¹⁴	1.260 x 10 ¹⁶	1.260 x 10 ¹⁶	1.260 x 10 ¹⁰	1.255 x 10 ¹⁶	1.210 x 10 ¹⁶	0
-87	4.8 x 10 ¹⁰ y	1.51 x 10 ¹⁵	6.767 x 10 ¹⁹	6.994 x 10 ¹⁹	1.154 x 10 ²⁰	9.025 x 10 ²⁰	1.215 x 10 ²¹	1.215 x 10 ²¹
Cs-135	2 x 10 ⁶ y	3.051 x 10 ¹⁴	1.117 x 10 ¹⁸	1.150 x 10 ¹⁸	1.828 x 10 ¹⁸	6.947 x 10 ¹⁹	1.918 x 10 ²¹	2.739 x 10 ²¹
-136	13d	2.899 x 10 ¹⁶	2.699 x 10 ¹⁸	2.700 x 10 ¹⁸	2.699 x 10 ¹⁸	2.685 x 10 ¹⁸	2.540 x 10 ¹⁸	0
-137	30y	2.996 x 10 ¹⁷	1.688 x 10 ²¹	1.727 x 10 ²¹	2.249 x 10 ²¹	2.657 x 10 ²¹	2.657 x 10 ²¹	2.449 x 10 ²¹
Sr-89	51d	1.116 x 10 ¹⁶	3.717 x 10 ²⁰	3.848 x 10 ²⁰	6.555 x 10 ²⁰	2.155 x 10 ²¹	2.127 x 10 ²¹	3.282 x 10 ¹⁴
-90	28y	2.701 x 10 ¹⁷	1.876 x 10 ²¹	1.916 x 10 ²¹	2.421 x 10 ²¹	2.655 x 10 ²¹	2.655 x 10 ²¹	2.454 x 10 ²¹
Ba-137 ^m	2.6m	1.338 x 10 ⁹	1.946 x 10 ¹⁴	2.005 x 10 ¹⁴	3.064 x 10 ¹⁴	4.476 x 10 ¹⁴	4.476 x 10 ¹⁴	4.127 x 10 ¹⁴
-140	12.8d	2.958 x 10 ¹⁸	2.517 x 10 ²¹	2.558 x 10 ²¹	2.819 x 10 ²¹	2.819 x 10 ²¹	2.664 x 10 ²¹	0
-142	11m	1.217 x 10 ¹⁹	1.142 x 10 ²¹	1.132 x 10 ²¹	7.372 x 10 ²⁰	5.575 x 10 ¹³	0	0

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TABLE 5 (continued)

Isotope	T _{1/2}	Population 20 Seconds After Startup	Population at Shutdown	Population at Various Decay Times				
				15 sec	300 sec	8800 sec	99,000 sec	10 ⁸ sec
Rare Earths								
Y-89 ^m	16s	1.067 x 10 ¹⁰	1.617 x 10 ¹⁶	1.703 x 10 ¹⁶	3.983 x 10 ¹⁶	2.597 x 10 ¹⁸	3.287 x 10 ¹⁹	2.160 x 10 ²¹
-90	64.2h	1.259 x 10 ⁹	5.382 x 10 ¹⁴	5.598 x 10 ¹⁴	1.045 x 10 ¹⁵	1.847 x 10 ¹⁶	1.786 x 10 ¹⁷	6.486 x 10 ¹⁷
-91 ^m	50m	8.314 x 10 ¹³	2.171 x 10 ¹⁸	2.263 x 10 ¹⁸	4.404 x 10 ¹⁸	6.994 x 10 ¹⁹	1.455 x 10 ¹⁹	0
La-140	40.2h	2.042 x 10 ¹³	6.610 x 10 ¹⁷	6.842 x 10 ¹⁷	1.164 x 10 ¹⁸	1.588 x 10 ¹⁹	1.357 x 10 ²⁰	0
Ce-141	32.5d	9.557 x 10 ¹⁴	1.200 x 10 ¹⁹	1.253 x 10 ¹⁹	2.517 x 10 ¹⁹	8.867 x 10 ²⁰	2.630 x 10 ²¹	3.412 x 10 ¹⁰
-144	285d	2.788 x 10 ¹⁹	2.742 x 10 ²¹	2.745 x 10 ²¹	2.745 x 10 ²¹	2.744 x 10 ²¹	2.738 x 10 ²¹	1.737 x 10 ²⁰
Metals								
Ag-109 ^m	39s	2.267 x 10 ¹⁰	7.580 x 10 ¹⁴	7.826 x 10 ¹⁴	1.264 x 10 ¹⁵	7.726 x 10 ¹⁵	2.668 x 10 ¹⁵	0
-111	7.5d	4.551 x 10 ¹⁴	1.693 x 10 ¹⁸	1.742 x 10 ¹⁸	2.610 x 10 ¹⁸	7.974 x 10 ¹⁸	7.306 x 10 ¹⁸	0
Pd-107	7 x 10 ⁶ y	7.574 x 10 ¹⁹	5.368 x 10 ²⁰	5.371 x 10 ²⁰	5.436 x 10 ²⁰	6.183 x 10 ²⁰	6.202 x 10 ²⁰	6.202 x 10 ²⁰
-109	13.6h	2.608 x 10 ¹⁴	1.063 x 10 ¹⁸	1.095 x 10 ¹⁸	1.694 x 10 ¹⁸	9.645 x 10 ¹⁸	3.322 x 10 ¹⁸	0
-112	21h	5.315 x 10 ¹⁶	4.929 x 10 ¹⁸	4.929 x 10 ¹⁸	4.916 x 10 ¹⁸	4.547 x 10 ¹⁸	1.992 x 10 ¹⁸	0
Sn-119 ^m	175d	4.832 x 10 ¹⁶	4.500 x 10 ¹⁸	4.500 x 10 ¹⁸	4.500 x 10 ¹⁸	4.499 x 10 ¹⁸	4.488 x 10 ¹⁸	2.451 x 10 ¹⁷
-121	27h	6.765 x 10 ¹⁶	6.280 x 10 ¹⁸	6.279 x 10 ¹⁸	6.267 x 10 ¹⁸	5.905 x 10 ¹⁸	3.145 x 10 ¹⁸	0
-123 ^m	125d	5.799 x 10 ¹⁵	5.400 x 10 ¹⁷	5.400 x 10 ¹⁷	5.400 x 10 ¹⁷	5.397 x 10 ¹⁷	5.368 x 10 ¹⁷	1.187 x 10 ¹⁵
-125	9.4d	5.799 x 10 ¹⁶	5.398 x 10 ¹⁸	5.398 x 10 ¹⁸	5.397 x 10 ¹⁸	5.360 x 10 ¹⁸	4.983 x 10 ¹⁸	0
Cd-113 ^m	14y	1.024 x 10 ³	5.427 x 10 ⁵	5.427 x 10 ⁵	5.427 x 10 ⁵	5.427 x 10 ⁵	5.425 x 10 ⁵	3.530 x 10 ⁵
-115 ^m	44d	1.966 x 10 ¹³	7.209 x 10 ¹⁶	7.416 x 10 ¹⁶	1.106 x 10 ¹⁶	3.160 x 10 ¹⁷	3.123 x 10 ¹⁷	2.659 x 10 ⁹
-115	2.3d	2.730 x 10 ¹⁴	9.997 x 10 ¹⁷	1.028 x 10 ¹⁸	1.533 x 10 ¹⁸	4.274 x 10 ¹⁸	3.098 x 10 ¹⁸	0

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B. NEUTRON ACTIVATION OF NUCLEAR ENGINE COMPONENTS

The normal power level of the nuclear engine is high compared to those of conventional reactor systems. The inherent thermal neutron flux is also high and will induce appreciable activity in engine component materials. While the engine is intact, the dose rates emanating from the activated materials will be overshadowed by those resulting from decay of fission products. There may be instances, however, when the engine is not intact, i.e., the engine is intentionally or accidentally fragmented. When this occurs, one needs to know what precautions are necessary to safely handle these fragments. This will be dictated by the degree of activity induced in the materials.

The induced activity can be closely estimated by considering only (n, γ) reactions for thermal neutrons. The basic expression for the formation of radionuclides as a result of thermal neutron bombardment is:

$$N = \phi \sigma_{\text{act}} N_0 \text{ (interactions/second),} \quad (1)$$

where N_0 is the total number of atoms exposed to an average thermal neutron flux of $\phi \text{ n/cm}^2 \text{ sec}$, and σ_{act} is the isotopic activation cross section. The rate of change of the number of atoms of a radionuclide is given by:

$$\frac{dN}{dT} = \phi \sigma_{\text{act}} N_0 - \lambda N \quad (2)$$

where λ is the isotopic decay constant and T the irradiation time.

The solution of Eq. (2), noting that $N = 0$ when $T = 0$, is:

$$N = \frac{\phi \sigma_{\text{act}} N_0}{\lambda} (1 - e^{-\lambda T}) \quad (3)$$

The activity, in curies, is expressed as:

$$A = \frac{\phi \sigma_{\text{act}} N_0}{3.7 \times 10^{10}} (1 - e^{-\lambda T}) e^{-\lambda t}, \quad (4)$$

where t is the decay time. For a material of weight W the activity of the i^{th} isotope is:

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$$A = \frac{WN' \phi}{3.7 \times 10^{10}} \sum_i \frac{f_1 f_2 \sigma_{act}}{M_1} (1 - e^{-\lambda_i T}) e^{-\lambda_i t}, \quad (5)$$

where

- N' - Avogadro's number
- f_1 - fraction of an element in the material
- f_2 - fraction of i^{th} isotope in the natural state of the element
- M_1 - molecular weight of i^{th} isotope

The dose rate, D , in air for gamma radiation can be estimated approximately by:

$$D \approx \frac{6 \times 10^3 A E}{d^2} \text{ mr/hr} \quad (6)$$

where A is the source strength in curies, E is the gamma photon energy in Mev and d is the distance from the source in feet. The limitations on this expression are:

- (1) The radioactive source is assumed to be a point source.
- (2) The energy absorption coefficient, in air, is assumed constant at $3.35 \times 10^{-5} \text{ cm}^{-1}$. This is a fair approximation since it varies only between 3×10^{-5} and $3.7 \times 10^{-5} \text{ cm}^{-1}$ for gamma energies between 0.07 and 2 Mev.

Combining Eqs. (5) and (6) results in the expression

$$D = \frac{6 \times 10^3 W N' \phi}{d^2 3.7 \times 10^{10}} \sum_i \frac{E_1 f_1 f_2 \sigma_{act}}{M_1} (1 - e^{-\lambda_i T}) e^{-\lambda_i t} \quad (7)$$

The nuclear engine is composed primarily of aluminum, beryllium, graphite and Inconel X. Since the impurity content of the first three materials is not known, typical reactor grade materials were chosen and investigated. Each material is considered separately in the following pages. Gamma dose rates were computed for one gram of each of the materials.*

*Based upon a power level of 1000 megawatts and an operating time of 313 seconds.

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1. Aluminum Pressure Vessel

The aluminum pressure vessel was assumed to be fabricated of Aluminum 6063. It will have an average thermal neutron flux of $\sim 2 \times 10^{14}$ n/cm²/sec for a 313-second irradiation time, this is the full-power operating time for the nuclear engine. Table 6 shows the composition of Aluminum 6063, activated component, activation product and the necessary data for computing gamma dose rates by means of Eq. (7); gamma dose rates are shown for various decay times (t).

Inspection of Table 6 shows that at shutdown of the nuclear engine the largest contributor of gamma dose is Al-28, but because of its short half-life (2.3 minutes), its contribution is rapidly diminished. After 1000 hours of decay the only significant radioisotopes are Iron-59, Chromium-51 and Zinc-65.

It should be pointed out that the aluminum support plate, assuming that it is also fabricated of Aluminum 6063, would contain a source strength 1/20, that of the aluminum pressure vessel. This is based on the fact that the average thermal neutron flux in the area of the support plate is $\sim 10^{13}$ n/cm²/sec.

2. Nozzle

The nozzle is fabricated of Inconel X and is exposed to a thermal neutron flux of 10^{13} n/cm²/sec. This flux value is probably high but will give a conservative estimate of the induced activity. Table 7 contains the same type of data as Table 6. At shutdown of the nuclear engine the gamma dose rate from one gram of Inconel X is ~ 130 mr/hr. After 1000 hours of decay, the dose rate has decreased to $\sim 1.6 \times 10^{-3}$ mr/hr.

3. Graphite Reflector Cylinder

The usual impurities found in reactor-grade graphite are:*

Aluminum	Nickel
Boron	Nitrogen
Calcium	Oxygen
Chromium	Potassium
Copper	Silicon
Hydrogen	Silver
Iron	Sodium
Lead	Titanium
Magnesium	Vanadium
Manganese	

*Graphite G is used in KIWI.

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TABLE 6
Thermal Neutron Activation of Al 6063

Component	f_1	Activated Component	f_2	Activation Products and Characteristics			Gamma Dose Rate (mr/hr) at One Foot From One Gram of Al 6063, for Various Decay Times (t)				
				Activation Product	$T_{1/2}$	-Energy (Mev)	$t = 0$ hr	$t = 1$ hr	$t = 10$ hr	$t = 100$ hr	$t = 1000$ hr
Al	0.979	Al-27	1.0	Al-28	2.3m	1.78^{100*}	2.1×10^5	6×10^{-3}			
Mg	0.007	Mg-26	0.113	Mg-27	9.5m	0.83^{70} , 1.01^{30}	8.3	1.12×10^{-1}			
Si	0.004	Si-30	0.0305	Si-31	2.62h	$1.26^{0.07}$	6.9×10^{-3}	5.3×10^{-3}	5.1×10^{-4}		
Fe	0.0035	Fe-58	0.0033	Fe-59	45d	1.1^{56} , 1.29^{41} , 0.19^3	2.1×10^{-4}	2.1×10^{-4}	2×10^{-4}	1.9×10^{-4}	1.1×10^{-4}
Cr	0.001	Cr-50	0.044	Cr-51	27.8d	0.32^{10}	5.43×10^{-4}	5.43×10^{-4}	5.4×10^{-4}	4.9×10^{-4}	2×10^{-4}
Cu	0.001	Cu-63	0.691	Cu-64	12.9h	1.34^1	5.2×10^{-2}	5×10^{-2}	2.7×10^{-2}	2.3×10^{-4}	
	0.001	Cu-65	0.31	Cu-66	5.1m	1.04^9	7.5	2.25×10^{-3}			
Mn	0.001	Mn-55	1.0	Mn-56	2.58h	0.84^{99} , 1.81^{23} , 2.11^{14}	1.7×10^2	1.3×10^2	11.4	3.2×10^{-10}	
Ti	0.001	Ti-50	0.0534	Ti-51	5.8m	0.32^{96} , 0.93^4 , 0.61^1	0.41	3.2×10^{-4}			
Zn	0.001	Zn-64	0.489	Zn-65	245d	1.11^{50}	4.2×10^{-4}	4.2×10^{-4}	4.2×10^{-4}	4.1×10^{-4}	3.7×10^{-4}
	0.001	Zn-68	0.187	Zn-69m	13.9h	0.44^{100}	10^{-2}	10^{-2}	6.1×10^{-3}	7.2×10^{-5}	
	0.001	Zn-70**	0.0069	Zn-71m	3h	0.61^{100} , 0.48^{100} , 0.38^{100}					
				Zn-71	2.2m	0.51^{100}	4.8×10^{-2}	1.8×10^{-10}			

*Superscripts indicate number of gamma photons emitted per 100 disintegrations.

**Isotopic activation cross section unknown.

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TABLE 7
Thermal Neutron Activation of Inconel X

Component	f_1	Activated Component	f_2	Activation Products and Characteristics			Gamma Dose Rate (mr/hr) at One Foot From One Gram of Inconel X, for Various Decay Times (t)				
				Activation Product	$T_{1/2}$	γ -Energy (Mev)	$t = 0$ hr	$t = 1$ hr	$t = 10$ hr	$t = 100$ hr	$t = 1000$ hr
Ni	0.7	Ni-64	0.011	Ni-65	2.56h	1.49^{20} , 1.11^{10} , 0.37^{3*}	2.92	2.23	1.95×10^{-1}	5×10^{-12}	
Cr	0.15	Cr-50	0.044	Cr-51	27.8d	0.32^{10}	4.07×10^{-3}	4.07×10^{-3}	4.07×10^{-3}	3.68×10^{-3}	1.5×10^{-3}
Fe	0.07	Fe-58	0.0033	Fe-59	45d	1.1^{56} , 1.29^{44} , 0.19^3	2.1×10^{-4}	2.1×10^{-4}	2.1×10^{-4}	1.97×10^{-4}	1.1×10^{-4}
Mn	0.006	Mn-55	1.0	Mn-56	2.58h	0.84^{99} , 1.81^{23} , 2.11^{14}	5×10^1	3.9×10^1	3.45	9.6×10^{-11}	
Si	0.005	Si-30	0.03	Si-31	2.62h	$1.26^{0.07}$	4.3×10^{-4}	3.3×10^{-4}	3.05×10^{-5}		
Nb	0.01	Nb-93	1.0	Nb-94m	6.6m	0.042^{100} , $0.87^{0.1}$	1.86	3.35×10^{-3}			
Ti	0.025	Ti-50	0.0534	Ti-51	5.8m	0.32^{96} , 0.93^4 , 0.61^1	5.1×10^{-1}	3.82×10^{-4}			
Al	0.007	Al-27	1.0	Al-28	2.3m	1.78^{100}	7.5×10^1	2.15×10^{-6}			

*Superscripts indicate number of gamma photons emitted per 100 disintegrations.

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Ordinarily, they are present in no more than a few parts per million. By comparing the possible activation products on the basis of half life, isotopic activation cross section, energy of emitted gamma photon and quantity of the parent isotope in the natural element one can estimate the degree of induced activity of a close approximation by considering only Al-28, Mn-56, Ag-110m, Na-24 and V-52. The average thermal neutron flux in the graphite reflector is 4×10^{14} n/cm²/sec. The results of the calculations for these isotopes are summarized in Table 8. It was assumed that each element was present at 10 ppm.

At shutdown of the nuclear engine, the gamma dose rate from one gram of graphite is 1.37 mr/hr. It rapidly decreases to 6.7×10^{-4} mr/hr after 1000 hours of decay.

4. Beryllium Reflector

The grade of beryllium used at the Materials Testing Reactor (MTR) is required to meet the following specifications:

Total beryllium	98.0% minimum
BeO	1.5% maximum
Be ₂ C	2500 ppm
Mg	3000 ppm
Fe	2000 ppm
Al	1500 ppm
Si	700 ppm
Ni	500 ppm
Cu	500 ppm
Mn	250 ppm
Zn	150 ppm
Ag	5 ppm
Li	3 ppm
Co	2 ppm
B	2 ppm

From information obtained at LASL, there will also be present 4 to 9 ppm of scandium.* Using the same basis as that for graphite, the components can be reduced to Ag-110m, Mn-56, Al-28, Sc-46, Co-60m and Zn-65. The results of the analysis are summarized in Table 9. At shutdown of the nuclear engine the gamma dose rate from one gram of beryllium is 670 mr/hr and after 1000 hours of decay it has decreased to 4.5×10^{-3} mr/hr.

*LASL specifications call for only 0.2 ppm Sc in beryllium.

TABLE 8

Thermal Neutron Activation of Graphite

<u>Isotope</u>	<u>T_{1/2}</u>	<u>Gamma Dose Rate (mr/hr) at One Foot From One Gram of Graphite, for Various Decay Times (t)</u>				
		<u>t = 0 hr</u>	<u>t = 1 hr</u>	<u>t = 10 hr</u>	<u>t = 100 hr</u>	<u>t = 1000 hr</u>
Aluminum-28	2.3m	4.2	6.5×10^{-8}			
Manganese-56	2.58h	1.6	1.2	1×10^{-1}	3.5×10^{-12}	
Silver-110m	253d	7.7×10^{-5}	7.7×10^{-5}	7.7×10^{-5}	7.6×10^{-5}	6.7×10^{-5}
Sodium-24	15h	1.54×10^{-1}	1.47×10^{-1}	9.7×10^{-2}	1.54×10^{-3}	
Vanadium-52	3.77m	3.1×10^1	5×10^{-4}			

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TABLE 9

Thermal Neutron Activation of Beryllium

Isotope	$T_{1/2}$	Gamma Dose Rate (mr/hr) at One Foot From One Gram of Beryllium for Various Decay Times (t)				
		$t = 0 \text{ hr}$	$t = 1 \text{ hr}$	$t = 10 \text{ hr}$	$t = 100 \text{ hr}$	$t = 1000 \text{ hr}$
Silver-110m	253d	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.8×10^{-5}	3.4×10^{-5}
Manganese-56	2.58h	40	30	2.5	8.8×10^{-11}	
Aluminum-28	2.3m	630	9.8×10^{-6}			
Scandium-46*	84d	6.2×10^{-3}	6.2×10^{-3}	6.2×10^{-3}	6×10^{-3}	4.4×10^{-3}
Cobalt-60m	10.5m	2.3×10^{-1}	4.5×10^{-3}			
Zinc-65	245d	1.2×10^{-4}	1.2×10^{-4}	1.2×10^{-4}	1.2×10^{-4}	1.1×10^{-4}

*Activation of scandium was computed on the basis of 10 ppm.

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VII. PARAMETRIC STUDY OF THE DISSEMINATION OF RADIOACTIVITY
BY AN EXCURSION*

The dissemination of radioactivity, or of other noxious materials, by an excursion of a reactor or similar event depends upon the prevailing meteorological conditions. The first quantity to be determined is the height of rise of the radioactive, or noxious cloud. Sutton's equation for this quantity is:

$$Z = \left[\frac{2(8 - 3n) H}{9C_p \rho \pi^{3/2} a C} \right]^{\frac{2}{8-3n}} \quad (1)$$

where

Z - cloud rise (meters)

H - thermal input (calories)

C_p - specific heat of air, at constant pressure (0.25 cal/gm °C)

ρ - density of air (1.18×10^3 gm/m³)

a - lapse rate of potential temperature

C - Sutton's diffusion coefficient

n - Sutton's stability coefficient

The quantities C_p and ρ are essentially constants with the values given.

In an incident such as a reactor excursion, the release of fission products and the heat energy development are closely related, and a reasonable estimate of the quantity H can be made. If the incident consists of two simultaneous events not closely related as, for example, a reactor excursion taking place during a propellant fire, it is more difficult to estimate the thermal input which contributes to the cloud rise. However, in a credible analytic model in which the exponent of the bracket in Eq. (1) has been given the value 0.276 (n = 0.25) it is found that a 45% change in H produces only a 10% change in Z, the height of the cloud rise.

*Cecil O. Riggs

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The quantity a in Eq. (1), the lapse rate of the potential temperature, is a small quantity which does not vary through a wide range;

Sutton suggests $10^{-3} \text{ }^{\circ}\text{C/m}$ as an average value. It should not be confused with the actual lapse rate.

The Sutton coefficients, C and n , are important in the determination of the cloud rise and its dissemination and their estimation has a great deal of uncertainty. These coefficients are related to the prevailing meteorological conditions, but they are not rigorously defined. Since the coefficient n occurs in the exponent of Eq. (1) and subsequent equations, the cloud rise and other factors relating to the cloud dissemination are more sensitive to variations in its value.

Sutton designates n a stability coefficient and states that it can have values between 0 and 1. For a neutral atmosphere, i.e., one in which the lapse rate is the dry adiabatic rate, he uses the value 0.25. As the lapse rate becomes less than the dry adiabatic, the stability of the atmosphere becomes greater and the value of n increases.

The diffusivity coefficient, C , is related to the gustiness of the wind. It is sometimes evaluated by relating it to the ratio of the difference in wind velocity at two points to the separation of the points. For the neutral atmosphere, Sutton suggests 0.45 as an acceptable value. As the stability of the atmosphere increases, the value of C decreases. It usually decreases with altitude. Values of 0.10, or smaller, are not infrequent. The effect of an increase in n , or a decrease in C , is to increase the height of cloud rise.

To study further the effect of these parameters upon the dissemination of the cloud, it is convenient to relate the downwind distance at which the maximum cloud effects occur to the cloud rise. The cloud effects maximized are the cloud concentration, exposure to a receptor on the cloud centerline and the ground deposition. The equation is:

$$(ut) \frac{2-n}{2} = \frac{Z}{C} \quad (2)$$

where

u - wind velocity (m/sec)

t - time from release (sec)

Consequently, ut is the downwind distance to the ground projection of the cloud center when the various effects are maximized.

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In this study, C was varied from 0.60 to 0.30 and n from 0.20 to 0.50. The effects of these variations on the cloud rise, downwind distance to point of maximum effects, cloud concentration and exposure are shown in Table 10. The latter quantity, expressed in curie sec/m³, is a convenient quantity from which to calculate external and internal dose, ground deposition and other significant quantities. The datum values, for $C = 0.45$ and $n = 0.25$, are taken from a previous study in which the analytical model was the release of 15% of the fission products from an instantaneous excursion which developed 10^4 mw-sec of thermal energy.

An inspection of Table 10 shows that with a decrease of C or an increase of n , the height of cloud rise is increased and the downwind distance to the point of maximum effects is increased. Not only is the distance to the point of maximum effects increased, these maxima are significantly reduced.

TABLE 10

Effect of Variation of the Parameters C and n

C	n	Cloud Rise (meters)	Distance of Maxima (meters)	Maximum Cloud Concentration ($\mu\text{c/cc}$)	Maximum Exposure (curie sec/m ³)
0.60	0.25	478	2,100	15.8×10^{-4}	26.72×10^{-2}
0.45	0.25	515	3,180	9.45×10^{-4}	17.30×10^{-2}
0.30	0.25	548	5,300	5.00×10^{-4}	7.85×10^{-2}
0.45	0.20	443	2,120	19.46×10^{-4}	30.6×10^{-2}
	0.25	515	3,180	9.45×10^{-4}	17.30×10^{-2}
	0.30	568	4,500	4.20×10^{-4}	8.55×10^{-2}
	0.40	740	10,300	0.858×10^{-4}	2.24×10^{-2}
	0.50	993	27,800	0.1055×10^{-4}	0.371×10^{-2}

The remaining quantity which can affect the cloud dissemination is the wind velocity. The effect of changing the wind velocity in the datum case from 5 to 2.5 m/sec is shown in Table 11. The distance to the point of maximum effects remains the same and the maximum is slightly decreased. A receptor close in to the source would receive a slightly

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higher exposure and one farther out would receive a lesser exposure. The reason is that the longer time of passage of the cloud over the receptor is compensated by the longer time for decay while the radioactivity is reaching the receptor. For noxious clouds not radioactive, for example, beryllium vapor, hydrazine or nitrogen tetroxide, there would be no decay and exposure would be increased; the point of maximum effect would remain essentially the same. In either case, the isodose contours would be widened.

In this study, the cloud has been considered isotropic, that is, $C = C_x = C_y = C_z$. Generally, C_z will be smaller than C_x and C_y . The result is a flat cloud and the various effects at the ground are further reduced.

TABLE 11
Effect of Variation of Wind Velocity*

Downwind Distance (m)	Exposure (curie sec/m ³)	
	Vel = 5 m/sec	Vel = 2.5 m/sec
900	1.42×10^{-3}	1.534×10^{-3}
1,800	1.21×10^{-1}	1.304×10^{-1}
3,180	1.72×10^{-1}	1.450×10^{-1}
3,600	1.26×10^{-1}	1.240×10^{-1}
5,000	7.55×10^{-2}	7.32×10^{-2}
12,000	1.13×10^{-2}	9.66×10^{-3}
18,000	3.16×10^{-3}	2.14×10^{-3}

* $C = 0.45$, $n = 0.25$

N. G. Stewart and his colleagues have made an experimental study of the values of C_y and C_z . They released the radionuclide Argon-41 from the stack of the BePo reactor at Harwell, England under various meteorological conditions. Determinations were made of the cloud concentration at various altitudes and distances downwind. From these data they essentially solved the equation backwards for the values of C_y and C_z ; the parameter n was held at 0.25. Some results obtained in this study are presented in Table 12.

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In conclusion, it appears that the analytical model previously adopted, using $C = 0.45$, $n = 0.25$, and giving a cloud rise of 515 meters, is conservative. Conditions for which these values of C and n are appropriate may exist for two or three hours in the afternoon. Changes from this condition are in such a direction as to produce greater cloud rise, move the point of maximum effects downwind and to decrease these maxima.

TABLE 12

Experimental Diffusion Coefficients Derived
by Stewart et al, from BePo Measurements

<u>Type of Survey</u>	<u>Meteorological Conditions</u>	<u>Sampling Range (meters)</u>	<u>Diffusion Coefficients (meters)^{n/2}</u>	
			<u>Cy</u>	<u>Cz</u>
Vertical	Unstable	150 to 1000	0.16	0.27
	Adiabatic		0.10	0.22
	Stable		0.10	0.12
Ground	Adiabatic and unstable	590 to 620	0.46	
		880 to 1050	0.28	0.32
		1200	0.33	
Ground	Adiabatic and unstable	2400 to 2800	0.26	
		6000 to 9700	0.18	0.19
Ground	Stable	1000 to 10,000		< 0.04

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VIII. TEST PROGRAM*

All effort during this report period has been directed toward the construction of an integrated safety test program. This program has two purposes--to provide information for and/or verification of the analytical solutions used in the safety analysis and to develop countermeasures to eliminate the problems exposed by the analysis. The KIWI-B1 is used as the reactor model for these tests and all of the tests and conceptual test model designs have been based on the KIWI-B1.

The first part of the program plan was issued during this report period (Ref. 14). This part of the test program includes detailed descriptions of the plasma jet tests, anticriticality destruct system development and test, fuel element additive development and test and fuel element leaching rate tests. Most of the additional tests which will be necessary to make the test program a complete package are briefly outlined in the issued program.

The purposes of the various tests which are proposed in the program may be grouped in three general categories:

- (1) To obtain empirical data for use in the analytical solutions of various problems in the safety study and to provide laboratory verification of the analytical techniques.
- (2) To develop countermeasures which will eliminate the hazards which might otherwise prevent the safe test of a nuclear rocket.
- (3) To demonstrate by proof tests that the final analytical solutions and the developed countermeasures are correct and that the study aim--safe flight test of nuclear rockets--has been achieved.

Highlights of the individual test programs are given. The first four tests are more fully outlined as they are the only programs fully developed at this time. However, no attempt has been made here to duplicate the great detail which is included in the actual program (Ref. 14).

A. PLASMA JET TESTS

The plasma jet tests are postulated to aid in the prediction of the fate of a reactor during re-entry. The test plan approach is three-fold:

*E. Jules

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- (1) Obtain data on the behavior of reactor materials in simulated aerodynamic heating.
- (2) Investigate the analytical methods.
- (3) Develop countermeasures which enhance destruction through aerodynamic heating.

The first two of these supplement the analytical treatment of re-entry. The third seeks a solution to the hazards problem which would result from insufficient burnup through re-entry heating of the reactor as it is presently designed.

To realize the objectives of this three-fold approach, tests are to be performed on:

- (1) Full scale fuel elements and modules to obtain burnup data.
- (2) Simulated core borings (stacked discs) and scale models of the engine and the entire nuclear stage to obtain transient heat transfer data.
- (3) Various size spheres of the engine materials to simulate fragments resulting from use of the destruct system and examination of core compositions which enhance burnup (additives).

The test program includes conceptual design of the test models to be used for each of these.

The test conditions for these specimens are developed in the program. The principal test conditions involve simulation of the re-entry trajectory and attitude. The missions under consideration result in three main trajectories: re-entry from orbit; ballistic re-entry and a re-entry between these extremes, such as a failure to establish orbit. Each of the trajectories has a different heating rate history which, in turn, will result in a different burnup rate.

The history for each of these cases may be determined since it is a function of initial re-entry altitude and velocity. The resulting heat flux versus time curve will be roughly bell-shaped. Because the available plasma jet facilities operate only at a constant heat flux applied in a square wave fashion, a simulation technique is employed. The simulation technique, detailed in the test program, yields a particular constant heat flux which when applied for a particular length of time gives a good simulation of the total re-entry heat. In addition, it is necessary to simulate the flight parameters of velocity and altitude. This is accomplished by manipulation of the machine settings to

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get proper stagnation enthalpy, indicative of velocity, and stagnation pressure, indicative of altitude. It is thus possible to get meaningful burnup data for the materials of interest.

The attitude of a re-entering body is the angle which its longitudinal axis makes with the flight path. The angle may have any value, but the two extremes for a symmetrical body occur when the axis is parallel or perpendicular to the flight path. The profile presented to the flight path will be different in each case (unless it is a sphere or a cube). This will result in a difference heating rate for each case. Therefore, plasma jet tests will be performed on specimens in each of these orientations so that the burnup data will be complete.

If a re-entering body is not aligned in either of these attitudes, it will not be symmetrical to the flight path (except a sphere). Then, the unsymmetrical pressure distribution on the body will cause it to tumble along the flight path. As the body rotates, the heating point will effectively move around the body and result in a time-variant heat input to any specific body surface. The burnup rate will be affected by this and it is therefore necessary to simulate the tumbling effect if the burnup data are to be complete. This can be accomplished in a plasma jet facility by either rotating or intermittently inserting the specimen into the plasma.

Four private facilities and three NASA laboratories have been approached about performing these tests. In most cases visits were paid to these facilities to discuss the basic plasma jet program. During these visits suggestions concerning the program were received and later reviewed and resulted in program changes where merited. After the program was discussed, on-the-spot cost and time estimates for the test work were obtained. It was determined that all of the desired tests could be performed with existing facilities. In general, the NASA laboratories were not anxious to undertake a program of this size because it would require them to postpone their own projects. However, the private facilities were prepared to start the program at approximately the time desired. The facilities contacted were:

- (1) AVCO (RAD Division).
- (2) Chicago-Midway Laboratories.
- (3) General Electric Company.
- (4) NASA-Ames Research Center.
- (5) NASA-Langley Aeronautical Laboratories.
- (6) NASA-Lewis Research Center.

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(7) Martin-Nuclear.

(8) Plasmadyne Corporation.

The test program includes a schedule of the tests that takes into consideration those tests which must be performed in sequence. The time spans estimated by the various facility personnel contacted were used for this plan.

The number of models to be tested is included in the program. The reasons for the particular test specimens and the number of runs required are also given. Cost estimates obtained from various facilities were included wherever possible so that an approximate cost of the program was derived.

B. REACTOR DESTRUCT SYSTEM DEVELOPMENT AND TEST

This program has been formulated as a countermeasure for the excursions which will occur if an entire reactor core is submerged in liquid propellants or water, and the event that burnup of the reactor on re-entry is insufficient to produce the required aerosol.

Immersion of the core might occur after a launch pad abort or if a flight were to terminate with impact into the sea. Present calculations indicate that if it is submerged in sea water the core would remain critical for a long time and "chug" until a large volume of fission products had been exhausted from the core. This would contaminate a large area.

A solution to this problem is to break the core into small sections before impact. Such small sections would not go critical if immersed. The destruct system will break up the core, and because of the importance of its function, must be extensively tested and highly reliable.

If an entire engine, after operation, cannot be reduced to an aerosol by burnup before it descends to 10^5 feet, it may still be possible to achieve this result by fragmenting the engine. In such a case the individual fragments would be subjected to re-entry heating for longer periods and, because of their smaller size, would receive heat at higher rates.

The plasma jet program included tests which would determine the required fragment size. The destruct program is proposed to develop a method of achieving the required fragmentation.

Present conceptual destruct systems employ two methods:

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- (1) Fire a number of shaped charges through the reactor core in a vertical direction.
- (2) Use a mortar-type device to fire a charge of explosive into the core at which point it would be detonated.

The program achieves its objectives in three phases:

Basic experimental work on the mechanism of destroying the core will be done to ascertain the feasibility of the destruct concept. A series of tests will be performed to explore the destructive capability of high explosives on the core material. Additional tests will be performed to determine the penetration and fracture formation ability of shaped charges. Particular consideration will be given to the requirements of geometrical similarity, physical properties and scaling factors. These are of concern because of the anisotropic properties of the core material and the cost of fabricating full scale models.

Based on the information obtained in the first phase, scale model engines will be destroyed. The effects of the explosives on the core when it is in the pressure vessel will be investigated for dispersal patterns and fragment sizes. Proper positioning and charge size will thereby be determined.

The development of an actual "flight" package will follow as the last phase. Full scale engines will be used unless previous tests yield a scaling method. The hardware for this test will be identical to that which will be used in the flight vehicle so that the destruct system objectives may be achieved.

This program was developed in conjunction with personnel of Aberdeen Proving Grounds. They have furnished cost and time span estimates and it is anticipated that the work will be done there.

C. FUEL ELEMENT ADDITIVE DEVELOPMENT AND TEST PROGRAM

One of the serious problems associated with nuclear rocket propulsion reactors is that of disposing of the highly radioactive reactor after the engine has been operated. One solution is to disperse the core as an aerosol in the upper atmosphere. Thus, by eliminating prompt fallout, the fission product decay would reduce the radioactivity to a tolerable level before the particles enter the biosphere. This may be done through aerothermodynamic heating and attendant oxidation and injecting an oxidizer into the core and dispersing it by thermochemical reactions.

This program is the systematic study of various additives which would increase the rate of these reactions. The additive must have the following properties:

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- (1) It must be compatible with the core materials in all atmospheres encountered during manufacture, storage and use.
- (2) It should have no adverse effect on the structural or heat transfer properties of the core materials.
- (3) It should have no adverse effect on the nuclear properties of the core.
- (4) It must contribute to the destruction of the core as described.

A literature survey has revealed approximately 50 materials which have sufficiently high melting points to survive the reactor operating temperature. The maximum permissible quantity which could be used without seriously affecting the nuclear characteristics of the core has been calculated for each additive. It is necessary to determine compatibility of these materials with the core material at the required high temperature and test chemical reactivity of additive loaded core materials in air, oxygen and water.

Those materials which pass the initial screening will be used in the fabrication of cylindrical test specimens. These will be prepared similar to the manner in which the core is fabricated. Those specimens which show poor structural properties, by visual and X-ray examinations, will be discarded. The remaining specimens will be tested in a plasma jet to determine the relative increases in ablation. The best of these will undergo larger scale tests as part of the previously discussed plasma jet tests.

This development and test program has been proposed by The Martin Company and would be done by the Nuclear Division. The cost and time span estimates submitted in the program plan were based on this anticipation.

D. FUEL ELEMENT LEACHING RATE TEST

The event of impact into the sea as the result of a mission abort, by failure of either the chemical or the nuclear stages, could result in immersion of the core in sea water. Under these conditions the core could be either thermally hot or cold when it enters the water. (It should be in fragments as the result of use of the destruct system.) This program will investigate the loss of uranium rate from the core materials. This indicates the rate of loss in fuel inventory.

The program is based on variation of the following parameters:

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- (1) Temperature--a thermally cold reactor simulated using room temperature water and a thermally hot reactor using boiling water.
- (2) Fuel loading--specimens with fuel loadings of approximately 160 to 450 mg u/cm³ will be tested.
- (3) Salinity--a comparison of the leaching rates in salt and fresh tap water.
- (4) Configuration--specimens which have different surface-to-volume ratios as a result of their different shapes.
- (5) Effect of metallic cladding--specimens with and without a metallic coating on some surfaces.

Specimens having the second, fourth, and fifth of these variations will be prepared by a method similar to that used in the core fabrication. If possible samples of IASL graphite fuel elements will be tested as controls. The specimens will be placed in fresh tap and salt water solutions at both room and boiling temperatures for a period of time. At the end of this period the macroscopic changes will be observed. The amount of uranium in the water and the remainder in the specimens will be determined as well as any gas generated. From this, the leaching rates of the various specimens can be determined.

This program was proposed by Martin Nuclear and the cost and time span estimates were submitted by the Materials Section.

E. ENGINE SEA WATER IMPACT TESTS

These tests will simulate the impact of a nuclear rocket engine under conditions which result from launch failures, in-flight aborts and terminal ballistic missions. The tests assume that there is no use of, or there is failure of the previously discussed destruct system.

Potential test variable include:

- (1) Impact temperature--an unfired engine which is thermally cold and an engine which has been run and is consequently thermally hot.
- (2) Impact velocity--the effects of impact velocity up to the terminal velocity will be studied.

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- (3) Impact angle--because the body will probably be rotating, several impact angles may have to be investigated or, a statistical analysis to determine the expected impact angle will be conducted.
- (4) Impact specimen--the entire engine as well as various components may require investigation.

The impact may be achieved by a drop from a helicopter or by using ballistic rockets to accelerate the specimen either vertically, horizontally or on an incline into the water. The size of the test specimen would influence the selected method. It is probable that some initial work in scaling factors for models will have to be done before full size engines are used for these tests.

Aberdeen Proving Grounds personnel have been approached on this program and they have made some preliminary cost and time span estimates.

F. PROPELLANT EXPLOSIONS AND FIRE TESTS

The thermal and mechanical energy release of exploding rocket fuels resulting from launch aborts pose a threat to the reactor and its control system. This program would investigate this problem using a three-phase approach:

- (1) Determine the energy yield of exploding missile propellants using 1/10 and 1/18 scale models of fueled missiles. The failure is simulated by inducing tank seam failure in the presence of a source of ignition. The resulting shock overpressures are measured at some distance and the yield is calculated from the peak overpressure. This type of test has been done by the Broadview Research Corporation.
- (2) The shock overpressure effects are determined by placing a scale model of the component to be tested at a scaled distance from a high explosive charge. After the explosion, the model is retrieved and examined. Information on the scaling of TNT charges to simulate propellant explosion yields and model scaling factors is presently available. Tests such as these have been performed by the Ballistics Research Laboratory located at the Aberdeen Proving Grounds, Maryland.
- (3) Thermal shock effects resulting from the propellant detonation may be investigated by placing the test specimen in such a way that it is subjected to a simulated propellant fire. The initial fireball effects as well as the results of immersion in the residual fire can be examined. Aberdeen Proving Grounds personnel have performed tests of this type.

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These tests will yield information on the engine integrity after being subjected to these thermal and mechanical energy shocks.

G. THERMOCHEMICAL DESTRUCT SYSTEM DEVELOPMENT AND TEST

This program is a parallel program to that of the explosive destruct system for an engine that has been operated. In this case the destruct mechanism is a thermochemical reaction which acts to destroy the core. The reaction is caused by injecting chemicals into the reactor and employing the afterheat or induced post-operation shutdown heat to trigger the reaction. The effluent gases would then exhaust the reactor material by erosion or a similar mechanism. The additives developed under a previously discussed test program could be employed to enhance the reaction.

Laboratory tests might consist of heating specimens in a furnace (or similar device) to temperatures approaching the afterheat temperature. (There is some doubt about achieving the actual afterheat temperature in a furnace.) A chemical would then be passed through a flow channel in the specimen and the effects of the reaction would subsequently be measured. Various chemicals and flow rates would be used on different specimens at various temperatures so that a complete parametric study will be made. This information will then be used to design the thermochemical destruct system.

When the feasibility of the thermochemical destruct system has been demonstrated, a proof test will be performed. This would most likely be done with an engine which has been run in a static test. The chemicals would be injected into the reactor and it would be run to destruction. Such a test would probably be done by LASL since they are conducting the static tests. The investigation would involve a post-mortem examination of the engine to evaluate the effectiveness of thermochemical destruction.

H. OPERATING ENGINE MONITOR PROGRAM

This program will investigate the following four major areas:

- (1) Component activation--to investigate the contribution which the activated engine components make to the radionuclide inventory. The extent of this additional activity can be determined by measuring the activation levels of components used during static firings at NTS. Preliminary and supplementary tests might also be performed in the MTR and the results extrapolated by nvt ratios. The investigation should include a breakdown of material impurities and the probable contribution of each impurity determined. The resulting information will be used to check and further develop the existing machine programs.

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- (2) Irradiation of destruct system--to investigate the radiation damage to destruct materials and hardware in the vicinity of the reactor. Initial tests could include placement of several packages of high explosive materials at various points near a KIWI-B during static tests to determine any radiation damage which results. This would also include treatment of electronic packages typical of the destruct system components. If necessary, basic data on radiation effects on both explosives and electronic components can be obtained in the MTR located at Arco, Idaho. A final design destruct package should be located in its approximate "use" position during a later KIWI-B static test.
- (3) Nuclear and temperature measurements--these measurements should be made during normal operation and after shutdown. Radial and axial profiles of temperature, neutron flux and gamma flux are desired. The temperature measurements are of particular interest in the case of afterheat for use in the re-entry burnup studies.
- (4) Fission product release measurements--to investigate the fission products released during operation and shutdown of the reactor. The effects of fission product "boil-off" phenomena are of particular interest in connection with decreasing the engine fission product inventory at high altitude. This information could be used in present machine codes which presently assume no leakage from the engine. The fate of the metallic cladding and the fuel element itself should also be checked in connection with this test. Post-operative examination of the reactor to determine what has not been released must also be considered.

I. FISSION PRODUCT RELEASE AND DISPERSION TESTS

These tests would involve release of a tracer element in a manner similar to that which might result if a reactor excursion occurred. A series of tests to investigate the variables in the Sutton Equations would provide a sound check on the analysis and place much more confidence in the results. In the event of a launch pad excursion of a nuclear rocket engine, there would not be a containment vessel to contain the fission products. A radioactive cloud would definitely result and the effects should be known. The properties of the resulting cloud, including radionuclide concentration, rate of rise, resulting fallout and pressure waves would be obtained in the tests. The test data should be taken at distances up to five miles employing collectors having "shutters" so that time-variant measurements could be made. The series of tests should include several different meteorological conditions at the time of the various dispersions. Mischmetal, which contains 50% cesium metal and is pyrophoric, might be used as the simulant for the release tests.

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J. CRITICALITY MEASUREMENTS

This program will investigate the criticality changes which result from certain environmental conditions.

- (1) Immersion--to investigate the effects of immersing the entire core or portions of the core in various fluids. These tests would be of the "importance function" type and would not be actual submersion of the entire core into the fluids. The tests on portions of the core will be used to determine the maximum size fragment which can be safely submerged in sea water. This condition could result after an abort and subsequent use of the destruct system. The fluids involved in the immersion tests will include, but not necessarily be limited to, sea water and RP-1, rocket propellant. If possible, the off-shore and deep sea water conditions (pressure effects) should be investigated.
- (2) Engine malfunctions--to investigate the effects of accidental control rod movements and the complete loss of one or more control rods. Various malfunction events will be postulated such as control rod loss due to pressure shock waves. The subsequent nuclear effects will then be examined.
- (3) Countermeasures--to investigate the effects of various countermeasures on the reactivity of the core. The effects of the best three additives should be investigated to determine any reactivity changes. The use of water, oxygen, fluorine, hydrogen peroxide, etc., as "fuels" which would destroy the core has been postulated. Because these employ afterheat and possibly sustain reactivity, it will be necessary to investigate their effects on engine operation. These tests may require examination of two-phase fluid systems.

K. FLIGHT TESTS

The flight testing of nuclear devices for space applications is presently open to the following alternatives: flight tests of non-radioactive components and/or flight tests using a nuclear engine.

In the first type of test, nonradioactive components (i.e., a simulated engine or its components) are placed in a ballistic trajectory, and the re-entering body is tracked by optical and electronic means. The position of burnup should be observed and the various aerodynamic parameters verified. The actual method of determining burnup has not

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been evolved at this time. Though this test does not simulate all of the potential missions*, it does serve to check analytical computation methods for the ballistic re-entry case.

The second type of test would be conducted as a ballistic flight test of the nuclear rocket. In this test the orbital destruct system could be activated at apogee and the effectiveness of the safety system proof tested. In this case if total burnup of the engine does not result, the radioactive fragments would fall in the ocean where its depth is three miles. This type of test is attractive because it utilizes the terminal part of the ballistic flight test after the vehicle performance has been demonstrated.

L. OTHER TESTS

It is anticipated that the requirements for additional tests will continue to be generated. Those that are generated in sufficient time to formulate detailed test programs will be included in the Safety Test Program Report, Volume II. Others, too late for inclusion as detailed test programs, will be listed in the report.

*Orbital re-entry cannot readily be simulated at present.

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IX. ORBITAL STARTUP*

This section has been prepared to provide an insight into the trajectories that are possible to achieve by utilizing a nuclear propulsion system to depart from a reference circular orbit. Instantaneous thrust application is assumed and all velocity increment magnitudes and directions are considered. The various velocity vectors are discussed independently and as deviations from a nominal application direction. The probability of such deviations are discussed.

It is recommended that this report form the basis of a more detailed study where finite burning time effects can be determined in a complete simulation of the propulsion phase. A great deal of effort is required to determine the modes of operation and probability of occurrence of deviations.

A. ASSUMPTIONS

The reference orbit is assumed to be a circular orbit at an altitude of 300 nautical miles. The circular orbit velocity is taken to be 24,890 fps and escape velocity is 35,194 fps. The period of the orbit is 95.6 minutes. The earth is assumed to be a spherical homogeneous body of radius equal to 2.09029×10^7 feet. The gravitational constant, μ , is assumed to be 1.40766×10^{16} ft³/sec².

The nuclear rocket system is assumed to have a specific impulse, I_{sp} , of 800 seconds. The initial weight of the space craft is 50,000 pounds and the vacuum thrust is 75,000 pounds. A propellant weight of 19,125 pounds is assumed, yielding a mass ratio, $\frac{W_{initial}}{W_{final}}$, of 1.6194 and a velocity capability of 12,427 fps.

The thrust is assumed to be instantaneous and finite burning time effects are not considered. The entry conditions for those trajectories that enter the atmosphere are computed at an altitude of 400,000 feet.

B. METHOD OF ANALYSIS

The trajectories are computed utilizing classical free-flight equations for a point-mass moving in a inverse square central force field. The initial circular orbit conditions are altered by vector addition of various velocity increments and application angles. The resultant velocity vectors are taken as the initial conditions for the free-flight equations. The initial altitude is always 300 nautical miles.

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C. DISCUSSION OF RESULTS

The velocity capability of the propulsion system has been defined as 12,427 fps and the direction of application is unlimited. Figure 49 shows the possible trajectories that can result from the utilization of this propulsion system. The burnout velocity and flight path angle are presented as a function of the velocity increment used and the direction of application. Fractional quantities of the total velocity capability are shown (100, 75, 50 and 25% of the total) and application angles of 0, ' 30, ' 60, ' 90, ' 120, ' 150 and 180 degrees are noted. The burnout conditions are the initial conditions of the free-flight equations.

Also noted on Fig. 49 are the classes of resulting trajectories. One line indicates the burnout conditions that yield a perigee at 400,000 feet and, therefore, graze the atmosphere as shown in Fig. 50. Every condition above and to the left of this line has a perigee above 400,000 feet and every condition below and to the right has perigee below 400,000 feet. A second line indicates escape velocity and conditions on this line yield parabolic trajectories. Conditions above the line yield hyperbolic trajectories and conditions below the line yield ellipses. Four classes of trajectories exist:

- (1) Impacting hyperbolic and parabolic flight paths.
- (2) Impacting elliptic flight paths.
- (3) Nonimpacting elliptic orbits including grazing orbits.
- (4) Nonimpacting hyperbolic and parabolic escape flight paths.

These data are independent of the propulsion system capabilities.

The impacting hyperbolic and parabolic flight paths are those that yield impact as the vehicle approaches the focus on the incoming leg or yield escape as the vehicle moves away from the focus on the outgoing leg (note Fig. 51). This class of trajectories is beyond the capability of the propulsion system as defined.

Table 13 presents the trajectory characteristics for the second class of flight paths, the impacting elliptic paths. This class of trajectories include those that have perigee below 400,000 feet and yield impact during the first day. In these cases the drag decay is significant. Figure 52 presents the entry conditions as a function of the velocity increment and application angle for this class of flight paths. Figure 53 presents the range from orbit departure to entry. This is the only quantity influenced by the positive or negative application angle. Hence, if the resultant velocity vector is directed upward then the vehicle must pass through apogee prior to entry and if the

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Fig. 49. Possible Orbits Resulting from Application of a Given Propulsive System

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Fig. 50. Grazing Orbits

Fig. 51. Hyperbolic and Parabolic Flight Paths Yielding Either Impact or Escape

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TABLE 13

Trajectory Characteristics for Vehicles on Impacting Flight Paths

Initial radius = 2.2726×10^7 ft (altitude = 300 naut mi)Initial velocity = 2.489×10^4 fps (circular orbit)Entry altitude = 400,000 ft ($r = 2.13029 \times 10^7$ ft)

Perigee conditions are computed assuming ellipse about a point force center

Application Angle, γ , (deg)	Velocity Increment, ΔV , fps				
		12,427	9321	6213	3107
180 (apogee con- dition)	V_A	1.243×10^4 fps	1.557×10^4	1.866×10^4	2.180×10^4
	r_A	2.2726×10^7 ft	2.2726×10^7	2.2726×10^7	2.2726×10^7
	V_P	8.729×10^4 fps	6.811×10^4	4.769×10^4	3.501×10^4
	r_P	0.3236×10^7 ft	0.5195×10^7	0.8893×10^7	1.4149×10^7
	e	0.7509	0.6081	0.4375	0.2326
	V_e	1.5013×10^4 fps	1.790×10^4	2.0779×10^4	2.3656×10^4
	r_e	2.13029×10^7 ft	2.13029×10^7	2.13029×10^7	2.13029×10^7
	γ_e	-28.5 deg	-22.4	-16.25	-9.9
	θ_e	11.0 deg	16.2	24.0	39.0
150	V_A	1.356×10^4	1.628×10^4	1.881×10^4	2.202×10^4
	r_A	2.382×10^7	2.348×10^7	2.356×10^7	2.295×10^7
	V_P	7.479×10^4	5.741×10^4	4.441×10^4	3.375×10^4
	r_P	0.4318×10^7	0.6659×10^7	0.998×10^7	1.497×10^7
	e	0.694	0.558	0.3985	0.2104
	V_e	1.8039×10^4	1.9648×10^4	2.1807×10^4	2.4036×10^4
	r_e	2.13029×10^7	2.13029×10^7	2.13029×10^7	2.13029×10^7
	γ_e	-33.4	-24.18	-17.2	-9.8
	θ_e	7.0 31.0 1 2	10.5 36.5	16.7 44.7	32.0 56.0
120	V_A	1.510×10^4	1.753×10^4	1.994×10^4	2.234×10^4
	r_A	2.809×10^7	2.623×10^7	2.493×10^7	2.371×10^7
	V_P	5.112×10^4	4.351×10^4	3.723×10^4	3.072×10^4
	r_P	0.8295×10^7	1.057×10^7	1.335×10^7	1.728×10^7
	e	0.545	0.425	0.3016	0.1567
	V_e	2.3440×10^4	2.3589×10^4	2.4152×10^4	2.5129×10^4
	r_e	2.13029×10^7	2.13029×10^7	2.13029×10^7	2.13029×10^7
	γ_e	-31.71	-23.54	-16.1	-8.7
	θ_e	6.0 80.0	9.0 84.5	13.8 89.8	26.0 104.0
90	V_A	1.246×10^4	1.558×10^4	1.867×10^4	2.178×10^4
	r_A	4.538×10^7	3.633×10^7	3.029×10^7	2.597×10^7
	V_P	3.743×10^4	3.422×10^4	3.107×10^4	2.796×10^4
	r_P	1.511×10^7	1.654×10^7	1.820×10^7	2.022×10^7
	e	0.500	0.374	0.2495	0.1246
	V_e	2.9252×10^4	2.8100×10^4	2.7229×10^4	2.6699×10^4
	r_e	2.13029×10^7	2.13029×10^7	2.13029×10^7	2.13029×10^7
	γ_e	-25.14	-19.06	-12.7	-5.6
	θ_e	7.9 186.9	10.4 190.4	15.7 195.7	23.0 213.0
60	V_A	0.4407×10^4	0.918×10^4	1.417×10^4	Orbital con- ditions
	r_A	16.031×10^7	7.319×10^7	4.491×10^7	
	V_P	3.545×10^4	3.274×10^4	2.981×10^4	
	r_P	1.993×10^7	2.052×10^7	2.113×10^7	
	e	0.780	0.562	0.358	
	V_e	3.4165×10^4	3.1962×10^4	2.9964×10^4	
	r_e	2.13029×10^7	2.13029×10^7	2.13029×10^7	
	γ_e	-13.71	-9.32	-3.7	
	θ_e	12.5 284.5	16.9 290.9	25.0 293.0	

*Perigee is sufficiently low to lead to impact during first day (drag decay is significant).

1 Burnout at negative flight path angle

2 Burnout at positive flight path angle

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Fig. 52. Entry Conditions for Flight Paths with Perigee Below an Altitude of 400,000 Feet

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Fig. 53. Range to Entry as a Function of Velocity Vector Applied in Reference Orbit

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resultant velocity vector is directed downward the apogee has theoretically been passed and the range to entry is less. Data for ranges in excess of one revolution (360 degrees) are not presented since these data are beyond the scope of free-flight analysis.

The nonimpacting trajectories are discussed together and their trajectory characteristics are presented in Table 14. It can be seen that none of the cases enter the atmosphere and that the lifetimes of all are

in excess of 10 years for a vehicle with a ballistic coefficient, $B = \frac{C A}{2M}$, of one. The lifetime in a circular orbit at 300 nautical miles is approximately 33 years for $B = 1$. Figure 54 presents a summary of perigee data for all classes of trajectories.

Now, consider the case of a nominal application angle of zero degree and a nominal velocity increment of 12,427 fps. All other conditions are deviations from the nominal and are the result of inaccurate measurements or equipment failures. From Fig. 49 it can be seen that the angular tolerance increases with decreasing velocity increment. For the full velocity increment the angle of application can vary between approximately +40 and -40 degrees and still yield escape conditions. At 75% of total velocity capability, the system will not escape but does not enter the atmosphere for application angles up to approximately ± 50 degrees. The angular deviation increases to approximately ± 58 degrees at one-half velocity capability and is about ± 75 degrees at one-quarter of the total velocity capability.

For conventional liquid fuel systems it can be shown that over 80% of the propulsion failures in any stage occur in the first few seconds of that stage's flight; where, for the case discussed here, the angular tolerance is greatest (± 90 degrees or more). In any event, the angular tolerance to yield early entry or impact is quite large and cannot be attributed to inaccuracies. Therefore, the big problem appears to be one of attitude knowledge and control. With adequate control of attitude early shutdown of the propulsion system will not significantly decrease the lifetime of the vehicle and in general will increase it.

The use of horizon scanners for pitch and roll reference and a suitable yaw reference will maintain good tolerances in attitude. The probability of receiving an erroneous signal is small but should be investigated. Otherwise, if the attitude control system has failed or fails during the power-on flight the propulsion system will be shut down and, as noted before, the early shutdown will abort the mission but will not yield early entry or impact.

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TABLE 14

Orbital Characteristics for Vehicles on Other Than Impacting Flight Paths

Initial radius = 2.2726×10^7 ft (altitude = 300 naut mi)
Initial velocity = 2.489×10^4 fps (circular orbit)
Entry radius = 2.13029×10^7 ft (altitude = 400,000 ft)

Application Angle, γ , (deg)	Velocity Increment, ΔV , fps				
		12,427	9321	6213	3107
60	V_A r_A V_P r_P e V_e r_e γ_e θ_e	Impacting ellipse	Impacting ellipse	Impacting ellipse	1.967×10^4 fps 3.054×10^7 ft 2.717×10^4 fps 2.212×10^7 ft 0.1555 Does not enter atmosphere Lifetime 10 yr for $\frac{C_A}{2m} = 1$
30	V_A r_A V_P r_P e V_e r_e γ_e θ_e	Escape 3.668×10^4 2.209×10^7 1.11	0.388×10^4 19.315×10^7 3.370×10^4 2.223×10^7 0.7921	1.015×10^4 6.782×10^7 3.08×10^4 2.238×10^7 0.504	1.714×10^4 3.652×10^7 2.776×10^4 2.255×10^7 0.2363 Does not enter atmosphere *
0	V_A r_A V_P r_P e V_e r_e γ_e θ_e	Escape 3.732×10^4 2.2726×10^7 1.247	0.200×10^4 38.864×10^7 3.421×10^4 2.2726×10^7 0.8879	0.870×10^4 8.125×10^7 3.111×10^4 2.2726×10^7 0.5625	1.626×10^4 3.911×10^7 2.799×10^4 2.2726×10^7 0.2656 Does not enter atmosphere *

*Lifetime is in excess of 10 years for $\frac{C_A}{2m} = 1.0$.

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Fig. 54. Summary of Perigee Characteristics

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D. CONCLUSIONS

It can be concluded that early shutdown of the propulsion system is not critical from the safety standpoint although it means an aborted mission. Early shutdown of the propulsion system will increase the vehicle lifetime and will not lead to an early entry and impact if adequate attitude control is available.

Escape missions require midcourse guidance systems or extremely accurate early attitude control. Therefore, the inaccuracies of the attitude control system can be neglected as a safety factor and only failures of the system considered. In case of failure in the attitude control, the propulsion system will be shut down immediately.

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