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EFFECTS OF LIQUID PROPELLANT
EXPLOSIONS ON NUCLEAR
ROCKET ENGINES

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*final report
prepared for*

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SPACE NUCLEAR
PROPULSION OFFICE
U. S. ATOMIC ENERGY COMMISSION

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FINAL REPORT

PREPARED FOR

SPACE NUCLEAR PROPULSION OFFICE

U. S. ATOMIC ENERGY COMMISSION

WASHINGTON, D. C.

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MARCH 14, 1962

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ARTHUR D. LITTLE, INC.

CAMBRIDGE, MASSACHUSETTS

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I. SUMMARY

This is the final report of a program designed to determine the hazards which might result from a launching mishap of a SATURN class vehicle with a nuclear-powered upper stage. The program has consisted of two phases. The first was an experimental effort in which characteristics of explosions of SATURN propellants were determined. The second phase was an analytical program designed to predict the effects of a propellant explosion on a nuclear reactor of the Kiwi-B class. This report describes the analytical procedures used in this second phase and the conclusions reached.

The Kiwi-B reactor was used as an analytical model and a propellant explosion was presumed with characteristics similar to those determined in the experimental phase. The characteristics of interest are peak-pressure, pressure duration, heat transfer, and movement of the gas cloud. The effects on the reactor of primary concern are distortion and fragmentation due to pressure, vaporization of reactor materials and scattering of the reactor components. An examination of the hazards which might result from these effects included hazards arising directly from the explosion effects, hazards arising indirectly as a result of a power excursion of the reactor, and hazards arising from combinations of these phenomena.

The potential hazards of a nuclear-powered engine include:

1. Blast effects
2. Radiation effects
3. Toxic material effects

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Each of these was examined under the conditions of the case of interest and the maximum credible degree of hazard was determined. Of particular interest were hazards which would require precautionary measures beyond those required for launching of a vehicle such as the SATURN without a nuclear stage.

Following the analysis of the potential hazards, an examination was conducted of the possible modes of failure of the nuclear-chemical vehicle. This examination was carried out in a generalized fashion with primary interest centered on the behavior of the reactor and its components. Results were predicted for the various modes of failure and a basis was established for estimating the probability of occurrence of the various hazardous effects.

After consideration of the various potential hazards and the mechanisms by which these hazards could be generated, the maximum credible effects predicted are as follows:

1. The quantity of beryllium vaporized by a propellant explosion depends upon the design of the reflector elements rather than the total quantity present. Only small fragments of beryllium would be susceptible to vaporization.
2. In the case of the Kiwi-B reactor, a release of beryllium vapor or particles could result within the fireball, but the maximum concentration occurring at ground level would not exceed the maximum allowable concentration for instantaneous exposure. Total exposures could exceed maximum recommended levels only if wind velocities were low (one mph or below).

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3. There is little liklihood of a propellant blast causing a nuclear-power excursion of a greater magnitude than that described in Reference 2 as the "maximum credible accident".
4. Dispersion of fission products could exceed that predicted for an accidental power excursion prior to launching (3). The increased concentrations of radioactive materials would not exceed tolerable limits except possibly within the immediate vicinity of the vehicle failure.
5. Fragments of reactor material could be scattered around the launching area to distances of up to one mile for a failure of the SATURN C-2 configuration.
6. Contamination of the launching area with beryllium particles and fission products could prevent further use of the area until radiation had subsided or until precautionary measures had been taken against beryllium poisoning.
7. The most serious effects would result from immersion of the reactor in a detonating liquid propellant mixture. The probability of this occurring appears to be very small.

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II. INTRODUCTION

A. General Problem

The current national interest in space exploration has necessitated the development of rocket vehicles producing total impulses far greater than those required for ballistic missions. Increased impulse is produced by increasing the size and performance (exhaust velocity) of the vehicle. Accompanying these increases in size and performance are increased hazards associated with the launching. In the event of failure of the vehicle, the explosive hazard due to spilled propellants increases with the weight of propellants involved. Since many propellant combinations can produce blast waves comparable to those produced by high explosives, rocket vehicle combinations containing millions of pounds of propellant constitute very serious explosive hazards.

To increase rocket performance in future vehicles, the conventional hydrocarbon-oxygen propellant combinations will be replaced by chemicals delivering higher specific impulses or by non-chemical systems. Associated with many of these high performance systems are hazards from toxic materials produced in the exhaust stream or contained within the propulsion device. The release of these materials due to a vehicle failure presents a further hazard which must be considered in addition to blast effects. Thus, the selection of launching sites and protection of personnel are becoming major factors in the planning of a space exploration program.

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Nuclear propulsion offers one means of providing a significant increase in exhaust velocity at the thrust levels required for launching. Existing nuclear technology is capable of producing a gas-cooled, solid-core reactor with an exhaust velocity twice that of chemical systems, and further advances in materials and reactor design will increase this factor. Because of the dead weight of the reactor, nuclear propulsion cannot compete favorably with chemical propulsion for missions requiring low total impulses. However, for gross payloads in excess of 1000 pounds requiring orbital or escape velocities, the nuclear rocket begins to compare favorably with chemical rockets, at least on a weight basis (1). Therefore, the development of nuclear rockets has received considerable support in recent years and progress is such that flight tests have been scheduled.

The specific hazards associated with nuclear propulsion stem from various reactor components and consist primarily of radiation or dispersion of toxic materials. Two mechanisms through which extensive damage to a reactor could occur are accidental power excursions and chemical propellant explosions. Either of these occurrences, or a combination of the two, could conceivably produce hazardous quantities of radioactive or toxic materials.

Accidental power excursions of the Kiwi-B reactor and their causes have been investigated to some extent by other organizations (2, 3). Durations, energy releases and physical results have been calculated and the probabilities of their occurrence estimated. Because of the low neutron containment and unfavorable geometry of the reactor design, there are several factors which could cause excursions. These include immersion in neutron-reflecting substances, malfunctioning of the control system, and distortion of the core

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into more favorable geometries. However, in any of these events, it appears that disruption of the reactor would halt the reaction quickly with small releases of energy or radioactivity.

The effects of chemical propellant explosions upon a kiwi-B type reactor do not appear to have been investigated as yet. Initial flight tests of a nuclear rocket call for a NERVA-powered vehicle boosted by a liquid fueled SATURN. The booster will be powered by LOX and RP-1 (kerosene) and the nuclear engine will use liquid hydrogen as a propellant. Start-up of the nuclear cycle is to occur after burn-out of the booster.

Explosions of chemical propellants have been investigated in the past, and a study of the explosive hazard associated with the SATURN vehicle in particular has been completed recently by Arthur D. Little, Inc. (4). The study consisted of an experimental determination of the maximum blast effect which could be expected from a detonation of spilled SATURN propellants. As an addition to this effort, a further study was carried out to determine the effects of propellant explosions on a nuclear rocket engine of the Kiwi-B type. It is this additional study with which this report is concerned.

This program has been divided into two tasks. The first task involved the measurement of pressures and heat fluxes occurring within propellant explosions, and the observation of other characteristics such as fragmentation and dispersion of debris, and movement of the fireball and dust-cloud. These measurements and observations were conducted in conjunction with the SATURN blast tests mentioned above. Detonations were initiated in mixtures of LOX, RP-1 and liquid hydrogen in quantities corresponding to 1/25 those which would be contained in a SATURN C-2 configuration at launching. The tests were

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conducted at Edwards Air Force Base, California. The results of the measurements are summarized in Section II-B below, and a detailed description of the detonation testing and methods of measurement are contained in an earlier report (5).

The second task has involved a determination of the behavior of a Kiwi-B reactor under conditions similar to those measured under Task I. Effects of particular interest are:

1. Fragmentation of reactor elements.
2. Vaporization and dispersion of core and reflector materials.
3. Reactor excursions resulting from distortion of the core.

Estimates of these effects have been completed and the resulting hazard to personnel in the vicinity of the launching site has been evaluated. In the determination of hazards, conservative assumptions have been made, particularly in areas where specific information on material behavior is lacking. As new data become available, the hazards can be reassessed. Because of the conservative nature of the assumptions used, it is expected that new information will result in a reduction of the predicted hazard.

B. Blast Conditions

1. Pressure Conditions

The SATURN vehicle utilizes three liquid propellants: RP-1 (kerosene), liquid hydrogen, and liquid oxygen. The C-2 configuration will contain approximately one million pounds of propellant, and the C-5 approximately five million pounds. Spilling and mixing of these propellants create a two-phase mixture - a gas phase consisting principally of hydrogen, oxygen

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and air; and a liquid phase (or liquid-solid mixture) containing RP-1, oxygen, and possibly a small percentage of hydrogen. Ignition of this mixture results in a violent detonation which produces a blast wave in the surrounding air similar to that produced by high explosive materials. A description of blast waves from liquid propellant explosions is contained in Reference 4. Within the detonating mixture the blast characteristics of the two phases are found to be quite different. Peak pressure measurements in the liquid phase have indicated pressures ranging from 7000 to over 90,000 psi. The wide variation results from the inhomogeneity of the mixture. The highest pressures were obtained in mixtures wherein the greatest degree of mixing had occurred. The maximum theoretical pressure attainable in these liquid propellant mixtures is approximately 150,000 psi. This value was calculated by a method described by Taylor (6).

In the gas phase, peak-pressures are of a lower magnitude than in the liquid. Gas phase pressure measurements ranged below 2000 psi in all instances with most measurements below 1200 psi. The gas phase pressures are caused by shock waves from the liquid reaction as well as reaction within the gaseous components. Therefore, peak pressures decrease rapidly with distance from the liquid body.

The dimensions of the zones of the detonation region are shown in Figure 1. A reduced distance coordinate is used in the form of $d/w^{1/3}$ where d is the radial distance in feet from the center of the detonation, and w is the weight in pounds of propellant which is spilled and mixed. Experimental results (4) indicate that only premixed propellants contribute to the blast and that the

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explosive yield* is approximately 1.0 lb of TNT per pound of propellant mixture. In predicting the extent of the detonation region for failure of a given vehicle, it would be unrealistic to assume that all the propellant would participate. The actual amount which could become mixed prior to ignition can only be estimated.

The dimensions shown in Figure 1 are based on results of the experimental program. Liquid detonation zone dimensions were taken from crater measurements, and vapor cloud dimensions were taken from photographic records. The dimensions shown are those predicted for a symmetric collapse of the vehicle creating a pool of mixed propellants on the launching pad. This is an unrealistic model, but represents the worst case from the standpoint of blast level. Asymmetry in the mode of failure of the vehicle would reduce the concentration and mixing of the propellants and would probably result in lower blast pressures.

Also shown in Figure 1 are the maximum peak-pressures to be expected at ground level as a function of distance from the center of the blast. The distribution of peak-pressures can be divided into three zones wherein the mechanisms producing the over-pressures are different. In Zone I, which is that area covered by a liquid propellant mixture, pressures up to 150,000 psi result from the detonation reaction within the liquid. In Zone II, pressures vary from 2000 psi near the inner edge of the zone to 100 psi at the outer edge. Peak-pressures within this zone are generated by the combined effects of the shock wave emerging from Zone I, continuing chemical reaction in Zone I, and vapor phase chemical reactions in Zone II behind the shock wave. In

* Explosive yield as used here is defined as the weight of TNT required to produce a blast wave of equal magnitude as that produced by the propellant mixture, divided by the propellant weight. The value of 1.0 pertains only to the SATURN C-2 propellant combination. Yields for other combinations of these propellants are contained in Reference 4.

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FIGURE 1

PREDICTED GEOMETRY OF SYMMETRICAL SATURN PROPELLANT

EXPLOSION AND DISTRIBUTION OF PEAK PRESSURES

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Zone III peak-pressures are below 100 psi and fall off rapidly with increasing distance from the center. Within this zone the shock wave is no longer supported by continuing chemical reaction, and its characteristics are similar to those of a wave produced by a point-source explosive.

It is expected that the distribution of peak-pressures in the vertical direction (upwards) would be similar to the ground level distribution, except that the extent of Zone I would be less.

It has been assumed here that ignition of the propellant mixture occurred at the center of the liquid, and that the detonation wave propagated outwards from this point. The maximum pressure would occur at each location at the time of passage of the initial wave. A complex system of reflected waves would follow the initial wave, but these waves would not produce pressures exceeding the initial detonation or shock-wave pressure. Occurrence of ignition at an off-center location would create a non-symmetrical distribution of peak-pressures, but would not cause higher pressures at any location than would result from central ignition.

Shock wave reflection from solid surfaces or colliding shock waves from multiple ignition sources could produce localized areas of pressure exceeding those shown in Figure 1. However, it would be impossible to predict the location and magnitude of such effects. In view of the mechanisms which act to reduce the pressure levels achieved, such as incomplete mixing and air dilution, it seems sufficiently conservative to assume that the pressures shown in Figure 1 are the highest which can reasonably be expected.

The duration of the over-pressures is also an important factor in predicting the effects of a propellant explosion. Pressure-time records have been obtained

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for the unsupported shock waves of Zone III (4). The shape of these waves is typical of blast waves and is shown in the sketch below.

The duration of the positive-pressure portion of these waves is approximately 40 milliseconds at the inner edge of Zone III (100 psi over-pressure). The duration increases with distance from the center such that the ratio of duration to distance is nearly constant.

No attempt was made during the experimental program to record pressure-time histories within Zones I and II. Therefore, pressure durations must be estimated from considerations of the phenomena occurring.

In Zone I, or the liquid detonation region, it is reasonable to assume that the mass of liquid is converted instantaneously to a gas at high pressure. The pressure at any point within the mass is relieved by the arrival of a rarefaction wave from the nearest free surface. Thus, an approximate peak-pressure duration can be obtained by dividing the minimum dimension of the liquid body by the acoustic velocity within the products of reaction. Utilizing this ratio for SATURN propellants, a duration of the order of 1 millisecond is obtained.

In Zone II it is reasonable to assume that over-pressure durations will be intermediate between those occurring in Zones I and II. This assumption

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would indicate durations between 1 and 40 milliseconds. During the progress of this program there was no need for a more precise estimate of the pressure duration in Zone II. Thus, no effort was made to improve upon this approximation.

By means of the methods which have been outlined, a prediction of the pressure conditions which could be experienced by an object within a SATURN failure has been formulated. These predicted conditions are summarized in Table I below.

TABLE IPREDICTED PRESSURE CONDITIONS WITHIN FULL SCALE SATURN C-2 FAILURE

<u>Zone</u>	<u>Description</u>	<u>Radial Extent</u> <u>(ft/lb^{1/3})</u>	<u>Peak</u> <u>Pressure</u> <u>(psi)</u>	<u>Peak</u> <u>Duration</u> <u>(msec)</u>
I	Liquid Detonation	.70	100,000	1
II	Supported Shock Wave	.70 - 3.50	100-2000	1-40
III	Unsupported Shock Wave	3.50 - ∞	<100	>40

In analyzing the effects of a propellant explosion upon a nuclear engine, these pressure conditions have been assumed. Experimental measurements have shown that these conditions can be expected to occur in an actual failure of the vehicle.

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2. Heat Flux Conditions

During the experimental blast tests, the following measurements and observations were made on the fireball produced in each test:

- a. Internal heat flux measurements
- b. External heat flux measurements (radiant)
- c. High speed motion picture recording
- d. Spectrographic recording of external radiation

These observations were made on fireballs resulting from tests ranging in size from 1/10,000 to 1/25 of the SATURN C-2 propellant load. As a result the characteristics and behavior of the fireball were well established and a basis was obtained for predicting the characteristics of the fireball which might be expected from a vehicle failure.

In the event of a failure of a SATURN C-2 wherein a major portion of its propellant load participated in the initial explosion, a fireball would be formed up to 1200 feet in diameter. The fireball diameter is less dependent upon propellant mixing than is blast level. Unmixed propellant can react quickly enough to contribute to the initial fireball. The average temperature of the fireball would be approximately 3000F. The fireball would remain in contact with the ground for a period of 3 to 8 seconds and during this time its temperature would remain nearly constant. (Radiant heat loss appears to be balanced by continuing energy release during this period). As the fireball began to rise from the ground, it would begin to cool, but would continue to glow visibly for 15 to 20 seconds after ignition. The initial rate of rise of the fireball would be approximately 75 fps and the hot gas cloud would reach a height of at least 2000 feet within 60 seconds after

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ignition. Heat transfer to objects within the fireball would be primarily by radiation, and would occur at an initial rate of approximately 0.5 Btu/sq in -sec. An object remaining of the ground with an absorptivity of 0.8 would receive a total heat input of 1 to 3 Btu/sq in. Material fragments carried upwards with the fireball might receive a greater heat input, but since the heat flux drops rapidly with temperature, the additional energy received would be small. In the case of the SATURN C-5, a greater diameter fireball would be produced (approximately 2000 ft), but other characteristics would not be significantly different.

Quantities of fuel which were not consumed during the initial explosion would remain on the ground and burn in an air-fuel diffusion flame. Because of its volatility, liquid hydrogen could be expected to vaporize and burn quickly. However, an RP-1 flame might persist for several minutes depending upon the depths of the pools formed. Results of experimental studies of burning pools of kerosene have been analyzed to determine heat transfer characteristics of such flames. The analysis has indicated that surfaces within kerosene-air diffusion flames could not be expected to rise above 1100F. Details of this analysis are contained in Appendix A. This value is in agreement with results obtained from heat flux gages which were enveloped in flames from burning RP-1 during the SATURN blast tests. Maximum temperatures attained in these instances were between 800 and 1000 F. These temperatures correspond to a maximum heat transfer rate of approximately 0.02 Btu/sq in-sec.

Because of the complex structures of the SATURN vehicles and the many possible modes of failure, the manner in which the propellants were consumed could vary considerably from the conditions of the SATURN blast tests.

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However, in any event it is unlikely that heat transfer rates could be obtained greater than 0.5 Btu/sq in-sec which was the maximum rate observed with premixed propellants.

C. Analytical Model of the Nuclear Engine

For purposes of the analysis, the nuclear rocket engine was assumed to be patterned after the Kiwi-B class engine. Characteristics of the engine were determined from descriptions contained in Reference 3. The Kiwi-B class consists of at least three engine models varying principally in reactor design. For the purposes of this program the model variations are not significant.

The engine is designed to operate at power levels up to 1500 megawatts with durations from 300 to 900 seconds depending upon the mission. The propellant used is liquid hydrogen which is also used for regenerative cooling of the nozzle, reflector, and pressure vessel. The engine is of the direct cycle type, that is, the propellant is heated directly by passage through the reactor. After being heated, the hydrogen propellant expands through a conventional convergent-divergent nozzle producing propulsive thrust.

A schematic diagram of the Kiwi-B engine is shown in Figure 2. The configuration shown is that of the Kiwi-B-1 and 3. Model 2 differs principally in the location and design of the core support plate. The dimensions shown are approximate and details not pertinent to this program have been omitted.

The core of the reactor consists of an assembly of slender fuel elements which are oriented axially and supported from the aluminum support plate. The elements are constructed of graphite and contain graphite-uranium carbide fuel-rods. Each rod contains a number of axial cooling passages which are

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FIGURE 2

SCHEMATIC DIAGRAM OF KIWI-B-1 ENGINE

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) nominally 0.17 inches in diameter. The volume of the core occupied by the cooling passages varies from 18 to 27 percent between different engine models.

The reflector consists of two concentric cylindrical-rings. The inner portion is a solid graphite ring. The outer ring consists of twelve beryllium segments, each containing a control drum which is a solid rod of boral and beryllium. The movement of the drum is rotational about its own longitudinal axis.

The outer pressure vessel is of aluminum and is designed for an operating pressure of 650 psi at the core inlet. There is no bonding between the various elements of the reactor. The beryllium reflector segments are held in place mainly by the pressure vessel and the fuel elements are retained laterally by the graphite reflector ring.

Approximate weights of the engine components are as follows:

Core	3000 lbs
Support Plate	200
Graphite Reflector	800
Beryllium Reflector and	
Drums	2200
Pressure Vessel	<u>600</u>
	6800

The condition of the reactor at the time of a launching mishap is of particular interest. Characteristics which are pertinent to this analysis are temperature distribution, reactivity, and fission product inventory.

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From the hazard standpoint, it is desirable that the reactor temperature be as high as practicable at the time of launching. Since the reactor has a negative temperature coefficient of reactivity, its sensitivity to accidental increases in reactivity is less at elevated temperatures. This sensitivity determines the severity of power excursions which could occur accidentally. An additional consideration is the effect of temperature on the physical properties of the beryllium reflector segments. The ductility of beryllium is very low at ambient conditions but increases with temperature up to approximately 700F. As the ductility of a material increases, its resistance to fragmentation under impulsive loading also increases. Thus, in the event of a propellant explosion, the fragmentation of beryllium would be reduced if the reactor temperature were high.

The reactivity of the reactor is also important in determining the likelihood of an accidental power excursion. The fission product inventory at launching is important in determining whether a radiation hazard might result from a vehicle failure.

Through conversations with the Space Nuclear Propulsion Office of the Atomic Energy Commission, it has been established that the most likely condition of the engine during launching is as follows:

1. The reactor will be critical and operating at a low power level.
2. Energy removal will be occurring through radiation from the outer shell.

Under these conditions the reactor temperature will be above ambient. The actual temperature is unknown, but it is safe to assume that no component would be below room temperature at launching.

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Some accumulation of fission products will have occurred at launching, but the total inventory will be small compared to that resulting from normal operation.

D. Modes of Failure

It would be difficult to enumerate all the ways in which failure might occur in a system as complex as the SATURN vehicle. In this program, however, we are concerned principally in the effects on a nuclear engine. Therefore, the failure modes can be classified according to the initial condition of the engine and its location within the liquid propellant explosion.

The physical state of the engine prior to a propellant explosion is limited to two most likely cases:

1. Engine physically intact.
2. Reactor elements scattered, but intact.

If the engine were not subjected to impact loading such as from a fall, or to an accidental excursion, it would probably remain intact before detonation occurred within the chemical propellants. By intact, it is meant that the pressure vessel is not ruptured and that the reactor elements remain in their original configuration. The engine may become separated from its propellant storage and pumping system, but for present purposes may be regarded as intact.

If the engine should suffer a free fall from its initial launching height or greater, the aluminum pressure vessel would fail. Bursting of this outer wall might also result from an excursion caused by immersion in propellants or water, or by distortion due to impact. Any mechanism which would rupture the pressure vessel would also rupture the graphite reflector which is the

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only other containment factor. Therefore, scattering of the various reactor elements would result. Considerable fragmentation of the graphite modules could be expected; however, the beryllium reflector segments probably would remain intact. Further consideration is given to the fragmentation characteristics of beryllium in Section III-D.

With regard to its location within a propellant explosion, it can be concluded at the outset that the engine would be unaffected unless it were within the region enveloped by the fireball, that is, within approximately 600 feet of the center of a SATURN C-2 explosion. Beyond this distance the pressure levels and heat inputs would be insufficient to cause physical damage or significant increases in temperature. Within the fireball region, the most important variation in conditions occurs across the boundaries of the liquid detonation region. Therefore, cases where the reactor is within or outside of the liquids must be treated separately.

From these considerations four distinct situations emerge as the basic failure modes which should be considered. There are:

1. Intact engine within liquid detonation.
2. Intact engine outside liquid detonation.
3. Reactor components within liquid detonation.
4. Reactor components outside liquid detonation.

Each of these modes will be analyzed in detail so that the behavior of the engine components can be predicted.

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E. Possible Hazards

1. General

There are a number of hazards associated with the launching of large liquid propellant rockets. Chief among these are:

1. Blast
2. Thermal effects
3. Acoustic effects
4. Toxic effects
5. Flying debris

For each vehicle the potential hazards must be estimated and protective measures taken to prevent injury to persons and property. The primary protective measure is the establishment of safe distances for personnel, equipment and property not associated with the launching operation. Additional protective measures are required for launching personnel and equipment.

In assessing the hazards that could result from launching of a combined nuclear-chemical vehicle, such as SATURN with a NERVA engine for upper stage propulsion, we are primarily interested in those aspects which might require protective measures beyond those normally provided for the launching of a chemically propelled vehicle of nominally the same size. The hazards which could result from damage to a nuclear engine are:

- a. Blast
- b. Radioactivity
- c. Toxicity
- d. Scattering of reactor fragments

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2. Blast Hazards

The missions contemplated for the NERVA engines include thrust durations up to 920 seconds at 1500 megawatt power outputs. This amounts to an energy release during normal operation of 1.3×10^9 Btu, and it is presumed that the energy content of the reactor is not exhausted at the end of the mission. In comparison, if all the propellants of the SATURN C-2 configuration were allowed to react with sufficient air to provide a stoichiometric mixture, the energy released would be approximately 7.6×10^9 Btu. This comparison indicates that the potential blast hazard of the reactor is comparable to that of the liquid-propellant booster. To determine the maximum probable blast effect which might be produced, the mechanisms by which energy is released must be analyzed.

3. Radioactivity

Power is generated within a Kiwi-B reactor through the fission of the uranium 235 isotope contained within the graphite fuel elements. The fission reaction is induced by the absorption of neutrons contained within the core from earlier reactions. The fission of uranium produces a variety of particles or nuclides, many of which have a high specific activity. These radioactive fission fragments can produce harmful levels of radiation if they are allowed to concentrate in areas occupied by personnel.

The production of radioactive materials is directly associated with the generation of thermal energy in the reactor. Therefore, the accidental release of energy and radioactivity will be considered together in a discussion of power excursions in Section IV.

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4. Toxic Hazard

The introduction of toxic materials into a propulsion system gives rise to the possibility of these materials being accidentally dispersed through abnormal operation of the system. The Kiwi-B type reactor utilized a neutron reflector containing approximately 2200 pounds of metallic beryllium. Beryllium in the form of vapor or fine particles is a highly toxic material. The pressures and heat fluxes resulting from a liquid propellant explosion provide a mechanism by which beryllium might be introduced into the atmosphere. Thus, an analysis of the process is required so that an estimate of the possible hazard can be obtained. A discussion of the pertinent characteristics of beryllium are contained in Section III.

5. Fragment Scattering

The positive impulse (overpressure-time integral) of blast waves increases with the mass of the explosive substance to the 1/3 power. It would be reasonable to expect that scattering of debris from a vehicle failure would vary similarly. Analyses of debris patterns and motion picture records from the SATURN blast tests have confirmed this expectation. On this basis, it is predicted that debris scattering from a failure of a SATURN C-2 would be limited to a radial distance of approximately one mile with isolated fragments traveling farther. The presence of a nuclear reactor would not increase the hazard from flying debris, but would result in the distribution of toxic and possibly radioactive material fragments in the vicinity of the launching area.

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III. BERYLLIUM HAZARDA. Beryllium Toxicity

The outstanding physical and chemical properties of beryllium have resulted in its increased use in metallurgical applications. During the early 1940's experience in beryllium fabrication and refining showed that the metal and its oxides and salts could be very harmful, especially under conditions where finely divided particles or vapors were produced. Continued investigations of beryllium toxicity, dust and fume control measures, and analytical detection procedures have led to the adoption of industrial hygiene programs which have reduced the occurrence of "beryllium poisoning". A bibliography of reports on the toxicity and safe handling of beryllium can be found in OTS Selective Bibliography SB 413 (7).

Two general types of "beryllium disease" have been observed; the acute and chronic diseases. The acute phase involves two principal classifications - dermal or mucous membrane manifestations and pneumonitis. The symptoms of the acute disease may occur immediately after exposure to the metal or its salts. The chronic disease has occurred up to 10 years after exposure to beryllium and usually involves lung disorders (berylliosis). A review of the medical aspects of beryllium disease is found in the Progress Report on Toxicity of Beryllium, AMC Technical Report 7-665 (8), which describes work carried out under Air Force Contract (AF 33(600)-37211) for the Air Materiel Command.

Aside from several cases of dermatitis in individuals who are extremely

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sensitive to beryllium, the principal medical problems arise when beryllium and its compounds are used in applications which result in vapor concentrations or airborne particles of the materials. If small particles of beryllium become lodged in skin lesions, the lesion will persist until the beryllium is removed. The more hazardous condition, acute or chronic beryllium pneumonitis may occur after breathing the vapor or airborne particulate material.

It was noted quite early in the study of beryllium toxicity that apparent exposure to very minute amounts of beryllium could result in various forms of beryllium disease. In 1949, an advisory committee of the Atomic Energy Commission recommended the following limits for atmospheric concentrations of beryllium or its compounds (8).

1. The in-plant concentration of beryllium shall not exceed 2 micrograms per cubic meter as an average concentration throughout an eight-hour day.
2. Even though the daily average might be within the limits of this recommendation, no personnel should be exposed to a concentration greater than 25 micrograms per cubic meter for any period of time, however short.
3. In the neighborhood of a plant handling beryllium compounds, the average monthly concentration should not exceed 0.01 micrograms per cubic meter.

There have been no reported cases of beryllium poisoning under conditions in which these standards were observed.

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B. Beryllium Fragmentation

The production of beryllium vapors or particles in a propellant explosion would be greatly augmented by fragmentation of the reflector segments. The increased surface area could result in a higher rate of vaporization, and fine particles could be produced in the fracturing process.

Beryllium, as compared to most metals, is a brittle material, and as such is subject to fracture when stressed. Its mechanical properties vary widely with methods of fabrication (9). Large beryllium parts are usually formed by powder metallurgical methods. Tensile tests on specimens fabricated from powder indicate elongations ranging from 0.2 to 15 percent at room temperature. These values increase with temperature to 700 F where elongations of 60 percent are reported.

The characteristics of the beryllium to be used in the Kiwi-B reflector are now known, except that a high degree of purity is desired to reduce formation of objectionable radionuclides. It is assumed that the reflector segments will exhibit some degree of ductility and, therefore, will not shatter when stressed.* This assumption has been substantiated to some

* This is an important assumption in that it affects the conclusions reached regarding the beryllium hazard. Attempts to learn the properties of the beryllium used have failed, however, the authors feel reasonably safe in making this assumption. If it is found that the reflector segments are glass-like in character, this analysis should be reviewed.

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extent by exposure tests of beryllium samples in conjunction with the SATURN blast tests. Small samples of beryllium were mounted within the liquid spill area in the final 1/25-scale test so that mechanical, thermal or chemical effects could be observed. The beryllium samples emerged intact whereas samples of materials such as glass, graphite, and silicon in earlier tests were shattered by the blast. Details of this work are contained in Reference 10.

Assuming a small degree of ductility, it can be concluded that fracturing of the segments would occur, but that the dimensions of the fragments formed would be of the same order as the thickness of the reflector. The pressures generated within the blast are not sufficient to cause scabbing or other fragmentation effects associated with explosive loading. (See Reference 5 for a description of fragmentation effects of the SATURN blast tests).

Some smaller particles certainly would be ejected from fracture surfaces, but they would constitute a negligible fraction of the total reflector weight. An exception to this behavior would occur at points of stress concentration within the structure. A diagram of a reflector segment cross-section is shown in Figure 3. Two areas are indicated in the section which are considered to be vulnerable to destructive forces. These areas might be expected to produce small particles susceptible to thermal heating. The most extensive vulnerable areas are the webs formed by the large control-rod hole. Forces on the segment of almost any form will produce high stresses in these areas. An analysis of various types of failure in these webs indicates that the area shown represents the maximum amount of metal likely to be removed. The edges

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~~CONFIDENTIAL~~ FIGURE 3CROSS-SECTION OF BERYLLIUM REFLECTOR SEGMENT~~CONFIDENTIAL~~

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of the area are the locations at which fracture would occur under uniform external pressure. The amount of metal contained within these areas is approximately 85 pounds. It is possible that fragmentation of this material could occur in fracture, or that it could be ejected at high velocity with fragmentation resulting upon impact with other surfaces.

In addition to the control-rod hole, there are cooling passages within the segment, however, details of these were not available to this program. It is assumed that the diameters of these are small compared to the segment thickness so that they do not produce stress concentrations.

The other vulnerable area occurs at the edges of the segment. Here chips of metal could be removed by impact or abrasion. In this case the extent of vulnerability was determined by the maximum fragment size susceptible to thermal heating by the blast. This size is found to be approximately .40 inch (see Section III-C). Therefore, the boundary of the vulnerable area was established at .40 inches from the edge. The amount of material represented by this area along all edges of the segments is approximately 20 pounds.

If another 5 pounds is allowed for small fragments created by other effects, the total amount of vulnerable beryllium is 110 pounds, or 5 percent of the total quantity present. It is considered improbable that this amount of small fragments could be produced. However, this quantity can be used as a basis for determining the maximum credible beryllium hazard.

C. Beryllium Vaporization

The high boiling point of beryllium (5030F) eliminates the possibility of vaporization due to boiling in a propellant explosion. However, beryllium does vaporize at measurable rates at much lower temperatures. Vaporization rates as a function of surface temperature are shown in Figure 4. Data for

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this plot were obtained under vacuum conditions (11). In the presence of oxygen or nitrogen, the rate of evaporation is considerably reduced due to the formation of protective coatings (9). On the other hand, in the presence of water vapor, the evaluation of BeO vapor can exceed that of beryllium by a factor of 10 (12). Therefore, under the conditions of a propellant explosion, the data of Figure 4 can serve only as a rough guide to the anticipated vaporization rates. It is apparent, however, that a runaway reaction (combustion) will not occur, even in the presence of pure oxygen, until surface temperatures above the melting point have been obtained.

To determine the surface temperatures which would be attained by beryllium fragments in a propellant explosion, temperature-time relationships were calculated for various geometric shapes. The results of these calculations are shown in Figure 5. A constant heat flux was assumed and the surface temperature was normalized by using the temperature-flux ratio. This ratio was determined as a function of time using transient heat conduction relations contained in Reference 13. The surface temperature of a fragment of a particular shape and after a given time of heating is obtained by multiplying the temperature-flux ratio by the actual heat flux. It is seen that in the time of interest in this program (fireball duration less than 10 seconds), any fragment with a minimum dimension greater than 2 inches behaves as a semi-infinite body. That is, its surface temperature is independent of its shape.

By combining these relations with the vaporization rates in Figure 4, it is quickly discovered that essentially no vaporization would occur from the surfaces of undamaged reflector segments or large fragments. Surface

CONFIDENTIAL FIGURE 4VAPORIZATION RATES OF BERYLLIUM**CONFIDENTIAL**

FIGURE 5

SURFACE TEMPERATURES OF BERYLLIUM SHAPES

WITH CONSTANT HEAT FLUX ON ALL SURFACES

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temperatures of such pieces would not rise more than 300F during the maximum exposure predicted (0.5 Btu/sq in - sec. for 8 seconds). Therefore, an analysis of the situation was conducted to determine a "critical fragment size" such that any fragment smaller than this size would be substantially vaporized. From a variety of considerations, it appeared that the critical size would be a sphere of 0.4 inch diameter. For non-spherical particles, the minimum dimension of the particle should be considered. As shown in Figure 5, a 0.4 inch particle would reach a temperature approximately equal to the melting point of beryllium (2340 F) if exposed to the maximum anticipated heat flux. The temperature distribution within particles of this size and smaller would be nearly uniform so that the entire particle would liquify uniformly. If liquifaction should be achieved, break-up of the fragment into small droplets would be likely to occur and the vaporization rate would be enhanced due to the increased surface area. Particles larger than the critical size would remain solid and would not reach a high enough temperature to cause a significant amount of vaporization. It can be shown that a fragment raised to a temperature near the melting point will lose the bulk of its energy by radiation and only a small amount by sublimation. As a result, only 1 or 2 percent of its mass would be vaporized.

An additional consideration is the possibility of particles being carried upwards with the fireball and thereby being exposed to a longer period of heating. If it is assumed that the updraft within the fireball is approximately of the same velocity as the initial rate of rise of the fireball itself, it has been found that particles smaller than 0.4 inches can be carried upwards by the updraft. This fact was determined by comparing terminal velocities of

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particles of the density of beryllium with fireball rise rates determined from the experimental program.

The fact that the critical size, as determined by aerodynamic considerations is the same as that determined from the standpoint of heat transfer is a coincidence. However, from the analysis a reasonable basis is obtained for predicting the maximum extent of beryllium vaporization. It is concluded that fragments of beryllium less than 0.4 inches in minimum size can be substantially vaporized within a propellant explosion.

D. Beryllium Dispersion

1. Instantaneous Release

Assuming that a certain quantity of beryllium is vaporized during a launching mishap, the dispersion of the resulting vapor or particles must be studied to determine whether a hazardous concentration will occur at any point near the ground. Dispersion occurs as a result of the combined effects of thermal rise, wind, and atmospheric turbulence. The dispersion of airborne particles by these mechanisms has been investigated by many workers, so that no attempt will be made to present the general subject here (14,15,16,17,18). A study directed at dispersion of toxic materials specifically arising from launching operations has been carried out by Aeronutronic (19). Only those aspects of the subject which affect this analysis will be discussed here.

Because of the short duration of the propellant explosion compared to dispersion times the beryllium vapor can be considered to have been formed instantaneously. Therefore, dispersion of the vapor can be expected to occur in accordance with Sutton's instantaneous point-source equation as follows:

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$$X = \frac{2Q}{\pi^{3/2} C_d C_y C_z (\bar{u} t)^{3/2 (2-n)}} \exp(-A)$$

$$\text{where } A = \frac{1}{(\bar{u} t)^{(2-n)}} \left[\left(\frac{d - \bar{u} t}{C_d} \right)^2 + \left(\frac{y}{C_y} \right)^2 + \left(\frac{h}{C_z} \right)^2 \right] \quad (1)$$

where

X = concentration (Mass/unit volume)

Q = source strength (Mass)

C_d, C_y, C_z = diffusion coefficients (length $\frac{n}{2}$)

n = stability parameter (index dependent upon temperature gradient)

$\bar{u}$ = wind velocity (length/time)

t = time

d = distance downwind

y = distance crosswind

h = release height

This equation indicates the instantaneous concentration as a function of time, position and meteorological conditions. Experiments have shown that reasonable agreement is obtained with actual dispersion behavior when suitable values are used for C_d, C_y, C_z and n.

In this program we are primarily concerned with the maximum concentration existing at any one time following the explosion. The maximum occurs directly below the vapor cloud so that equation 1 reduces to the following:

$$X = \frac{2Q}{\pi^{3/2} C_d C_y C_z d^{3/2 (2-n)}} \exp \left[- \frac{1}{d^{2-n}} \left(\frac{h}{C_z} \right)^2 \right] \quad (2)$$

This relation indicates that if the vapor is released above ground level ($h > 0$), the concentration beneath the cloud will rise to a maximum at some

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distance from the release point and will then drop off with increased distance.

An equation for this maximum is obtained by differentiating equation (2) with respect to d and setting the result equal to zero. The result is as follows:

$$X_{\max} = 0.147 \frac{Q}{h^3} \frac{C_z^2}{C_d C_y} \quad (3)$$

and the distance at which the maximum occurs is given by:

$$d_{X_{\max}} = \left(\frac{2 h^2}{3 C_z^2} \right)^{\frac{1}{2n}} \quad (4)$$

Recommended values of the diffusion coefficients vary between 0.2 and 0.6 meters $n/2$ and recent work indicates that C_z is usually less than C_d and C_y (18). The stability parameter varies between 0.0 and 0.8 with commonly accepted values running from 0.15 for lapse conditions to 0.50 for a strong inversion.

From the standpoint of maximum concentration a pessimistic assumption would be isotropic conditions, that is, $C_d = C_y = C_z$. In this case, $X_{\max}$ is dependent upon Q and h alone (equation 3).

The value to assign to the release height h must be given careful thought since the ground concentrations near the release site are strongly dependent upon this factor. Due to the great release of energy in a propellant explosion, the resulting hot gas cloud rises soon after it is formed. Theoretical predictions of the rise vary widely (15) but the maximum rise is found to be dependent upon meteorological conditions and the quantity of energy released. Due to the variance in theoretical predictions, it appeared best in this case to utilize the results obtained from the experimental blast tests (5). The

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clouds formed in these tests were similar in composition to those which would occur in a failure of the SATURN, even though the energy contents were lower. The increased energy release of a full-scale SATURN failure would result in a greater cloud rise. Therefore, the use of the scaled-down experimental results is a conservative procedure appropriate to this analysis. The clouds resulting from the tests achieved a height of approximately 2000 feet within 60 seconds after each explosion. After this time, additional rise varied between the two tests. Thus, a 2000-foot release height is used here.

Using this value for h and a maximum credible source strength of 110 pounds (section III - B), a maximum concentration is obtained of 32 micrograms per cubic meter. This value is of the same order as the maximum allowable concentration for instantaneous exposure (25 micrograms/cubic meter). Because of the conservative nature of the assumptions used in arriving at the maximum concentration, it is improbable that this value would be achieved.

The maximum concentration occurring at points at ground level in the downwind direction are shown in Figure 6. This plot was obtained using equation 2 with the following values for the meteorological parameters:

$$C_x = C_y = C_z = 0.2$$

$$n = 0.5$$

These values represent adverse conditions from the standpoint of dispersion of toxic materials. As seen in the figure, the highest concentration occurs at a distance of 21 miles from the launching site, and drops off slowly with distance. Variations in the stability parameter n (temperature gradient) would change the distance at which the maximum concentration occurred, but

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FIGURE 6MAXIMUM INSTANTANEOUS BERYLLIUM CONCENTRATIONSOCCURRING DOWNWIND AT GROUND LEVEL~~CONFIDENTIAL~~

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not the magnitude of the concentration. Non-isotropic diffusion conditions ($C_z < C_x$) would result in reduced concentrations.

In addition to the maximum instantaneous concentration, consideration must be given to the cumulative exposure occurring at each point downwind. Total exposure is obtained by integrating equation 1 with respect to time from zero to infinity. For any position the total exposure in units of concentration multiplied by time is:

$$E = \frac{2Q}{\pi C_y C_z \bar{u} d^{2-n}} \exp - \left[\frac{1}{d^{2-n}} \left(\frac{y^2}{C_y^2} + \frac{h^2}{C_z^2} \right) \right] \quad (5)$$

The maximum exposure occurs in the downwind direction ($y = 0$) and its magnitude is obtained by differentiating equation 5 with respect to d and setting the result equal to zero.

$$E_{\max} = \frac{2Q C_z}{\pi e C_y h^2 \bar{u}} \quad (6)$$

Maximum exposure occurs at a downwind distance:

$$d_{E_{\max}} = \left(\frac{h^2}{C_z^2} \right)^{\frac{1}{2n}} \quad (7)$$

In contrast to the maximum instantaneous concentration, the maximum exposure is dependent upon the wind velocity and occurs farther from the release point. The maximum exposure for a release of 110 pounds of beryllium at 2000 feet with isotropic conditions ($C_y = C_z$) is shown in Figure 7 as a function of wind velocity. It is seen that the maximum allowable daily exposure (2 micrograms/cubic meter x 8 hours = 5.8×10^4 microgram-seconds/cubic meter) would be

CONFIDENTIAL FIGURE 7BERYLLIUM EXPOSURE AT GROUND LEVEL IN DOWNWIND DIRECTION**CONFIDENTIAL**

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exceeded only if the wind velocity were less than 1 mph. Thus, the beryllium exposure hazard could be maintained below safe levels by avoiding launching at extremely low wind velocities.

Two factors which affect dispersion of airborne materials have not been included in this analysis. These are rainout and fallout.

The removal of material from the cloud by precipitation is termed rainout. Its effect is to reduce the air concentration of the contaminant, but to increase the ground coverage in localized areas. This effect is important for radioactive materials, but not chemically toxic materials such as beryllium. Rainout would reduce the beryllium vapor hazard if it occurred and so was not included in the analysis.

Fallout is the term used to describe the descent of contaminant particles due to gravity. Its effect is a downward motion superimposed on wind movements, and it can result in increased airborne concentrations at ground level. However, in the case of beryllium the particles of interest are those smaller than 10 microns, since larger particles do not constitute a hazard. The fallout rates of beryllium particles below 10 microns are so small that the effect on ground concentrations is negligible.

2. Continuous Release

It is possible that some conditions could exist during a vehicle failure wherein beryllium vapors were released over an extended period of time. Non-volatile fuels which were not consumed in the initial explosion could continue to burn for several minutes or even hours after the failure. If beryllium fragments were included in these flames, vapor would be produced continuously. If the beryllium release rate and the wind velocity were constant, an

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equilibrium concentration distribution would be established in the downwind direction. This distribution is described by Sutton's continuous point source equation as follows:

$$X = \frac{2 \dot{Q}}{C_y C_z \bar{u} d^{2-n}} \exp \left[-d^{(n-2)} \left(\frac{y^2}{C_y^2} + \frac{h^2}{C_z^2} \right) \right] \quad (8)$$

where

$\dot{Q}$ = the release rate of the contaminant.

The effective release height for continuous burning of a liquid fuel is zero since dilution with air occurs quickly. Photographic records of the SATURN blast tests show that the smoke from afterburning of RP-1 remained close to the ground. Thus, for the downwind direction ($y = 0$), equation 8 reduces to the following:

$$X = \frac{2 \dot{Q}}{C_y C_z \bar{u} d^{2-n}} \quad (9)$$

In Figure 8 this relation is shown for various wind velocities. The ratio of concentration to release rate is plotted against distance. The strange combination of units used for this ratio results from an attempt to use engineering units consistently throughout this analysis, except in the case of beryllium concentrations where cgs units are in common usage.

In Appendix A an analysis of heat transfer in a kerosene-air diffusion flame has shown that the maximum temperature that would be attained by a surface immersed in such a flame would be approximately 1100F. If the vaporization rates of beryllium in Figure 4 are extrapolated to 1100F, the rate obtained is 2.0×10^{-15} lb/in²-sec. The total surface area of the beryllium reflector

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FIGURE 8

BERYLLIUM CONCENTRATION AT GROUND

LEVEL FROM A CONTINUOUS SOURCE

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segments is $2.3 \times 10^4 \text{ in}^2$. Using the maximum allowable concentration for instantaneous exposure (25 micrograms/cubic meter), the concentration-release rate ratio is found:

$$\frac{X}{Q} = \frac{X_{\max}}{r_v A} = 5.4 \times 10^{11} (\mu\text{gr}/\text{m}^3) \quad (\text{lb}/\text{sec})$$

Referring to Figure 8, we see that this value would not be obtained anywhere, except at the release point. Even if fragmentation were to occur causing an increase in surface area by a factor of 10 or 100, the hazard would not extend to any significant distance.

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IV. EXCURSION HAZARD

A. Blast Effects

The primary effect of a reactor excursion is the sudden release of energy. This energy release is manifested primarily in the heating and vaporization of reactor components. Component vaporization can result in hazardous concentrations of radioactive or toxic materials. These aspects will be discussed in Sections IV-B and IV-C below. The kinetic energy resulting from component vaporization creates a blast wave which, in the case of a rocket vehicle failure, could augment the blast effects from the chemical propellants and increase the blast hazard.

Energy release from a reactor occurs at a high rate whenever some factor causes its reactivity to become super-critical with respect to prompt neutrons. In the case of the Kiwi-B, this result can be caused by the following:

1. Control system malfunction.
2. Increased reflectivity due to immersion in or flooding of the core with reflecting liquids.
3. Distortion of the core into a more favorable geometry.

The rate of energy release continues to rise until the reactivity of the reactor is reduced to a delayed-critical level. The mechanisms by which this occurs are:

1. Reduced reactivity with increased temperature.
2. Increased reactor volume due to expansion of vaporized fuel element materials.
3. Loss of fuel from reactor by escape of fuel vapor.

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Theoretical analyses have been made of various accidents which could occur during flight testing of the Kiwi-B (2, 3). Several of these could result in a reactor excursion. The "maximum credible accident", that is, the worst accident with a finite probability of occurrence, would result in an energy release of approximately 8.5×10^6 Btu, more than half of which would be absorbed by heating of fuel elements. An excursion of this magnitude could result from immersion of the engine (intact) in water or propellant, or by removal of all control rods.

A more severe excursion would result if the reactor were compressed uniformly to the extent that cooling passages were completely collapsed. A 20 percent reduction in volume would produce an energy release of 7.1×10^7 Btu. The probability of such an event is regarded as nil and such an accident has been labeled the "maximum incredible accident". Thus, those who have studied this problem earlier regard the blast potential of the Kiwi-B as a very small fraction of that of the liquid-propellant booster (7.6×10^9 Btu maximum).

To provide information relating to this program, a series of tests were conducted to determine the compressibility of nuclear grade graphite. Details of the test procedure and results are contained in Appendix B. It was discovered that under pressures equal to measured liquid detonation pressures (100,000 psi) a permanent compression is obtained in graphite equal to the void volume. In addition, an elastic compression is produced of approximately 16 percent. This elastic deformation would be removed upon release of the pressure, but for a brief period of time, compressions of up to 40 percent could occur theoretically.

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Analysis of the structure of the Kiwi-B shows that the pressure vessel and reflector would offer little or no resistance to compression at these pressures. (A discussion of the mechanical behavior of the reactor is contained in Appendix C). The increased reactivity caused by this deformation theoretically could result in a high energy release rate and a total release greater than the above-described "maximum credible accident". The probabilities of various accidents are discussed further in Section V wherein each mode of failure is considered separately.

B. Radioactivity Effects

The dispersion of radioactive fission products released during a reactor excursion without a propellant explosion is discussed in Reference 3. The conclusion reached is that radiation doses occurring at ground level would be within tolerable limits. The effects of a simultaneous occurrence of an excursion and a liquid propellant explosion could be the following:

1. Increased excursion energy.
2. Increased vaporization of fission products.
3. Greater effective release height of radioactive products.
4. Scattering of reactor fragments.

The probability of producing a more severe excursion than the maximum credible accident described above is regarded as small. Therefore, it is concluded that the fission product inventory probably would not be increased. For the maximum credible accident, 15 percent vaporization has been predicted, and a release of 15 percent of the fission products was assumed for the dispersion study. If, following the excursion, fuel elements were separated

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from the reactor, additional release of included fission products could occur. Because of the high sublimation temperature of the graphite structure, it would remain in the solid state, and vaporization of fission products would be limited to the surfaces of the fragments. However, combustion of smaller fragments could occur, particularly if they came in contact with high concentrations of oxygen while at high temperature. If 100 percent release were obtained due to combustion or heating from the propellant reaction, an increase in radiation dosage would occur by a factor of 7.

The increased release height caused by the rise of the hot gas cloud would reduce the radiation exposure near the launching site. The combined effects of increased vaporization and release height would produce an increased exposure over that calculated in Reference 3 only at distances of the order of 10 miles or greater. At these distances the calculated doses are small and even an increase by a factor of 7 would not render them harmful.

The scattering of radioactive debris in the vicinity of the launch site could create a local problem affecting reuse of the launching facility. Thus, it is concluded that the occurrence of a propellant explosion in a combined nuclear-chemical vehicle would not create a serious radiation hazard beyond the immediate area surrounding the explosion.

C. Toxicity Hazard

The possibility of a beryllium vapor hazard arising from a propellant explosion has been discussed in Section III. It is of interest here to examine the possible release of beryllium vapor through a reactor excursion.

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Two mechanisms can be postulated by which an excursion might affect the amount of beryllium released. These are:

1. Fragmentation of reflector segments.
2. Vaporization of reflector segments.

The physical behavior of a Kiwi-B reactor during the maximum credible accident is described in Reference 2. Rates of pressure rise and thermal effects are predicted. Since the beryllium segments are insulated from the fuel elements by the graphite reflector, it is apparent that these effects would be attenuated before reaching the beryllium. The maximum pressure predicted is of the same order as that occurring in a liquid propellant explosion, but the rate of rise is probably less. Therefore, it is safe to assume that beryllium fragmentation resulting from an excursion would not be more extensive than that resulting from the propellant explosion.

Thermal energy from the heated core would not reach the beryllium segments during the course of the excursion or the propellant explosion. Therefore, if the reactor remained intact, no beryllium would be released within the fireball. The beryllium would be heated slowly, however, by conduction of heat through the graphite reflector. The quantity of energy contained within the graphite core following the excursion would be sufficient to raise the reflector to a high temperature, and energy generation continues after the excursion due to the decay of fission products.

Because of the high thermal conductivity of beryllium as compared to graphite, the thermal gradient between the core and the aluminum pressure vessel would be the highest in the graphite reflector. The temperature distribution within the beryllium would remain nearly uniform. Thus, the beryllium temperature could not rise far above the melting point of aluminum, since at this

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point the pressure vessel would fail and disassembly of the reactor would occur. At the aluminum melting point the vaporization rate of beryllium is very low so that the quantities released would be harmless. Therefore, it would appear that any beryllium release resulting from an excursion would be negligible compared to that which could result from a propellant explosion.

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V. ANALYSIS OF FAILURE MODES

A. Intact Reactor Outside Detonating Liquid

If an explosion of liquid propellants should occur during the launching of a combined nuclear-chemical vehicle, it is most likely that the reactor would be physically intact and would be outside any region of detonating liquids. Under these circumstances it would experience blast pressures below 2000 psi followed by immersion in the fireball. It is very unlikely that these conditions would have any effect on the reactor which would cause a hazard. Damage to light structures such as the rocket nozzle, the head end of the chamber, and the propellant storage and feed system would certainly occur. Collapse or removal of the nozzle with exposure of the core is a distinct possibility. However, the blast pressures would not be sufficient to cause distortion of the core or fracturing of any of the reactor elements. The pressure vessel, being supported by the core from within, would probably remain intact and continue to hold the assembly together. If the nozzle were carried away and the core exposed, or even if disassembly should result, the thermal effects of the fireball would not cause significant vaporization of the reactor components.

It is possible that the propellant blast might contribute indirectly to a reactor excursion. For example, the reactor might be torn from its mountings by the blast and caused to impact on the ground or in water. In this case a comparatively harmless excursion could result from distortion or immersion. Thus, it is safe to say that this mode of failure would not produce a serious hazard other than that from the propellant blast.

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B. Separate Reactor Components Outside Liquid Detonation

In Section II-D a number of possible mechanisms were postulated whereby disassembly of the reactor could occur prior to the propellant explosion. Under these circumstances the components would be exposed to the conditions described in Section V-A above. Here again the blast pressures would be insufficient to cause fracture of the reactor components directly. However, considerable momentum could be imparted to the components so that fragmentation could occur upon impact. Fragmentation of the beryllium segments would probably be less than the maximum credible degree established in Section III-B since it is improbable that all segments would be damaged. However, it is likely that a small quantity of beryllium fragments would be formed by abrasion or impact and that some vaporization would occur within the fireball.

A higher degree of fragmentation would probably occur in the fuel elements. The shape of the elements is such that they are susceptible to fracture, and because of the brittleness of graphite, a considerable fraction of the fuel element material would be reduced to fine particles. Fragmentation of the graphite would not be hazardous in itself, but if an excursion had preceded the blast, fragmentation of the fuel elements would allow an increase in the quantity of fission products released. The total release might exceed the 15 percent assumed for the maximum credible excursion accident, but, as discussed in Section IV, the radiation dosages resulting would not be serious.

The fragmentation of beryllium and fuel elements in the launching area might result in local contamination which would require precautionary measures during future use of the area. The radiation hazard would disappear with time but concentrations of beryllium particles on the ground could present a continuing problem.

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It is assumed that with the reactor disassembled, there is no possibility of an excursion. Analyses of the reactivity of individual fuel elements (3) indicate that no mechanism could bring about criticality in an individual element. Since there is no bonding between elements, it is unlikely that a sufficient number could remain in contact for prompt neutron criticality to occur. The effect of a propellant blast would be to increase the extent of disassembly and dispersion.

Thus, it is concluded that this failure mode might result in the release of both beryllium and radioactive fission products, but the quantities released would not create hazardous conditions beyond the immediate vicinity of the vehicle failure.

C. Intact Reactor Within Liquid Detonation

Considering the probable extent of the liquid detonation region as shown in Figure 1 and the many possible variations in the manner in which a vehicle failure might occur, it appears that a finite probability exists that immersion of the reactor in mixed liquid propellants could result prior to an explosion. Under these circumstances the following sequence of events would take place:

1. Because of immersion, the reactor would be super-critical and a power excursion would result. The total duration of the excursion would be 35 milliseconds or greater. This is the duration calculated (2) for instantaneous immersion. Since immersion requires a finite time, the time from beginning of immersion to vaporization of graphite would probably be greater than 35 milliseconds.

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2. Unless ignition had occurred earlier, heating of the graphite and release of graphite vapor would ignite the propellant mixture causing a detonation.
3. The detonation would cause compression of the reactor resulting in a further increase in reactivity.
4. Under the combined effects of internal and external pressures, rupture of the pressure vessel would probably occur and the reactor components would become separated and exposed to the thermal effects of the fireball. Fragmentation of the reflector segments would result in a release of beryllium vapor of an amount not exceeding 110 pounds. Fragmentation and combustion of the fuel elements would allow release of a large portion of the fission products.

The maximum credible release of beryllium vapor has been investigated in Section III, and it was concluded that concentrations resulting would be within tolerable limits.

From the nuclear reaction standpoint it appears that an excursion of some degree would result.

The various reactivity increments available are listed below:

Immersion	9 dollars
Inelastic compression	9-14 dollars
Elastic compression	8 dollars

The increment caused by immersion was obtained from Reference 2. The increments due to compression were estimated by assuming compression of the reactor core with no change in the reflector. This condition appeared to simulate the actual reactor behavior as predicted in Appendix C. The

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increased reactivity under this condition has been estimated at 50 cents per percent change in core density (20).

It would be unrealistic to expect that the various reactivity increments could be achieved simultaneously. The following are a number of the factors which act to decrease the additional reactivity.

1. The time required to compress the reactor is comparable to the maximum predicted pressure duration. Therefore, the increments due to immersion and compression would not be effective simultaneously, since at the end of the pressure pulse the density of the surrounding fluid is reduced and the immersion increment is removed.
2. Even if immersion and compression were to occur simultaneously, their reactivity increments would not be additive. With the increased reflectivity due to immersion, the effect of compression is reduced.
3. Removal of elastic compression by expansion of the core would take place in a time which is short compared to the predicted duration of the excursion.
4. Compression of the core would be non-symmetrical and would create gaps between the beryllium reflector segments. The resulting neutron leakage would cause a decrease in reactivity.

In view of these factors, it appears that the maximum reactivity increment which could be sustained long enough for a self-limiting excursion is not greater than that caused by immersion alone. The only conceivable exception to this conclusion would be the case where detonation of the propellants

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occured simultaneously with the attainment of the graphite vaporization temperature in the core. In this case the external pressure would resist the self-terminating mechanism of the excursion and a more extensive reaction than the maximum credible accident would result. This event would require the detonation and temperature rise to be coincident within a period of one millisecond (the predicted duration of the detonation pressure). The probability of this occurring would seem to be sufficiently remote so as to warrant no further consideration. However, the possibility of propellant ignition by the heated core presents a mechanism by which the two events could occur simultaneously. Predicted behavior of the core during immersion is presented in Reference 2. The predicted temperature history of the fuel rods indicates that a temperature sufficient to ignite a propellant mixture would be attained approximately 2 milliseconds prior to the commencement of graphite vaporization. If the propellants were in contact with the core, chemical reaction could be initiated at a time such that the detonation pressures would resist the expansion of the core due to graphite vaporization. As a result, the energy release could exceed that predicted for immersion alone. It is likely that this event could be ruled out if a more detailed description of the reactor behavior were available. Because of non-uniform power generation in the core, the temperature of exposed fuel-rod surfaces probably lag behind those within the core volume. Therefore, internal pressure would develop before propellant ignition occurred. Since the information required to draw this conclusion is not at hand, the possibility of an excursion more serious than the "maximum credible accident" cannot be ruled out. Arthur D. Little, Inc., can only point out that this mechanism exists in theory. Those familiar with detailed characteristics of the reactor can determine whether an actual hazard exists, and can predict the probable results.

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During this program no quantitative calculations have been made of energy releases for various reactor accidents. Information on which this type of analysis would be based (2) has been found to be overly-conservative, and, in addition, excursion calculations are being carried out currently at the Los Alamos Scientific Laboratory.

Other possible effects of this failure mode include extensive scattering of reactor components. It has been estimated that debris would be scattered over distances up to one mile from the point of failure. This area would be contaminated with radioactive core material and beryllium fragments, and would require precautionary measures for further use.

D. Separate Reactor Components Within Liquid Detonation

An explosion wherein reactor components were contained within the liquid detonation would produce results similar to that predicted for the mode previously discussed. The major difference would be that an excursion would not result from immersion of the components. Therefore, if an excursion had not occurred prior to disassembly of the reactor, there would be no significant release of radioactive fission products. Fragmentation of beryllium could certainly be expected with some degree of vaporization. In addition, extensive scattering of fragments of reactor elements would be expected.

E. Other Possible Failure Modes

This study has been primarily concerned with a vehicle failure wherein a propellant detonation resulted. The experimental program which preceded this analysis was directed at this type of failure. It is possible, however,

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for a vehicle to fail and burn with little or no blast effect resulting. In fact, a review of launching records of large vehicles indicates that this might be the case in the majority of mishaps. Thus, it would seem appropriate to comment on this type of failure.

If a nuclear reactor were involved in a launching failure wherein no blast was produced, reactor excursions and thermal effects would be the only hazard-producing mechanisms. The likelihood of an excursion would not be significantly reduced, so the presence of fission products would be possible. The reactor could be exposed either intact or disassembled. However, it is not likely that a large degree of fragmentation would occur. Beryllium segments would remain intact or in large fragments, and this would require prolonged heating before significant vaporization could occur.

The factors in this type of failure which could create hazardous conditions are:

1. Prolonged period of energy release and heat input to reactor components.
2. Reduced release height of contaminants due to lower rate of energy release.

With regard to heating effects, it seems likely that heat fluxes would not exceed those occurring in explosive failures (0.5 Btu/sq in-sec.). The vaporization rate of beryllium fragments would be low until surface temperatures approached the melting point (2340F). The rate of temperature rise of large beryllium fragments is seen in Figure 5 to be approximately 20 degrees F per second at a flux rate of 0.5 Btu/sq in-sec. Therefore, it would require nearly two minutes of continuous exposure before hazardous rates of vaporisation would begin. It seems unlikely that mixing and combustion of

The radiation hazard would not be increased in this type of failure since there would be no mechanism by which fission products could be released to a greater extent than predicted in the maximum credible accident.

F. Probability of Maximum Effects

With regard to immersion, the total volume of propellants contained in the SATURN C-2 configuration is approximately 33,000 cubic feet, or a volume

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equal to that of a hemisphere of 25-foot radius. If it is postulated that the position of the reactor at the time of the blast will be somewhere within a hemisphere of radius equal to the initial height of the reactor and that this height is 100 ft., this "position volume" is 64 times as great as the propellant volume. On this basis the probability of the reactor being immersed at any given time would be 1.6 percent. If it is assumed that the volume of mixed propellants was less than 20 percent of the total propellant volume, the probability of the reactor being exposed to a liquid detonation is found to be less than one-half of one percent.

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VI. CONCLUSIONS

During this analysis it has been necessary to make assumptions or estimates regarding the extent of various processes. In each case an effort was made to assure that the assumption was conservative, but not unrealistic. As a result the effects predicted for a nuclear-chemical vehicle failure are regarded as improbable but not impossible, or in terminology used in References 2 and 3, the predicted effects are the "maximum credible" hazards which could result. After consideration of the various potential hazards and the mechanisms by which these hazards could be generated, the most serious effects predicted are as follows:

1. The quantity of beryllium vaporized during a propellant explosion depends upon the design of the reflector elements rather than the total quantity present. Only small fragments of beryllium would be susceptible to vaporization.
2. In the case of the Kiwi-B reactor, a release of beryllium vapor or particles could result within the fireball, but the maximum concentration occurring at ground level would not exceed the maximum allowable concentration for instantaneous exposure. Total exposures could exceed maximum recommended levels only if wind velocities were low (1 mph or below).
3. There is little likelihood of a propellant blast causing a nuclear power excursion of a greater magnitude than that described in Reference 2 as the "maximum credible accident".

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4. Dispersion of fission products could exceed that predicted for an accidental power excursion prior to launching (3). The increased concentrations of radioactive materials would not exceed tolerable limits except possibly within the immediate vicinity of the vehicle failure.
5. Fragments of reactor material could be scattered around the launching area to distances of up to one mile.
6. Contamination of the launching area with beryllium particles and fission products could prevent further use of the area until radiation had subsided or until precautionary measures had been taken against beryllium poisoning.
7. The most serious effects would result from immersion of the reactor in a detonating liquid propellant mixture. The probability of this occurring appears to be very small.

From this description of possible effects it is apparent that the presence of a nuclear engine does not constitute a hazard to personnel or property beyond safe distances which would be required for propellant blast effects. However, the contamination of the launching area would be objectionable, and the release of airborne contaminants, though not harmful, could constitute a public relations problem.

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APPENDIX AHEAT TRANSFER IN KEROSENE-AIR DIFFUSION FLAMES

A number of investigators have conducted experiments on the burning of pools of liquid fuels in air (21,22,23,24,25). Several of these experiments have involved burning kerosene which is similar to the RP-1 propellant used in SATURN boosters. From a survey of these experimental results, the following characteristics of the flame over a burning pool of kerosene have been determined:

1. Heat transfer within the flame is primarily by radiation.
2. Flame characteristics and burning rates do not vary strongly with pool diameter for pools larger than 4 feet.
3. For narrow-boiling petroleum fractions such as kerosene, the thickness of the heated layer of liquid remains constant after an equilibrium condition has been attained.
4. Burning of large pools of kerosene in still air proceeds at 0.62 ft/hr.

No experimental measurements have been found of heat transfer to surfaces immersed in a kerosene-air flame. However, from the above characteristics, the effects on an immersed surface can be predicted.

The surface of the kerosene pool has a high absorptivity, and since radiant heat transfer predominates, it can be assumed that heat flux to any surface within the flame would not exceed that to the liquid surface. An energy balance at the surface can be written as follows:

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$$\alpha \dot{q} = \rho (c \Delta T + \Delta h_v) + \epsilon \dot{q}_R$$

where

$\dot{q}$ = heat flux to surface

$\dot{q}_R$ = radiant heat flux from surface

α = surface absorptivity

ϵ = surface emissivity

ρ = liquid density = .0296 lb/cu. in.

r = burning rate = .62 ft/hr

c = specific heat = .47 Btu/lb - °F

T = temperature

Δh_v = heat of vaporization = 85 Btu/lb

This relation assumes that an equilibrium situation is established wherein the heat received by the surface is balanced by losses through evaporation and radiation. The absorptivity and emissivity of the liquid can be assumed equal to unity without introducing a significant error (26). If the temperature of the liquid surface is assumed equal to the 50 percent distillation point for kerosene (436 F), and that the bulk of the liquid is at ambient temperature (70 F), the rate of heat transfer to the surface is found to be 0.0185 Btu/in² - sec. Approximately 10 percent of this energy is reradiated from the surface. This heat flux corresponds to a black body temperature of 1080 F. It is probable that portions of the flame are at temperatures greater than this value. However, the emissivity of the flame is less than unity, and the view-factor of the surface is also less than unity due to discontinuities in the flame. A black body placed in the flame would achieve a maximum temperature of 1080 F, whereas

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a body with a positive temperature coefficient of emissivity would reach a higher temperature. According to data reported in Reference 9, the temperature coefficient of emissivity of beryllium is small. Thus, it can be assumed that a beryllium surface immersed in a flame from kerosene burning in air will not attain a temperature greater than 1080 F.

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APPENDIX BCOMPRESSION TESTS OF GRAPHITE

To predict the behavior of the reactor under compressive loading, it is necessary to determine the compressibility of the graphite core material. Graphite consists essentially of a sintered matrix of carbon crystals with an apparent density of approximately 1.8 gr/cc. The crystal density is 2.25 gr/cc. Therefore, compression of a graphite structure could result in volume reduction consisting of three components:

1. Reduction of crystal lattice dimensions (reversible).
2. Reduction of micro-spaces between crystals.
3. Collapse of structural void spaces (irreversible).

To determine the behavior of graphite under compression, a hardened steel die was prepared which is shown schematically in Figure B-1. The die contains a 3/8-inch hole fitted with hardened steel pistons. Graphite samples were prepared from Graphite G (Graphite Specialties Corporation, Niagra Falls, New York) and were nominally 3/8-inch in diameter and 1/2-inch long. The axis of the cylindrical sample was always parallel to the extrusion direction of the graphite stock. Graphite samples tested are also shown in Figure B-1.

The test procedure consisted of pressing a sample into the die with a piston at each end, and applying a compressive load by means of an Instron Universal Testing Instrument. Sufficient loading was applied to attain a pressure within the sample of nearly 100,000 psi, and a record was obtained of pressure versus deflection. To determine the deflection occurring within the testing system, the graphite sample was replaced by a hardened steel pin and the compression was repeated. Deflections occurring with the steel pin in

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FIGURE B-1

DESIGN OF DIE AND SAMPLES FOR COMPRESSION
TESTING OF GRAPHITE

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the die were subtracted from those obtained with the graphite sample to obtain the compression within the graphite alone.

First tests were conducted with solid graphite samples (type A). The compression diagram obtained is shown in Figure B-2. It is observed that under initial loading, elastic deformation occurs with a modulus approximately equal to the calculated bulk modulus for graphite ($1.1 - 1.7 \times 10^6$ psi). At pressures above 5000 psi, yielding occurs followed by approximately 10 percent compression up to a pressure of 30,000 psi. With increased pressure, the slope increases until at 70,000 psi and above it is again equal to the initial modulus. Upon unloading, little expansion occurs until the pressure reaches 10,000 psi. At complete release a permanent set remains of 2 to 3 percent of the initial volume. When recompressed, the stress-strain curve differs from the first compression in that the initial high modulus deflection is not obtained. However, the same deflection is obtained at full load and the unloading curves are identical. After the initial compression, no further permanent set occurs and repeated cycling of the sample produces identical traces. A hysteresis loop occurs between loading and unloading indicating that energy is absorbed during the cycle.

It appears that the original graphite structure is lost after compression of approximately 5000 psi. Failure of the inter-crystal bonds at this pressure results in the observed permanent compression. Beyond this point, the sample behaves as a compacted bed of powder. Of the 16 percent compression attained at 90,000 psi, approximately 6 percent can be attributed to crystal lattice deformation and the remaining 10 percent to reduction of the inter-crystal spaces. It is significant that all but a small percentage of the compression is removed upon release of loading.

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FIGURE B-2STRESS-STRAIN CURVE FOR COMPRESSION OF SOLID GRAPHITE**CONFIDENTIAL**

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To determine the behavior of structural voids, samples were prepared as shown in Figure B-1 (types B and C) with a single hole of .040 inches drilled in the axial or transverse direction. Under compression to 90,000 psi only partial collapse of the holes occurred and the stress-strain diagrams were not noticeably different from that in Figure B-2.

To determine the effect of a multiple-hole pattern, samples were prepared with three .093 inch holes drilled axially as shown in Figure B-1 (type D). The void volume of each sample was 18 percent. This structure was considered to typify that of a reactor fuel element. Compression of these samples produced stress-strain curves as shown in Figure B-3. It is apparent that collapse of the holes occurs at pressures above 9000 psi. The permanent compression of 18 percent indicates that the collapse is nearly complete. Further compression produces a stress-strain diagram similar to that for a solid sample.

To determine whether the graphite structure might be more resistant to compression under dynamic loading, one sample of the type D shown in Figure B-1 was subjected to a simple impact test. The die with sample and steel pistons in place was placed upon a steel plate, and a 25 lb weight was dropped onto the upper piston from a height of 4 feet. The total impulse and average pressure transmitted to the sample were calculated to be approximately equal to those predicted for the liquid propellant detonation. Permanent compression of the sample in this test was identical to that occurring under static loading of 90,000 psi.

It is concluded from this study that compression of a graphite structure such as a Kiwi-B fuel element will occur under pressures generated by a liquid propellant detonation. A permanent reduction in volume is possible in an amount equal to the original void volume.

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FIGURE B-3STRESS-STRAIN CURVE FOR COMPRESSIONOF GRAPHITE WITH .18 PERCENT VOIDS~~CONFIDENTIAL~~

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APPENDIX C

MECHANICAL BEHAVIOR OF REACTOR UNDER DETONATION PRESSURES

1. Mechanical Characteristics of Reactor

The Kiwi-B reactor is a composite structure consisting primarily of two materials, graphite and beryllium, which have widely different mechanical properties. An exact determination of the behavior of the reactor under detonation pressures would be difficult even if all the characteristics of the detonation wave were known. Under the present circumstances where peak-pressures are known, but where pressure durations and detonation velocities are largely unknown, only qualitative remarks can be made about the behavior of the reactor.

The following table lists some of the properties of graphite and beryllium which are pertinent to this analysis:

	<u>Beryllium</u>	<u>Graphite</u> (Graphitite G)
Density (lb/ft ³)	113	115
Tensile Strength (psi)	30 - 90,000	2500
Compressive Strength (psi)	20 - 80,000	8500
Modulus of Elasticity (psi)	43 x 10 ⁶	18 x 10 ⁵
Sound Velocity (fps)	41,300	9000 (calculated)

In addition to these properties, an investigation was conducted to determine the behavior of graphite structures under compression (Appendix B). It was discovered that at pressures above 10,000 psi, the inter-granular bonds formed during graphitization are broken and the material is reduced to powder. Void

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spaces within the original structure become filled and a decrease in volume occurs equal to the original void volume. As pressure is increased further, an elastic compression occurs up to about 16 percent at 100,000 psi. This compression is removed upon release of the pressure.

Under the detonation conditions predicted in Section II-B it is apparent that the reactor would not be particularly affected by conditions occurring outside the liquid detonation region. Therefore, the liquid detonation pressures will be the conditions of interest here. A peak-pressure of 100,000 psi will be assumed with a duration of one millisecond. At this pressure, the graphite structure will offer little resistance to change in shape, and both permanent and temporary compression are apt to occur. The beryllium parts, on the other hand, have strengths comparable to the pressures to be encountered. They would be expected to retain their shapes, though some fracturing would be expected, particularly in the webs formed by the control rod holes. The aluminum pressure vessel would offer no resistance to changes in shape of the core, but would act to hold the core elements together. It is doubtful that this vessel would remain unfractured under the full liquid detonation pressure.

The reactor, therefore, can be considered as having a compressible core surrounded by a continuous arch of incompressible segments, all retained by a flexible outer skin. The time required for distortion of the reactor can be approximated by determining its natural frequency under various modes of vibration. In the axial direction, compression of the graphite core can occur independently of the reflector. The period of the fundamental longitudinal mode of vibration can be expressed as follows:

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$$t = 2L \sqrt{\frac{\rho}{Eg}}$$

where

L = core length

E = modulus of elasticity

g = proportionality constant, Newtons' law

ρ = density

Because of the hysteresis loop in the stress-strain curve for graphite, the modulus of elasticity is different for loading and unloading. As a result, the period will also vary with direction of loading. From Figure B-2 approximate values of the moduli were picked-off. Average slopes of the curves were used over the portions where the greatest strain occurred. The following values were obtained.

Loading	2.8×10^5 psi
Unloading	1.0×10^5 psi

Using these moduli, half-periods (t/2) were obtained for the graphite core as follows:

Loading	0.9 millisecond
Unloading	1.5 milliseconds

In the transverse direction, the period would be more difficult to predict. But since the reactor diameter is similar to its length, the transverse period would be comparable to the axial period. Thus, the time required to compress the reactor and that required for expansion are of the order of one millisecond. This time is comparable to the predicted duration of the detonation pressure, but short compared to predicted durations of excursions. Therefore, it can be concluded that maximum compression could occur during the detonation, but that

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elastic compression would be relieved prior to the core reaching the graphite vaporization temperature.

2. Axial Loading

In the case where the detonation wave approached the reactor in the axial direction, it can be assumed that the detonation pressures would be applied to the ends of the core and reflector segments. The nozzle would offer little resistance to the pressure wave. The graphite core would be compressed into the reflector cylinder, and the external pressure would tend to hold the reactor together. Upon release of the pressure, some expansion of the core would take place. The expansion would not be limited to the axial direction so that the reactor diameter would increase and gaps would be formed between the beryllium reflector segments. If the pressure vessel stretched but did not rupture, the final reactor configuration would be expected to appear as shown in Figure C-1. The result would be a reduction in core volume equal to the original void space (18 to 27 percent). The increase in reactivity due to compression would be counteracted by the loss of reflectivity.

3. Transverse Loading

In the case where the detonation wave approached the reactor in the transverse direction, pressures would be transmitted to the graphite through the reflector. The beryllium segments would behave as a ring of incompressible blocks with the outer shell tending to hold them in place. As a first approximation, the reflector ring would maintain a constant perimeter due to the bridging action of segments. As the pressure wave reached the near side of the reactor, the foremost segments would begin to move into the core. The pressure would be transmitted circumferentially through the beryllium segments

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FIGURE C-1

REACTOR DISTORTION CAUSED BY AXIAL LOADING

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and buckling would occur on the sides. As a result, the reactor shape would become non-circular as shown in Figure C-2. Once buckling had commenced, the shape would be unstable and continued pressurization would accentuate the asymmetry. The final shape of the reactor cross-section would be approximately elliptical with a reduction in area, but with little change in perimeter, assuming the pressure vessel did not rupture. As in the axial case, gaps would appear between the beryllium segments and fracture would probably occur in the vicinity of the control rods.

4. Actual Loading

In the actual case, if the reactor were immersed in a detonating propellant mixture, the approach of the detonation wave would be between the transverse and axial directions. The resulting distortion would be a combination of the effects predicted for these hypothetical cases. Compression of the graphite core would certainly result, but it would not be symmetrical and it would be accompanied by a loss of reflectivity. In addition, it is unlikely that the pressure vessel would remain intact. It is more likely that rupture would occur with a loss of reflector segments and a large reduction in reactivity. Even if the integrity of the vessel were maintained, the increased reactivity probably would not exceed that for immersion or control rod malfunction.

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FIGURE C-2

REACTOR DISTORTION CAUSED BY TRANSVERSE LOADING

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