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REON

ROCKET ENGINE OPERATIONS - NUCLEAR

REPORT NO. RN-S-0033

TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

EVALUATION OF POST-OPERATIONAL
DESTRUCT SYSTEM CONCEPTS

(UNCLASSIFIED TITLE)

NERVA PROGRAM

CONTRACT SNP-1

MAY 1964

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ABSTRACT

A number of candidate explosive post-operation destruct system (PODS) concepts were investigated to evaluate the performance and feasibility of each concept for possible application to provide satisfactory disposal of the NERVA engine.

This report presents a summary of the significant conclusions that were based upon the work performed on the post-operative destruct system (PODS) during the program in Contract Year 1963.

Of the numerous concepts that were under investigation, the Mark D produced the most promising results. The Mark D concept offered the best possibilities for a bifunctional utility as an anti-criticality destruct system, and indicated the most promise of achieving the tentatively established requirement for particle size of 1/32 inch or smaller.

The work described in this report was performed by the NERVA Engine Destruct System (NEDS) group of the Ordnance Research Division of the Aerojet-Downey Plant under the direction of REON.

W. D. Stinnett
Nerva Program Manager

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I. INTRODUCTION

This revised special report is submitted to AEC-NASA Space Nuclear Propulsion Office (SNPO) to detail the preliminary technical evaluation of the performance and feasibility of various candidate post-operation destruct system concepts investigated. A comparative analysis and evaluation of the different candidate PODS concepts provides the basis for selecting the most promising post-operation destruct system (PODS) concept. This report is a revision of the original report of this effort (REON Report No. 2597) previously submitted to SNPO. The purpose of this revision is to clarify certain significant conclusions and to include discussions of work completed subsequent to March 1963; which is not applicable to discussions in other reports.

The work covered in this revised report was accomplished by the Aerojet-General Corporation, Ordnance Research Division under the provisions of Sub-Subtask 1.6.5 (AGC IWA A00785).

The preliminary technical evaluation of candidate anti-criticality destruct systems (ACDS) was reported in the REON Report RN-S-0020 Special Summary Report for Milestone 19, Contract Year 1963.

The preliminary design of the ejectable ACDS selected was reported in the REON Report RN-S-0022 Special Summary Report for Milestone 25, Contract Year 1963.

The Fragmentation Research program results were reported in the REON Report RN-S-0021 Special Summary Report for Milestone 5, Contract Year 1963.

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II. SUMMARY

The tentatively established post-operation destruct core-fragmentation objective was to reduce the entire mass of fueled NERVA engine core elements to fragments not exceeding 1/32 inch size prior to their reentry into the earth's atmosphere.

Explosive techniques applied in this research and preliminary design effort have a long history of successful employment as a primary mode of destruct for both missiles and spacecraft. The advantages of explosive techniques over other destruct concepts include: high specific energy, rapid reaction time, controllability, and reliability.

Transforming the entire mass of core material into aerosol-size particles is not within the present state-of-the-art of explosive application. However, a large percentage of conversion is possible if suitable explosive techniques are applied in an efficient, controlled manner. The major problems encountered in this explosive application are the complexity of the NERVA engine design and the energy-attenuation properties of the engine materials. The core pulverization achieved by an externally-placed explosive configuration is greatly influenced by the massive, layered structure surrounding the core; while the performance of an injected, internal explosive is affected by the complex, three-dimensional geometry of the fuel-element material surrounding the explosive detonation center. (The core elements in most of the targets used in the test program were simulated with 3/4 inch diameter solid commercial grade graphite electrode stock, National Carbon Co., Type AGSX.)

The Mark D PODS concept produced the best fragmentation test results of all concepts that were investigated to date. The best performance of any of the variations of the basic Mark D concepts tested was provided by a configuration consisting of approximately 340 lbs of high explosives contained in six 133mm-diameter full-core-length projectiles (Test PO-82). The total system weight, including extra radiation shielding and thermal conditioning devices, is estimated to be ~3500 lbs for this configuration.

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A conservative interpretation of the results of this test indicated that one-half of the crudely simulated core material could be reduced to fragments of less than $1/32$ inch.

The fragment-size distributions discussed in this report were obtained by sampling a large portion of the post-test fragments dispersed on the dry lake bed of the Aerojet Garfield Flats Test Site, near Hawthorne, Nevada, followed by cleaning, screening, and weighing of the samples. High-speed color photography was used to observe the velocities and angular distributions of discrete groups of fragments.

The best pulverization demonstrated in a test of the Mark D concept was attained in the Aberdeen Proving Ground Test APG-2. Data furnished from APG personnel indicated that between one-third and one-half of the core material of a simulated NERVA reactor target, having one quadrant comprised of depleted NERVA B-4 fuel, was reduced to fragments of less than $1/32$ inch. Since the methods used in analyzing the results of Test APG-2 did not seem as conservative as those applied to other tests of this concept, it is felt that a value between the two fractions might be more realistic than the higher value. This destruct system consists of four 105mm, full-core-length projectiles containing approximately 120 lbs of high explosives. The total system weight of this Mark D concept configuration, including radiation and thermal protection devices, is estimated to be ~1500 lbs. Although the results obtained thus far have not adequately achieved the fragment-size objective, the general trend of test data indicates a capability for systematically controlling the fragment-size distribution over a wide range of conditions. This implies an inherent capability for this concept to be modified to satisfy a broad-spectrum of less stringent objectives as might evolve from future changes in flight safety criteria, NERVA engine evolution, and operational flight modifications.

Figure 1 is a $1/5$ -scale model of a typical example of the Mark D PODS as attached to the NERVA engine. The configuration utilizes six recoilless launchers mounted on the lower thrust structure with follow-through, shaped charge, projectile initiators attached to the outer ends of the launch tubes. Note that the launchers extend through clearance holes in the upper thrust

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Figure 1

Mark D PODS Mockup

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structure and beyond Station 0-0. This extension is imposed because test results indicate the following are desirable for optimum Mark D PODS performance: parallel projectile alignment within the core, complete full-core-length projectile insertion, balanced radial and polar projectile dispersion, and full-length projectile standoff from the initial point of target impact. A preliminary design of a system which attempts to incorporate these desirable features appears to present several structural interference problems. Hence, eventual integration of the PODS in the NERVA thrust structure and RIFT tankage may force design modification requirements upon the destruct system that are incompatible with the fragmentation performance required; or, conversely, the destruct system finally developed might necessitate changes in the design of the NERVA engine and RIFT tankage.

To accomplish the difficult task of core material pulverization, the explosive PODS must be much larger than the ACDS, which must only disperse the core material. The possibility exists that the PODS could be used in a bifunctional capacity; that is, as a single system capable of meeting all destruct mission phases. Such a system would eliminate the need for an additional ACDS. It is also possible that a powerful bifunctional destruct system (BDS) would be capable of destroying the interstage structure under all conceivable booster phase malfunctions without the necessity of providing a heavy auxiliary interstage-structure-removal system, that would probably be needed with an ACDS, to permit adequate core dispersal. In addition, there are no ejection requirements for a BDS.

Detailed PODS performance comparisons were made with 24 applicable, full-scale, tests out of a total of 33 accomplished by Aerojet during the program (Contract Year 1962 and 1963). About 460 additional subscale tests were conducted in support of the PODS effort to study the fragmentation mechanisms contributing to maximum graphite-dust production. Of these performance comparisons, the basic studies relating to the feasibility of achieving the fragment-size objective are summarized herein.

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* Refer to REON Report RN-S-0020

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The external charge (implosion concept) effectiveness study indicated that a point of diminishing returns is reached which negates the effect of increasing the explosive weight for such concepts. Lateral compaction or plastic deformation of the inner core elements is produced by localized zones of long-duration pressure and temperature extremes, resulting in a trend of increasing fragment sizes. This condition has even been observed with the fragile NERVA B-4 geometry, indicating that long-duration and well-confined destruct pulses are not desirable for the efficient production of graphite dust.

The internal charge (explosion concept) effectiveness study indicated that a continuing reduction in fragment size will result in association with increasing system weight over a wide range of total destruct system weights (370 to 4700 lb). This indicates that the Mark D PODS has good potential for controlled fragmentation.

The energy-utilization study indicated that the Mark D concept is the best of all concepts, comparing systems on an equivalent explosive weight basis. A study was made of the energy utilization of internal charges, external charges, a combination of internal and external charges, and multiple external shaped charges. The study demonstrated that access to the core can have major effects upon the efficiency of energy utilization. Since the achievement of direct action is impossible in this complex target, the most important consideration is to minimize the wasted energy during penetration into the core and yet to produce well-distributed explosive action within the core. The control of factors such as sequential timing and pressure duration of explosive components was found to enhance the efficient use of the available energy.

The system-efficiency study indicated that a minimum weight internal charge produces better performance than a minimum weight external charge. This would tend to support the choice of the Mark D concept. However, fragmentation performance cannot be related to explosive weights alone. The total system weight is the proper basis for comparison, since it reflects the difficulty of explosive application.

After a trend was established, indicating that the Mark D PODS had the best chance of achieving the critical fragment size objective, further studies and comparisons of tests were made to improve this concept by increasing its graphite dust producing efficiency.

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The target-geometry effects study, with particular emphasis on the explosive charge mass to target mass (c/m^*) ratio, indicated that accurate simulation of engine components is mandatory to obtain meaningful test results. The c/m ratios are established as:

$$\text{Low } c/m = \frac{23\text{-lb explosive}}{2750\text{-lb engine core}} (1 \text{ small projectile}) = 0.84 \times 10^{-2}$$

$$\text{Medium } c/m = \frac{126\text{-lb explosive}}{2750\text{-lb engine core}} (\text{four } 105\text{mm}) = 4.6 \times 10^{-2}$$

$$\text{High } c/m = \frac{340\text{-lb explosive}}{2750\text{-lb engine core}} (\text{six } 133\text{mm}) = 12.4 \times 10^{-2}$$

Note:

For fragmentation performance studies the engine core weight (2750 lb) is used as a base, and for fragment-dispersion performance studies, the total engine weight (14,000 lb) is used.

Low c/m ratio tests require accurate physical property simulation of materials, as well as dimensional simulation of the engine design. This condition is difficult to achieve with low-cost simulation materials.

Medium c/m ratio tests are considered in a marginal zone and, in certain cases, require material strength simulation in addition to density and dimensional simulation for an adequate test. Because of this marginal condition, the majority of the testing must be accomplished as accurately as possible.

As a minimum, high c/m ratio tests require the density and dimensional simulation of the engine cross-section. This condition is more easily achieved on a low-cost basis.

The target scaling effects study indicated that all full-scale, simulated engine (FSSE) targets used on this program (Mod 1, Mod 2, and Mod 5) are dynamically similar enough to make adequate comparisons describing engineering trends. All data indicated that small-scale tests were not satisfactory to

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* c/m : Ratio of explosive charge mass to target mass; a dimensionless parameter.

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accurately forecast the performance of full-scale tests, and therefore, only full-scale dimensional simulations were studied. End effects are extremely important in low c/m ratio tests and require accurate physical property and dimensional simulation of the NERVA engine forward head and nozzle assemblies. Medium and high c/m ratio tests with parallel full-core-length projectiles are less sensitive to end effects and require little more than density and dimensional simulation of end conditions.

The explosive charge spatial distribution effects study indicated that reduced fragment size results from an increased spatial distribution of explosive charges. However, a point of diminishing returns occurs beyond about six charges, since a hydrodynamic condition is formed in the core much like that of the implosive concept; that is, the Mark G. The effects of varying angular, radial, and longitudinal (spatial) distribution of full-core-length projectiles, and the effects of sub-core-length projectiles upon the fragmentation performance, is not presently known. Fragmentation performance would probably suffer as a result of greater magnitudes of spatial distribution and by the use of sub-core-length projectiles. Integration of the PODS with the RIFT structure may force extreme inclination of the projectile launchers that would result in excessive angles of projectile entry relative to the longitudinal axis of the core and thereby cause an undesirable focal concentration of projectiles within the core.

The inter-projectile explosive initiation delay or "jitter" effects study indicated insignificant effects upon the fragmentation performance of the Mark D PODS over a time range from 0 to 3.5 msec between charges. This is a wide range in terms of explosive systems. It suggests the use of impact fuses instead of complex inter-projectile communication systems, originally thought to be necessary for the Mark D PODS. A test to further evaluate the effects of initiation jitter is planned to be conducted during Contract Year 1964.

The explosive brisance, or shock effects, study indicated that high-brisance explosives should be selected if graphite dust is desired, and low-brisance explosives should be selected if dust production is to be minimized. The low-brisance explosives are typically less sensitive to

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radiation and thermal damage mechanisms. It is physically impossible to fracture graphite without producing some dust, and therefore, the use of explosives will produce a finite quantity of graphite dust.

The charge-confinement effects study indicated that thick projectile casings reduce core-fragment size. If dust is desired, projectile casing design will be dependent primarily upon the fragmentation performance requirements. If dust is not desired, projectile casing design will be dependent primarily upon projectile launch and penetration loads.

The controlled casing fragmentation study indicated a reduction in the quantity of long core fragments surviving destruct action when the projectile casing was designed to fracture into small metal fragments and interact with the core material in a well-distributed fashion. Another test of this mechanism in conjunction with a thick-walled projectile casing is planned for Contract Year 1964.

The FSSE test-reproducibility study indicated that redundant tests were not necessary to define engineering trends needed to select the most promising PODS. This observation would not be valid if rigorous analytical techniques are required of the test program to satisfy special-purpose inputs for formulating a Flight Safety Model.

The fragment-velocity study indicated that the velocity of the expanding graphite-dust-cloud profile is between 600 to 3000 ft/sec and that the 4-projectile Mark D concept produces extremely high-velocity dust jets containing a large fragment-mass fraction in the dispersion pattern. This is caused by the reinforcement of hydrodynamic effects between the explosive charges. This condition, however, does not exist for the 1-, 2-, and 6-projectile designs. The peak graphite-dust velocities were recorded within the fireball at a test altitude of 5400 ft above sea level. These particles would continue at high velocities if the destruct function occurs in space and should be important considerations in the fragment-reentry studies.

It was not possible, using standard scientific techniques and equipment, (within the scope of the program in Contract Year 1963) to obtain either an

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empirical or an analytical relationship between the space-time distributions of fragment size (mass), shape, velocity, and angle (polar and longitudinal). A program was initiated (but not completed) to determine if the generation of such a complex relationship might be feasible, and if feasible, under what conditions it could be utilized in defining a mathematical destruct model; to furnish data input to the reentry model or reentry code (WANL); and a physiological model or dosage study (NUS) that would in turn contribute to formation of the flight safety model. This model would serve as the basis for the final post-operation destruct safety criteria under which RIFT and future space missions employing the NERVA engine must be considered.

The fracture-mechanism study indicated that the primary core-fragmenting mechanism is mechanical interaction between neighboring core elements and structures and not explosive shock effects, except in proximity of the explosive detonation centers. Since the explosive centers cannot be divided into an infinite number of point sources within the core mass, some quantity of core elements might be expected to partially escape the primary fragmenting mechanism and retain dimensions exceeding the fragment-size limitation of $1/32$ inch.

It was determined that the strongly anisotropic nature of the NERVA engine structure and core design makes it extremely difficult to eliminate silver-shaped core fragments (regardless of the element hole geometry) even under strong explosive shock and mechanical interaction conditions. This is evident in the NERVA B-4 element design, primarily because of the approximate 0.075-inch characteristic minimum structural web dimension, which is better than twice the $1/32$ -inch maximum size allowable after destruct. This dimension is an averaged value obtained from the maximum and minimum longitudinal breakage surface lengths inherent to the NERVA B-4 cross-sectional diamond hole pattern. Element geometry appears to have a more pronounced effect upon fragmentation than grain structure and other physical properties.

Tests using solid graphite rods indicated that the minimum characteristic fracture dimension was the $3/4$ -inch rod diameter, when the shock loading was below a certain threshold value. Shocks above this threshold value produced

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longitudinal splinters originating from the tangent lines of concentrated cylindrical contact. Subsequent mechanical interaction reduced the splinter lengths considerably, without reducing their thicknesses appreciably. This observation is based upon the rough ends and smooth sides of the splinter fragments. Extremely high-intensity shocks were attenuated so rapidly by the core material that a characteristic dimension (geometry, grain size, location), which might have influenced this mechanism, was not identified even though numerous ultra-high-speed photography and microphotography techniques were used. Grain size and orientation, as detailed fabrication process, and the primary direction of attack are important in understanding these damage mechanisms.

The influence of the new pyro-coated fuel design, or of the fission product status on the localized fracture mechanisms of the NERVA B-4 design is not known at this time. It is expected that the new fabrication process will aid the fragmentation performance because of better fuel-dispersion control. This should reduce the random fragment-size tendency. Any reduction in basic element strength as a result of the fission product buildup will produce better fragmentation performance.

Under the extreme explosive destruct conditions, intense pressure and temperature zones are formed within the core that compact or plastically deform a significant portion of the normally fragile graphite material into large dense pieces instead of pulverizing the material into dust. This condition has been observed over a wide range of element and destruct concept (including Mark D) geometries and in both full- and small-scale tests. This condition might be indicative of a statistical impossibility of reducing the entire reactor core to dust particles.

The material-correlation study indicated that graphite is a high-incident energy-absorbing material. The study also indicated that graphite is an extremely complex structural material whose exact physical nature is difficult to determine, reproduce, and extrapolate to new and more critical environmental and operational conditions. The temperature effects upon the physical properties of graphite as related to fragmentation are not known

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at present. High-temperature core conditions might reduce the fragmentation effectiveness of explosives, because high-temperature conditions may increase the possibility of creating localized zones of plastically deformed graphite material.

It was determined that both the unloaded NERVA B-4 simulant and the depleted fuel-loaded NERVA B-4 simulant fractured more easily, produced smaller average fragment sizes, and transmitted less incident energy under all types of loading conditions than did the crude solid graphite rods.

The extruded, unloaded NERVA B-4 simulant transmits lateral explosive shock loads only 0.4 times as well as the extruded, round rods. Extruded graphite, when machined to NERVA B-1 fuel element configuration, transmits explosive shock loads only 0.75 times as well as the extruded, round rods. This would indicate the relative lateral attenuant properties of the various design geometries. It was also determined that regardless of the type of core-element geometry (NERVA B-4, NERVA B-1, and solid rod) and of the strain rate applied (explosive or mechanical); lateral loading causes greater fragmentation and shock attenuation than longitudinal loading.

Extruded graphite, when machined to NERVA B-4 configuration, is noticeably weaker than the extruded, unloaded, NERVA B-4 simulant supplied from government sources. This indicates that the specific fabrication process greatly influences the fragmentation properties of the basically similar graphite material. Such influence is primarily caused by the tough "skin" effect produced by the extrusion process. This is predominant in the case of the NERVA B-4 design and less significant in the NERVA B-1 design, but is hardly noticeable in the solid, round rods.

It was determined that the larger grained graphite material provides better attenuating characteristics to incident energy than the finer grained material. It also produced considerably more fragmentation data scatter. The large grained graphite provides increased void volume. In finer grained material the extrusion process produces increased grain/void alignment and "skin" toughening over and above large grain material. Reactor grade graphite is typically fine grained. The addition of the heavy fuel particles in the

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light graphite matrix may cause localized concentrations of stress around the heavy point masses under intense shock loading, thus influencing the fragmentation properties of the elements.

The NERVA engine/dynamic-response simulation study indicated that destruct concepts of low to medium c/m ratios that rely primarily upon internal pressure generating mechanisms must be tested against FSSE targets designed to reflect the overall response characteristics of the actual NERVA engine under the same dynamic conditions of pressure vessel failure. The load-transmitting properties of simulated cores must be closely compatible with the fracture characteristics (toughness) of the simulated pressure vessel to provide an accurately simulated test target and obtain conservative test data. If the simulated core material has higher load-transmitting properties than the actual NERVA B-4 core, the simulated pressure vessel design must also reflect a higher toughness than the actual NERVA pressure vessel, or the test will produce overly pessimistic fragmentation results (i.e., partially completed fragmentation) resulting from the premature release of the confinement. These considerations have greater effects upon the ACDS dispersion performance, but are sufficiently important to warrant careful design and analysis considerations prior to conducting a PODS FSSE test.

The fragment-recovery study indicated that debris removal and weather conditions are important factors for consideration. Debris is considered to be all material not simulating the fueled core elements. Since Aerojet tests were not conducted with depleted fuel-loaded material, simple differential density techniques could not be used for separation of materials. Inaccurate weather forecasting greatly affected dispersion patterns and recovery of suitable samples during Contract Year 1963. This problem should be alleviated during Contract Year 1964 by the full-time assistance of the U.S. Weather Bureau at Garfield Flats Test Facility.

The fragment-sampling study indicated that selecting a representative sample area and obtaining sufficiently large samples are problems requiring further study. The extreme variation in polar distribution of fragments resulting from tests of the 4-projectile Mark D concept, (which was selected

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as the control-test-design configuration), made it difficult to obtain a truly representative sample. Also, since the important fragment-dispersion area generally covered the better part of 1 million square feet, it was difficult to obtain a large enough sample to represent the total population. A raised, expansive, metal sampling surface placed over the dry lake bed and mobile vacuum sweepers are proposed to implement highway sweepers to improve the recovery task during Contract Year 1964.

The fragment-screening study indicated that fragment sphericity and screening data repeatability are important factors. Since simulated materials do not provide a distinction between fueled graphite (core) and unfueled graphite (core and reflectors) and were used for all Aerojet tests conducted during Contract Year 1963, it was impossible to determine the fueled core fragment sphericity factors and to obtain a coherent fragment-size and -shape distribution. The large quantity of material to be hand-screened, the number of screens used, the individual handling of each screen, and the difficulty in removing all debris and lake dust, affect the reliability of the data obtained by the screening technique. Better debris removal (possibly mechanically driven separating and screening devices) and use of differential density techniques (when fueled core material becomes available) will permit simultaneous screening of all sizes.

The fragment-data presentation study indicated that rigorous statistical techniques were not warranted during Contract Year 1963. Their application was impossible because of the gross simulations and wide extrapolations required to compensate for unannounced weather changes and for the lack of time, funds, core material (Government-furnished), and technical data. However, useful engineering trends were produced upon which a destruct system design could be based. When the other large errors currently involved are reduced sufficiently to permit the accuracy of data analysis to become a significant factor, more rigorous, statistical methods will be applied. The best method of presenting relative fragmentation performance is to use a plot of percent cumulative mass of sample as a function of screen-size opening in inches. Rosin-Rammler analysis procedures are considered desirable when rigorous presentations are made, since they reduce the complex comparisons to the simplest of characteristic

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terms. However, the Rosin-Rammler analysis involves a confusion of testing setup parameters and performance parameters that are neither easily separated nor well understood at this time. These procedures may be used for future test analysis, when the number of variable quantities is reduced to a reasonable level for each FSSE test.

The concurrent mechanical feasibility study, conducted in support of selecting the most promising PODS, included a preliminary analysis and evaluation of the following.

- Stress and vibration
- System weight
- Response time
- Jitter
- Placement and interference
- Safety and arming (S/A) requirements
- Control and firing system (CFS)
- Sensors for the telemetry circuit
- Interfaces and operation
- Basic criteria for the destruct package
- Shielding geometry (qualitative)
- Cryogenic requirements (qualitative)
- Parametric tradeoffs

Evaluation of the feasibility studies indicated that the Mark D or Mark J concepts rate higher than the remaining PODS concepts when related to the following.

- Response
- Reliability
- Operational capability in any static, dynamic, and radiation environment
- Minimum system weight
- Ready integration into the reactor complex
- Minimum mechanical translation of the explosive array prior to initiation
- Fail-safe initiation
- Possible employment as a BDS

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Concepts utilizing various types of initiating devices have been investigated for possible use with the Mark D or Mark J concepts. Preliminary evaluation of existing data indicates that an exploding bridgewire (EBW) firing system might be suitable for a variety of firing techniques. If required, this type of unit would be applicable in achieving interprojectile communication and synchronization, whether the charges used in the Mark D or Mark J concept are initiated by a followup shaped charge technique, a radio-frequency (RF) device, or a trail-cable device. If the requirements for simultaneous projectile initiation are relaxed sufficiently, simple mechanical impact fuses will be adequate. Further studies and FSSE testing are planned for Contract Year 1964 to determine this relationship in conjunction with unsymmetrical spatial distribution.

A study is being conducted to identify, define, and evaluate the technical and operational relationships between the most promising bifunctional concepts and various related and supporting components, systems, vehicles, facilities, and safety programs. This study is also expected to disclose any critical problem areas inherent in these relationships.

A thorough preliminary design study of the Mark D BDS is presented in REON Report RN-S-0022, Evaluation of Anticriticality Destruct Systems.

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III. TECHNICAL DISCUSSION

The long-range objectives of this program are to develop an explosive destruct system for use either during or after the NERVA engine operative period to ensure that no dangerous accumulation of radioactive particles falls on populated areas of the earth's surface.

The immediate program objectives during Contract Year 1963 were: (1) to determine the feasibility of reducing the entire mass of NERVA engine core elements to fragments of less than 1/32 inch, and (2) based on comparative tests, to select the conceptual system that demonstrates the most promise for achieving the tentative fragmentation objective.

This discussion presents summary descriptions and conclusions regarding the explosive destruct concepts under study. It includes concepts which indicate explosive feasibility as well as those in which the feasibility is in doubt because of mechanical and reliability considerations.

Conclusions are based upon tests performed with FSSE and upon preliminary engineering judgments reflecting presently available NERVA engine design data.

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A. POST-OPERATION DESTRUCT CRITERIA

Under typical operating conditions, the vehicle will have achieved an altitude beyond the earth's atmosphere, although well within its gravitational field. In addition, the NERVA engine will have been operating for a relatively long period of time prior to its shut-down and the beginning of its cooling cycle. Post-operation destruct might be required at any time after the start of engine operation. The nuclear power level required to generate the required forward thrust will have resulted in high-level radioactivity within the reactor core. This level of activity, contained in a matrix of graphite (a material capable of surviving severe ablative conditions upon reentry), could be catastrophic if allowed to return to the earth's habitable surface in a concentrated form.

To prevent this potentially hazardous situation, the tentative post-operation destruct criteria specify that:

- (1) The reactor core material shall be pulverized to such a degree that the material either is transformed into aerosols and remains in space, or is made small enough to burn up upon reentry into the earth's atmosphere.
- (2) If fragments are produced of a size precluding reentry burnup, they must have an activity low enough that they cannot present a physiological hazard upon reaching the earth's surface.

Transforming the entire mass of core material into aerosol particles is not presently within the capability of explosive destruct state-of-the-art, although a high-percentage conversion can be obtained. The results of early particle reentry studies conservatively described the requirement for a destruct system capable of fragmenting the entire reactor core into particle sizes of 1/32 inch or smaller. The statistical probability of completely achieving such a condition appears to be low at this time. The extremely complex reactor configuration influences the mechanics of fracture toward a wide distribution of elongated shapes and sizes such that a small, but finite, quantity of material might exceed 1/32 inch regardless of the quantity of explosive that are used. However, the general trend of the test

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results obtained to date has indicated the possibility of decreasing the particle mass median dimension (MMD) by controlled variations of the type, quantity, and distribution of the explosives employed.

Recent parametric studies^{*} conducted on the relative physiological effects of external and internal damage to humans caused by skin contact and ingestion of typical size ranges of fragments suggest that the previously selected size limitation requires continuous reevaluation. Based upon results from these studies, plus further and more refined analyses of fragment reentry studies, it is possible that better defined criteria will alter the present particle-size requirements. This should greatly simplify the problems involved in the development of a PODS of reasonable size, weight, and performance characteristics.

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^{*}Rover Flight Safety Committee Meeting, week of 24 March 1963, held at Aerojet-General Corporation, Azusa, California.

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B. EXPLOSIVE DESTRUCT MECHANISM DESCRIPTION

1. Explosive Categories

Using explosives in a complex destruct task requires an understanding and combining of many factors. Comparatively, the chemistry of explosives is a well-developed science, while the efficient application of high explosives is still an art. Explosives are categorized as either "low" or "high." Low explosives are generally spark- or flame-initiated and produce large volumes of high-pressure gas.

The following are typical examples of low explosives.

- Black gun powder
- Smokeless gun powder
- Double-base propellant
- Triple-base propellant
- Composite propellant

Typical applications of low explosives include the following:

- Propellant ignitor
- Gun propellant
- Rocket propellant
- Gas generator

High explosives are shock-initiated and characteristically produce intense shock with large volumes of high-pressure gas.

The following are typical examples of high explosives.

- TNT
- TETRYL
- PETN
- RDX
- HMX

Typical applications of high explosives include the following.

- Warheads
- Explosive boosters

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Destruct charges
Detonating cord (Primacord)
Detonators
Shaped charges

2. Explosive Function Relationships

Explosives, like tools, can be applied to specific functions. Since high efficiency is desirable, an explosive must be selected in a form that is compatible with its intended function. Two types of bulk charges are found to be useful for destruct system design. The internal explosion of a projectile charge which provides a bursting function; the external implosion of a wrap-around charge which produces a crushing action.

Shaped charges are special purpose tools. The conical shaped charge, set in a cylindrical container, produces concentrated penetration of material much like drilling a hole. The continuing angle, or linear, shaped charge permits elongated, continuous cutting of material in an action much like splitting a piece of timber with an axe. These various explosive tools can be combined to form a destruct system with specific capabilities. The following paragraphs describe the detailed destruct mechanisms involved in external and internal explosive charge application.

a. Externally Placed Explosives

Externally placed and externally acting explosives as applicable to the NERVA engine requirements, are designed to create an implosive action in which the chemical energy of the charge is converted to kinetic energy. The kinetic energy is transmitted inward through the highly absorbent engine pressure vessel and reflector structures in the form of jets or flying plates, thus causing the core material to be mechanically crushed. Under such a circumstance, the breakup of the material is the effect of the following.

- (1) Explosive jet action produced by the impact of minute particles of matter moving at extremely high velocities.
- (2) Intense shockwaves produced by the detonation of high explosives.

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- (3) Intense local pressure and temperature regions produced by great volumes of hot expanding explosive gases surrounding the engine pressure vessel.
- (4) Mechanical pressure transmitted through massive structural components produced by long-duration explosive gas pressure pulses.
- (5) Mechanical impact by massive structural members that have been accelerated to high velocity by the action of explosive gas pressures.
- (6) Subsequent collision and interaction between neighboring core fragments and structural members at high velocity.

An accurate simulation of the outer engine structure is extremely important in testing the performance of a selected concept utilizing externally placed explosives. It was determined that the proposed simulation of material density and dimensions would provide adequate information for the initial PODS evaluation of these externally placed concepts.

b. Internally Placed Explosives

These concepts create a highly confined explosion within the core, causing the graphite elements to be crushed against the engine pressure-vessel and reflector structures. Since graphite typically exhibits high energy-absorption characteristics, particularly under lateral attacks in the anisotropic NERVA engine design, the explosive effects contributing to core breakup are somewhat different from those described for the externally placed explosives. The primary effects include the following.

- (1) Intense, local explosive shockwaves produced by the high-explosive detonations.
- (2) Intense local pressure and temperature regions produced by great volumes of hot expanding explosive gases momentarily confined by the massive pressure-vessel and reflector structure.
- (3) Mechanical impact by small explosive projectile-casing fragments that are propelled at high velocities through the core material by the action of the explosive gas pressure.

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- (4) Subsequent high-velocity collision and interaction between neighboring core fragments, causing further fragmentation.

Accurate physical simulation of the reactor core material and engine structure is extremely important to the performance evaluation of these internally acting concepts. This is especially true when the explosive quantities are small compared to the target (low c/m), and the failure modes produced might be marginal. When the explosive quantities are large compared to the target (high c/m), accurate simulation of the reactor core material and of the closely associated inner reflector structure is imperative, although simulating only the density and the dimensions of the outermost structure would probably suffice under most developmental test conditions.

c. Explosive Charge Distribution

The exact explosive charge location is extremely important. Various spatial distribution of the explosive action can produce large differences in destruct results from test to test, all other factors being the same. For instance, a concentrated attack from a single direction adequately destroys the nearest material, but allows a large portion of the target to escape damage. A cylindrical attack, being distributed around or within the material to be destroyed, produces much better results. End effects are important in this case since these affect the escape of material. Complete distribution of explosive energy (infinite number of point sources) is practically impossible to achieve, but would probably be the best method of obtaining total destruction.

Access to the target, and consequently, direct explosive action, could have major beneficial effects upon explosive efficiency; yet, direct action is almost impossible to achieve in complex targets. The indirect mode, generally the only one available to the destruct system designer, involves minimizing the wasted explosive energy during penetration into the intended target. When the target is inside a highly absorbent structure, considerable penetration energy is required.

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d. Explosive Function Timing

Another important destruct performance aspect is function timing. Reinforcing shock, pressure, and temperature effects can sometimes be accomplished through simultaneous initiation of multiple charges distributed about or within a target. Also, destruct-duration control can sometimes be obtained through timing. Artificial confinement by explosive means can augment both the strength of the outer structure and the inertial confinement of the inner target by creating back pressure, thereby producing greater total damage to the contained material.

Sequential timing capability is useful when various combinations of charges are to be used in their most efficient fashion to accomplish a series of related functions.

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C. DEVELOPMENTAL APPROACH

A long range program plan was generated to develop an explosive destruct system for the disposal or dispersal of radioactive fuel material for any time after nuclear engine startup. The first objective of this plan was to determine the method of approach consistent with the safety criteria presented and with the status of the engine design program. The approach consisted of evaluating the most promising destruct system concepts in detail in order to select the concept thought to be best capable of achieving the applicable safety criteria. An operational analysis would be performed to identify major problem areas regarding relationships between the various program participants and their respective functional components and systems. Then the selected destruct system would be designed and developed to a high level of performance. Next, the system would be integrated with the engine, the vehicle, and the vehicle-launch facilities. Finally, the destruct system would be qualified by performance testing and produced in sufficient quantities to meet delivery requirements.

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D. LIMITATIONS

1. Technical

There are technical limitations in the use of explosives for a NERVA engine destruct system. In addition to wide ranges in thermal environment, the explosives must withstand extreme high-radiation fields expected during flight. The mechanical stress environment induced by booster engine, NERVA engine, and high-performance gun operation (internally placed explosives) is also extreme. The explosive charges must have adequate capability to achieve their intended function in a reliable manner, and yet present minimum hazards, until the destruct command. The explosive destruct system must exhibit minimum weight and minimum NERVA engine structural interference. RIFT interference must also be minimized. The destruct system must be compatible with the available launch facilities and with all phases of future flight operations.

2. Work

Program limitations prevented separate investigation of many important parameters. Several parameters were considered during each test instead of a single variable. Tests could not be repeated to obtain a cross check on data reproducibility. Subscale simulation was found to be inadequate after numerous and varied attempts to use this technique. Hence, only engineering trends could be obtained instead of more desirable rigorous solutions.

Low-cost commercial materials were used in all of the 33 FSSE that were destructed during the program because actual materials were not available. Because of the tentative status of the RIFT Flight Safety Criteria and of the NERVA engine design, the program attempted to establish a suitable range of parametric destruct performance based on a wide selection of physical possibilities. This was done so that the destruct system design could quickly respond to future modified safety criteria and to engine design evolution without undue system redesign and further development.

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E. PODS CONCEPTS UNDER STUDY

A wide variety of explosive configurations employed in a large number of concepts, were initially suggested for PODS application. For ease of reference they are now designated as Mark D, Mark E, Mark F, Mark G, Mark H, Mark I, Mark J, Mark K, Mark L, and Mark M. These concepts are illustrated in simple schematic form in Figures 2 through 11. Concepts designated Mark A, Mark B, and Mark C are anticriticality types which are incapable of accomplishing the PODS function, and are not presented in this report.

The critical elements of each PODS concept were tested and analyzed in full scale to eliminate all but the most promising system. A short description of each concept follows.

1. Mark D

Multiple, internal burster projectiles launched from tubes located forward of the shadow shield

In this concept (Figure 2), a number of core-length projectiles are fired from aimed launch tubes, through the forward head structure into the core. Simultaneous initiation of the main charges may be required for best fragmentation performance. Projectile penetration into the core, or the requirement for core-length projectiles, may not be mandatory, depending on whether the production of graphite dust is desirable or not. Determination of proper spatial distribution of projectiles will be one of the objects of further empirical investigations.

The Mark D concept is capable of bifunctional utility as an ACDS through the use of one or more of the projectile units. All projectiles may be required for ACDS operation if defeat of the interstage structure is needed to guarantee adequate fragment dispersion without reliance upon an auxiliary interstage-removal system.

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Figure 2

Mark D PODS Concept

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2. Mark E

External combination of linear and conical shaped charges arrayed about the pressure vessel and the forward head structure

In this concept (Figure 3), a rectangular configuration of linear shaped charges is mechanically transported from a shielded forward storage location to a position around the pressure vessel after the destruct signal is received. These deep-penetrating charges cause cutting and separation of the engine pressure vessel and reflector structure. Incidental core fragmentation can be achieved from the residual jet action. Delayed initiation of large conical shaped charges, statically emplaced around the engine thrust structure and shielded by the forward head structure, cause core pulverization with the residual penetration energy of the multiple jets. If sufficient pressure-vessel rupture energy can be converted from the jet action, the need for the rectangular linear shaped charge array around the pressure vessel may be reduced or eliminated, and thereby greatly simplify the concept.

3 Mark F

External combination of linear and conical shaped charges arrayed about the pressure vessel

In this concept (Figure 4), a rectangular configuration of linear shaped charges is coupled with large conical or hemispherical shaped charges attached to the linear shaped charge grid intersections. The explosive assembly is mechanically transported from a shielded forward storage location to a position around the pressure vessel after the destruct signal is received. These deep penetrating charges cut and separate the pressure vessel and reflector structure. Multiple core penetrations and pulverizations are achieved by the residual hypervelocity jet interaction and by the added benefits of implosion action through reinforced blast effects of the numerous, closely spaced explosive charges.

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Figure 3

Mark E PODS Concept

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Figure 4

Mark F PODS Concept

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4. Mark G

External combination of linear shaped charges and curved panel bulk-charges arrayed around the pressure vessel

In this concept (Figure 5), a rectangular configuration of linear shaped charges, with bulk panels of explosive placed within the linear grid, is mechanically transported from a shielded forward storage location to a position surrounding the pressure vessel after the destruct signal is received. The linear array is initiated first, causing deep cutting of the pressure vessel and separating of the reflector structure into massive blocks. The high-explosive panels are delay-detonated, causing a mechanical implosion by forcing the massive metal blocks radially inward against the core material. The core material is pulverized, and fragment dispersion is provided by the reaction wave moving outward from the implosion center.

5. Mark H

External parallel linear shaped charges

In this concept (Figure 6), massive linear shaped charges with deep penetration capabilities are distributed, either longitudinally or circumferentially, in a closely spaced array about the pressure vessel. These charges are initiated, in some preferential manner, resulting in implosion reaction fragmenting from the residual penetration energy of the hypervelocity jets attacking either perpendicular (circumferential charges) or parallel (longitudinal charges) to the core axis and from the reinforced blast effects of the numerous closely spaced explosive charges.

6. Mark I

External, offset linear shaped charges

In this concept (Figure 7), four (or more) massive linear shaped charges with deep penetration capabilities are placed longitudinally at equidistant points about the pressure vessel. The included angle of each charge is oriented so its hypervelocity jet will not intersect the geometrical axis of the core. By this orientation, each jet enters the center of its

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Figure 5

Mark G PODS Concept

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Figure 6
Mark H PODS Concept

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Figure 7

Mark I PODS Concept

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neighboring core zone, with a resultant overall twisting, scooping action and reaction being imparted to the entire target for fragmentation and eventual dispersion.

7. Mark J

Multiple internal burster projectiles, coupled with leading conical shaped charges, launched from tubes located forward of the shadow shield

This concept (Figure 8) is similar to the Mark D, including its capability of bifunctional operation as an ACDS. As in the Mark D concept, projectiles are launched into the core where they are detonated to produce fragmenting effects. However, in the Mark J concept, paths of entry are opened for the projectiles by the hypervelocity jets of conical shaped charges placed in front of the projectile launch tubes. Placement and launching is similar to the Mark D concept, but because of the reduced penetration requirements, the launcher and projectile-component design details may vary considerably from those of the Mark D concept (Figure 8).

8. Mark K

Mechanical impact by an explosively accelerated metallic plate

In this concept (Figure 9), a heavy, hydrogen-cooled plate which forms a portion of the forward head structure is forced to impact upon the upper surface of the reactor core, thus achieving core fragmentation. The acceleration of such a plate, preferably located behind the shadow shield, is advantageous to the application of liquid explosives. The explosive is transferred from a radiation shielded and thermally cooled storage container (located forward of the engine), into a cooled container behind the plate just prior to the final destruct command.

9. Mark L

Application of liquid explosive in shaped charges

In this concept (Figure 10), a liquid rather than solid explosive is used in some of the various internal and external concepts

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Figure 8

Mark J PODS Concept

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Figure 9
Mark K PODS Concept

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Figure 10

Mark L PODS Concept
(As applied to Mark G System)

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previously discussed. As in the Mark K concept, the liquid explosive is stored in a shielded, cooled container until needed. When required, it is distributed to the container which provides the required explosive shape. Fragmentation performance will probably be less than that of any of the concepts which use solid explosives, primarily because of brisance effect and specific energy. However, if reaction time is not a restrictive function, and if adequate thermal control of the explosive material is achievable throughout the entire destruct system configuration, certain mechanical translatory and reliability advantages may result.

10. Mark M

External liquid-explosive layer combined with
internally-injected explosive projectile

In this concept (Figure 11), liquid explosive is stored in a forward protected area, and is transferred to a cooled, double-wall container surrounding the engine pressure vessel on destruct command. This results in a configuration similar to a wrap-around panel configuration of explosive, as used in the Mark G concept. The initiation of this external explosive annulus produces the effect of an intense, explosive-induced confinement which augments the core fragmentation effects of a small, internally-injected, high-explosive projectile fired through the forward head structure. Used alone, the single projectile would serve as the bifunctional portion of this concept to satisfy the anticriticality destruct criteria.

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Figure 11

Mark M PODS Concept

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F. TEST AND ANALYSIS PROCEDURES

1. Method of Approach

An outline of the PODS explosive fragmentation test sequence is presented in this section to assure a better understanding of the continuity of the PODS test program.

The basic goal of the PODS fragmentation program is to determine the feasibility of explosively pulverizing the NERVA engine reactor core into fragments not exceeding 1/32 inch.

The validity of each of the various candidate concepts was first investigated (as discussed in Section III,E) using inexpensive "slab targets" that simulate a cross-section of the engine complex in a hydrodynamic "one-dimensional" mode. The term slab target is generic, and several modified versions were used, depending upon the particular area of investigations or upon the method of target defeat being investigated. Throughout the PODS fragmentation program, additional tests using slab targets were performed as required, to further improve (or define) the explosives performance. Based upon the results of the slab-target tests, the candidate concept was deemed unfeasible or worthy of added investigation.

If the concept appeared worthy of added investigation, an attempt was then made to determine concept performance as applied to the most unsophisticated of the FSSE, a "two-dimensional" cylindrical target (described in Subsection III,F,4). This cylindrical target represents a full-diameter, half-length (26-inch) "slice" through the center of the NERVA engine reactor, and serves to simulate the circumferential restraint as well as the cross-sectional heterogeneity of the reactor.

Depending upon the test results obtained, the concept was either investigated further (using targets of the same configuration) or if considered necessary for proper concept performance, was investigated through the use of a more sophisticated, full-length FSSE.

A total of 33 major tests were conducted by Aerojet during Contract Years 1962 and 1963 using FSSE targets of various degrees of

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refinement. Twenty-four of the tests were applicable to the PODS studies and the remaining nine concerned the Mark A, B, and C ACDS concepts. Six of the 24 PODS tests investigated the feasibility of concepts other than the Mark D/J type. The other 18 tests were conducted to evaluate the Mark D/J concept, of which 14 were conducted for application to the PODS fragmentation-size objective. Two of the 14 tests were considered to be basic concept feasibility investigations. However, the data acquired from these two tests were subsequently entered into parametric and performance studies. The remaining 12 of the 14 tests were considered parametric or developmental Mark D/J concept investigations.

The remaining four Mark D/J tests of the 18 were conducted in pursuit of the ACDS criteria. These ACDS data have been used, where applicable, to define small c/m performance (minimum explosives) of the single sub-core-length projectiles.

Six other FSSE tests were planned during Contract Year 1963, but were cancelled because of:

- (1) Technical adequacy of previous data.
- (2) Lack of funding.
- (3) Lack of time.

Two FSSE tests were conducted by Aberdeen Proving Ground (APG-1 and APG-2) in support of the PODS effort.

A combined total of 470 supporting tests and test series were performed during the test program. The actual number of individual tests total several thousands.

Three problem areas were investigated during the program.

- (1) Determining the feasibility of the candidate concepts
- (2) Defining the relationship between the results of the crude simulated targets and the geometrically similar fuel elements to be used in actual NERVA engine reactor

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- (3) Establishing techniques for sampling and statistically evaluating the performance of the candidate concepts.

All tests fell into one or more of the three general categories.

The basic approach of the PODS test program was first, to establish the gross explosive charge size needed to adequately perform its intended function on a slab-type target, and then to apply the concept to half- and full-length simulated engine targets, respectively. Full-scale investigation of candidate concept feasibility was generally limited to a single test per-concept. Two of the concepts tested (the Mark G and Mark D/J) appeared promising, however, and several additional tests of each were performed. At the conclusion of the first eight FSSE tests, ending the concept feasibility comparisons, the decision was made to pursue the most promising concept (the Mark D/J) and cancel further testing of the alternate concepts. A program was then initiated to determine the overall capability of the Mark D/J concept through investigation of the parameters thought to be critical in adequate performance.

During the parametric investigation of the Mark D/J concept, the need for improved evaluation techniques became apparent because of fragment sampling and parametric evaluation considerations. The philosophy of test "standards" was necessarily established for purposes of relative data reference in evaluating cause-and-effect relationships.

The potential feasibility of a Mark D/J PODS concept was evaluated based upon the following:

- (1) Ability to reduce the reactor core to the PODS fragment-size objective.
- (2) Ability to function properly under the influence of the operational restrictions (engine design considerations).

The minimum number of tests required to adequately perform a parametric investigation of either of these areas, was found to be

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prohibitive. The need to consider both areas limited the effectiveness of the investigation in that several parameters were tested simultaneously. The number of tests required for separation of each variable would have been prohibitive. The derived data was limited, therefore, to establishing "engineering trends."

The difficulty of deriving a maximum of quantitative-type data from a minimum testing activity, can be shown by listing some of the most important parameters relating to the explosive fragmentation feasibility of the Mark D/J concept as follows:

- (1) Explosive charge sizes (diameter, length, and total quantity)
  - (2) Number of explosive charges only
  - (3) Effect of polar distribution of explosive charges
  - (4) Effect of radial distribution of explosive charges
  - (5) Effect of longitudinal distribution of explosive charges (simulated "jitter," short charge distribution, etc.)
  - (6) Effect of angular insertion of explosive charges
  - (7) Explosive charge casing fragmentation characteristics (controlled fragment casing geometry, casing thickness, metal condition, etc.)
  - (8) Explosive charge initiation simultaneity
  - (9) Explosive type (brisance, density, etc.)
- } Symmetry

It should be noted that the preceding list outlines only the basic variable parameters associated with the explosive fragmentation feasibility program. There is no provision for examining the parameters associated with either the dynamic implantation and detonation of the explosive projectiles or the adequacy of target simulation. It should also be noted that the test series needed to adequately define these parameters would necessitate conducting at least several tests to investigate each individual parameter and an additional number of tests to determine the effects produced by several variables in combination.

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The results of two tests, PO-55 and PO-64, were established as standards-of-reference for the Mark D/J concept parametric evaluation. Test PO-55, represents the results obtained from four 105mm charges, and Test PO-64, the results from four 155mm charges. The two established standards-of-reference were based upon the potential of the explosives to produce nonlinear core fragmentation. Nonlinearity is defined as the apparent diminishing efficiency of the explosives to further reduce sizes as smaller fragment sizes are produced.

These standards were used as a basis for comparison during the test program. The investigation of a parameter such as the more efficient use of a given quantity of explosives through wider distribution within the core (that is, a greater number of smaller charges) was based upon a "105mm charge equivalent" and "155mm charge equivalent" class designation. The relative effect of such explosives distribution was ascertained by referencing the established standards, and by noting variation in fragment-size-distribution characteristics produced. This variation was then used in the definition of the "trend" to be anticipated under various conditions of explosives distribution.

The data derived from this approach have been used to define fragment-size distributions associated with parametric variations, and has resulted in establishing basic engineering trends. It appears that this basic trend information, although extremely valuable in establishing gross system capabilities and limitations, must be supplemented by a much more extensive and more detailed analysis before system function, optimization, and reliability can be determined accurately.

2. Remote Test Site

The test site used by Aerojet for performing major PODS tests is a dry lake basin of 6 sq miles located in the Garfield Flats area, near Hawthorne, Nevada. The altitude of the lake bed surface is 5400 ft and is surrounded by rugged mountains rising to 8200 ft. The lake bed itself is 2-1/2 miles in length and 1-1/2 miles wide, and consists of fine alkali dust packed, by the settling of basin drainoff water, into an extremely hard flat surface. The basin area surrounding the lake bed is composed of loose sand and gravel with an average grade of 4%. This surrounding area

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is sparsely covered with sage and other, small, high-desert plant life. The test site is illustrated in Figures 12 and 13.

All small slab-target (one-dimensional) tests in support of the ACDS and PODS FSSE work were conducted at the Aerojet Chino Hills Ordnance Research Laboratory. Certain full-scale, confined concrete target tests were also conducted at this facility in support of the ACDS. Three early tests with more sophisticated targets were conducted at Chino Hills, but results indicated that the effects of the confining topography in the relatively small canyon-like test areas did not permit adequate post-test sampling procedures. In addition, the facility has an enforced safety limitation which restricts the detonation of explosive charge to less than 100 lb.

3. Test Setup

At the Garfield Flats test site, two test pads of approximately 300 ft diameter have been constructed along the northern edge of the lake bed to facilitate the fragment recovery operations (Figure 13). The distance between test pad centers is approximately 1000 ft, and the distance between the instrumentation and personnel barricade and the test pads is approximately 900 ft.

Construction of the test pads consisted of distributing a gravel and asphalt-oil mixture (desert road mix) over the areas, followed by machine rolling, and subsequent highway sweeping. The center sections of the test pads were reinforced to withstand the close proximity of large explosive detonations. This was accomplished by excavating a 50 ft diameter hole in the lake bed to a depth of 4 ft and filling rock and large quantities of asphalt material into the hole to form an extremely resilient foundation. A 6 ft square piece of tough steel plate 6 inch thick was then placed on the foundation and steel test stands 10 ft high were positioned over the steel plate. An adapter ring supported the various FSSE targets on top of the test stands. Targets weighing approximately 14,000 lbs were supported by a heavy rectangular "angle iron" test stand, and those weighing 4000 lbs or less were supported by a triangular space frame of tubular steel. The test setups are illustrated in Figures 14 and 15.

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Figure 12
Garfield Flats Test Site

Figure 13
Garfield Flats Landscape

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Figure 14
Heavy-Target Test Stand

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Figure 15
Light-Target Test Stand

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The vertical axis FSSE test setup, raised 10 ft above a flat sampling plane, was selected rather than a test setup using recovery boxes or butts, as it provided the best method of obtaining a detailed comparison of PODS test results. The 10-ft altitude was selected to assist in interpreting fragment-pattern symmetry and distribution. A greater test elevation, or attitude, would affect the fragment dispersion pattern by altering concentrations on the sampling plane. The 10-ft altitude is believed to be high enough to not be affected by blast reflection from the ground. Hence, in addition to economic considerations, it is felt that using this particular test height and target orientation produces conservative results that are sufficiently valid and comprehensive for comparative purposes.

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4. Full-Scale Test Model Designs

The FSSE targets designed for use in the ACDS and PODS programs simulated the physical characteristics of the NERVA engine. It was necessary to modify the design of the FSSE targets to be compatible with the component designs and materials of the modified NERVA engine. Consequently, three basic types of FSSE targets were evolved:

a. Mod 1 (Figure 16)

The Mod 1 FSSE, designed in the middle of Contract Year 1962 crudely simulated the NERVA engine as it existed at that time, utilizing a Polaris missile rocket motor with an external diameter of 5 $\frac{1}{4}$ inches. Various versions of the basic design were fabricated in support of both the Aerojet and the APG testing efforts. Some versions incorporated semi-accurate internal, head, and shadow-shield structures, in conjunction with both steel and aluminum pressure vessels. One quadrant of NERVA B-4 depleted fuel-loaded core elements was utilized in Test APG-2. All other units included commercial, electrode stock graphite as the simulated core materials.

b. Mod 2 (Figure 17)

The Mod 2 FSSE target was designed in Contract Year 1963 and continuously modified to be continuously modified to be consistent with the current NERVA engine design. Various versions of this basic design were fabricated in support of the Aerojet effort. Some versions incorporated a semi-accurate internal structure, a nozzle closure, and a dynamic head-structure simulant. All of the Mod 2 FSSE targets incorporated the commercial, electrode stock graphite, core-material simulant.

c. Mod 5 (Figure 18)

The Mod 5 FSSE, also was designed in Contract Year 1963 and based on the current NERVA engine design. It consisted of a 26-in. thick cross-sectional portion of the engine, without internal support or complete end constraint. Three of the early Mod 5 targets (used in Tests PO-36, PO-41, and PO-45) were based on the Mod 1 design. The Mod 5 target was a successful tool in evaluating all medium to high c/m ratio concepts for either ACDS or PODS application

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Figure 16
Mod 1 Target

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Figure 17
Mod 2 Target

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Figure 18
Mod 5 Target

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(that is, Mark B, D, F, G, H, I, J, L, and M) in which only symmetrical full-core-length, statically emplaced explosive configurations (internal or external) were tested. Tests of concepts specifying unequal explosive, or unequal explosive effects, distribution about the engine structure (the Mark A, C, E, and K) or concepts exhibiting low c/m ratio performance cannot utilize the Mod 5 target and must be tested against full-length Mod 1 or, preferably, Mod 2 targets.

The use of sub-core length projectiles or the introduction of large variations in either spatial location of detonation centers, or in simultaneity of initiation deny the use of Mod 5 targets because of the pronounced end effects anticipated. The cost of the Mod 5 target is less than one third the cost of either the Mod 1 or the Mod 2. Consequently, it was selected whenever technical suitability was established. All of the Mod 5 FSSE targets used to date have incorporated the commercial, electrode-stock graphite, core-material simulant. The NERVA B-4 simulant is not suggested for use in the Mod 5 target.

d. Slab Targets (Figure 19)

Slab targets used in the ACDS and PODS programs represent a one-dimensional simulation of the NERVA engine cross-section to different levels of accuracy. If the test objective required severance of the pressure vessel only, similar material fabricated in flat-plate geometry was used as the component-test target and combined with a witness plate to measure the latitude of effectiveness. A complex, "sandwich," slab target (representing the radial cross-section dimensions of the NERVA engine) was assembled for the explosive configuration test when the full-scale test application called for penetration to a given point in the engine structure to accomplish the desired destruct function. In the early tests, in which such targets were used, no attempts were made to optimize the test setup, rather, the emphasis was placed on relative performance trends that could guide the selection of suitable configurations to be applied to the expensive FSSE tests.

5. NERVA Engine Material Simulation

Simple design and low-cost-material simulations were selected to represent the significant parameters affecting the response of each component to dynamic loads imposed by explosive action.

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Figure 19
Slab Target

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The NERVA engine aluminum pressure vessel was simulated, in 6061 Aluminum Alloy, as a rolled and welded cylindrical structure per applicable ASME unfired pressure vessel codes. Three thicknesses (0.80, 1.00, and 1.13 inch) and two different conditions of heat treatment (-O and -T6) were used at various times during Contract Years 1962 and 1963. In the -O condition, all but three Aerojet PODS FSSE tests used a 1.13-inch thickness. The three tests using an alternative 1.00-inch thickness in the -O condition were tests of the implosive-type Mark G concept. The 0.80-inch-thick pressure vessels available for use during Contract Year 1964 are in the -T6 condition. Three others of this type were used during Contract Year 1963 in tests of the Mark A and Mark C ACDS concepts.

The NERVA engine beryllium outer reflector assembly was simulated, in AZ 31-b magnesium alloy, as 12 solid cast sections in two thicknesses (4.00 and 4.50 inch) to fit the Mod 1 and the Mod 2/Mod 5 target designs, respectively. The 4.00-inch thickness was selected to provide a better component-mass compatibility with the larger diameter Mod 1 target design. The cast-magnesium section design was selected over extruded, and machined tooling plate types because of its fracture characteristics which provided a better match with the anticipated beryllium behavior under the same loading conditions. Magnesium (density = ~ 1.7 specific gravity) provided the most reproducible and accurate simulant for beryllium of all metallic and nonmetallic materials tested. Recent designs have provided magnesium sections with a longitudinal hole representing the control drum interface. It is planned to insert extruded magnesium bar stock into this hole and attach the bar stock to the upper and lower reflector tie rings to represent the final assembly.

The inner reflector assembly simulation consisted of two concentric cylinders of flat graphite slabs, housed within a steel barrel with three circumferential spacer strips encircling the barrel on its outer surface. This simulation is gross, since in the actual engine design a larger number of geometric interfaces exist in a more tightly packed form. Also, the barrel material is aluminum and has 48 longitudinal spacer strips on its outer surface.

The FSSE cores were simulated by 3/4-inch-diameter, solid, round, electrode-stock graphite. The Mod 1 and Mod 5 targets are tightly packed bundles

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of solid rods. The Mod 2 targets, and one Mod 1 target, provide actual core support through one hundred and sixty-three 3/16- to 1/4-inch-thick steel tie rods distributed within the core mass and attached to a thick-aluminum, simulated forward support plate. In the Mod 2 target, the core mass is supported on plywood representing the unfueled core bottom support blocks. The forward support plate is physically attached to both the upper reflector tie ring and the forward pressure vessel flange through a cylindrical housing.

The forward head structure was simulated in three basic ways. The Mod 1 targets, to simulate the shadow-shield, utilize ellipsoidal 6061 Aluminum Alloy domes that were filled with Densite plaster and an assembly of salt-filled steel tubes sealed with steel end plugs. The Mod 2 targets utilize a "sandwich" of steel and aluminum plates that simulate the mass and thickness dimensions of the forward-head structure to represent the expected shock absorbing characteristics of the actual structure. The Mod 5 targets, representing a central 26-inch-thick slice of engine cross-section, are not designed to maintain an exact simulation of end conditions. Hence, only the thin steel security cover plates form the primary confinement. To assist in simulating mass, sandbags were placed on top of the upper cover when assembling the test setup.

6. Data Analysis Methods

a. Fragment-Size Distribution

When considering methods of interpreting raw fragment screening and weighing data into somewhat quantitative terms to permit detailed analysis, the various parameters surrounding the fragment deposition, recovery, and preliminary size analysis must first be reviewed. This review must be made to define the following.

- (1) What the data means.
- (2) How valid are the data.
- (3) How these data should be treated.
- (4) Which areas within the analysis should be considered as having the greatest significance.

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The fabrication techniques and reasoning behind the choice of particular designs and simulants are presented to point out both their significance and the approach used in data evaluation.

Any form of mathematical expression that will adequately project a relationship between the test results obtained from the simulated models to those of the actual reactor is extremely complex, and therefore it was necessary to conduct a number of tests using a wide variety of target configurations and simulations in the hope that the cause-and-effect relationships, or trends, might be established to the degree that the destruct effect of the actual reactor might be postulated with some reasonable degree of accuracy. Funding restrictions and availability of materials for fabricating targets prevented the use of other than relatively crude simulations. Depleted fuel-loaded and geometrical simulant core modules were not available. The result of this was that only data from the single APG-2 test was available upon which to postulate the destruct effect on the actual NERVA engine. A number of tests have been conducted, using various types and geometries of targets of the semicrude class, from which some reasonable relationships have been established. Although sufficient data does not exist to allow an accurate calculation of the destruct effect of a so-called theoretical model, it is anticipated that with more refined targets, the data derived from previously conducted "crude-target" tests will become of increased significance without repeating the previous tests.

All data presented in this report is considered "conservative", in relation to the postulated destruction of the actual NERVA engine; although in most cases to an undetermined degree. This is because the low-cost reactor simulants that were used tend to degrade rather than improve test results; that is, solid-rod core-module simulant indicates reduced explosive pulverization efficiency when compared to geometrical simulant or fuel-loaded depleted NERVA B-4 configuration modules (as evidenced in Test APG-2).

The method of sampling the geometrical pattern of post-test fragments tends to provide conservative data. The quantities of debris unpreventably collected along with the post-test fragments, and the intrinsic error introduced

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by collecting either too small or too localized a fragment sample, make it necessary to sample the fragment-array from that portion of the standard 10^0 radial recovery arc which contains the greatest fragment concentration as visually ascertained. It has been demonstrated by this method that the yield of mass sample-per-square-foot of recovery area is greater, and therefore the ratio of fragments-to-debris is lower.

In the case of the PODS concepts that produce somewhat radially-symmetrical fragment dispersion (such as, Mark G and Mark M), this type of sampling pattern does not introduce too great an error in the fragment-size distribution data, since only a small portion ($\sim 2.8\%$) of the fragment array that appears to be representative of the overall fragment-size distribution is recovered. However, the Mark D/J concept, does not normally produce a radially-symmetrical fragment dispersion, and the sampling operation through the area of greatest fragment population produces "nonrepresentative" results. The fragment sampling yields an excess of larger size fragments, so that the resultant data would be even more conservative.

All material constituting the post-test fragment dispersion array which does not originate from a fueled core element is considered "debris" in this program. The unavailability of a simple and inexpensive method of differentiating between fuel-loaded graphite (core) and unfueled graphite (inner reflectors) necessitates the definition of "debris" to be modified to include all nongraphite material. Such a definition, results in some unknown contribution of the inner graphite reflector simulants to the large fragment sizes. This is brought about by the larger radial position of the crude inner reflector simulants, their random assembly and increased dimensional spacing, their larger individual characteristic dimensions, and their inherently larger grain structure as compared with the simulated core material.

Since the debris (which should include the fragments from the inner graphite reflectors) is collected in the sampling, it becomes necessary to attach "debris factors" by which the raw fragment-screening data can be properly adjusted. The debris factors are analytically derived from chemically reducing

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a number of samples (normally 8 to 10) that visually appear to contain the same quantity of debris as the remainder of the collective mass sample. The first step in the chemical reduction procedure is to weigh the sample, and secondly, to remove all water- and acid-soluable contaminants. In the third step, the sample is dried, weighed again (noting the sample weight reduction), and placed in a furnace where the graphite is sublimated. In the fourth and final step, the crucible is weighed again and the graphite-per-sample quantity is calculated on the basis of total weight of both soluable and insoluable contaminants. The approach has again been conservative, since the larger fragments are usually free of debris, and the smallest fragments are adulterated by a 95% debris content (in extreme cases). The smallest fragments (as a product of the averaging process) thus add to the conservatism by normally receiving a greater correction than is perhaps required. Also, no correction is made for the quantity of the core that is pulverized into aerosols and lost in the subsequent cloud drift.

It should be noted, that in evaluating the debris correction procedure, the particle-size mass-differential of the larger fragments is warranted a greater significance in the analysis. The definition of particle-size mass-differential in this usage, is the incremental mass differential (percent cumulative mass sample) between the grouped samples of fragments of various sizes. It follows, that in the relative comparison of particle-size-distribution curves resulting from different tests (although the mass-per-mesh-size differential for the larger particle sizes will assume a reasonably valid relationship) because of the more questionable and variable nature of the smaller particle-size data, the particle-size-distribution curve can shift because of either increased or reduced contributions by the smaller mesh particles to the total sample mass. In other words, the deviation of the individual mass samples, caused by the debris factor, induces a relative shift of the entire particle-size-distribution curve (up or down) by implying that the larger fragments constitute a greater (or lesser) percentage of the cumulative-mass sample.

Although the fragment shapes produced from the 3/4-inch-diameter solid, round rods effect the reduced data, they probably remain constant throughout the data. It can be said, however, that based on the smallest characteristic geometrical dimension (3/4-inch-diameter), the fragment-size trend is

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conservative with respect to the pulverization objective of 1/32 inch. Also, when using the method of relative test comparison employed in this analysis, any data variation is considered to be of little significance. An evaluation of the effect is being conducted in concurrent fragmentation research study^{*}, and use of these data is planned for future reference to the NERVA B-4 geometry. The relationship between simulated and actual core elements is considered to be of greater importance; and it is within this analysis that the shape factor becomes vitally significant because of the smaller characteristic geometrical dimensions of the NERVA B-4 design.

As previously stated, the method by which the test data have been compiled and analyzed was predicated, to a great degree, by the limited funds available. It has thus been necessary to evaluate the concept performance on the basis of a recovered fragment sample that, first, does not necessarily represent a true cross-section of the fragment-size distribution, and second, is consistently conservative. Furthermore, any attempt to manipulate the raw data into a meaningful mass balance introduces errors to such a degree that data become of even more questionable value. It is considered the better approach to accept the data as presented, to consider the data as qualified, and to evaluate concept performance on the basis of relative effectiveness. This approach is adequate for both comparative evaluation of the concepts and then for initial parametric evaluation. It is not sufficiently quantitative for extensive data usage in areas such as the RIFT Flight Safety analysis.

As previously outlined, the bulk of recovered fragments is first screened by progressively smaller screen meshes, and then the fragments retained by each screen mesh are weighed. The resultant data indicate the mass of fragments that are equal to or smaller than the preceeding larger screen mesh, and are larger than the retaining screen mesh. The mass of fragments (m) retained by a given screen mesh then takes the form of:

$$0.625 \geq m > 0.312 \quad (1)$$

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^{*}Refer to REON Report RN-S-0021.

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Considering the statistical methods available to present the data for easy comparison, it appears that the fragment particle-size distribution might best be presented numerically, as a single, definitive, composite expression (preferably quantitative), to allow for accomplishment of test evaluation by a simple numerical index. Supporting this approach, the characteristic fragment size at a given percent of the cumulative mass sample might appear to be an adequate comparison of test results; for example, screen mesh at 50% cumulative mass sample or in effect, at the characteristic fragment mass median dimension (MMD). This type of evaluation has however, been found somewhat inadequate for anything beyond gross comparison because the particle-size spread for two different tests can have widely divergent characteristic distributions, and yet if common at the MMD, can give the indication of comparable results (in relation to satisfying the PODS fragment-size objective).

From the observation, one can conclude that a more valid comparison would be derived if, in addition to the 50% point, several more points (25% mass, 75% mass, etc.) were introduced. Thus, the range of the distribution under consideration would be extended. This has been effectively accomplished by Wackerle^{*} in his statistical approach, where the entire screen mesh vs percent cumulative mass sample curve is reduced to a straight-line function by mathematically expressing the fragment-size-distribution curve through the use of the Rosin-Rammler equation. The slope of the curve indicates the efficiency of fragment-size reduction; and indirectly, affords a means of test comparison.

The Rosin-Rammler equation is a mathematical function that is suitable in describing some exponential distribution functions. The equation used in this analysis is:

$$v_c = 1 - e^{-(x_i/x_o)^\delta} \quad (2)$$

where:

v_c = cumulative mass fraction of fragments having an upper size,
 x_i/x_o and δ = the Rosin-Rammler parameters

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^{*}Wackerle, A Feasibility Study of the Disposal of a Rover Reactor with High-Explosives (U), Los Alamos Scientific Laboratory, LAMS-2688, (1962).

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Physically, x_0 is an average diameter, which is not to be confused with the average mean diameter, δ is a measure of the dispersion about x_0 , similar to the standard or average deviation. Los Alamos Scientific Laboratory (IASL) conducted reactor fragmentation tests on a reduced scale, and the results were compared by using the parameters of the Rosin-Rammler function. Further, it was found that in most cases, the size distribution did not exactly fit this distribution. Therefore, an additional parameter, termed the theoretical maximum ($x_{\max}$) was added, which is merely a truncation parameter.

The fragment-size distribution of the five most successful PODS tests were compared, using the Rosin-Rammler equation, to describe their overall degree of fragmentation success. The results of this analysis appear in Table 1. A least-squares fit has been computed for each of the five tests, defining both a slope and an intercept. The equation is:

$$y = mx + b \quad (3)$$

where:

m = slope

b = intercept on the y axis

The Rosin-Rammler equation conforming to this equation is:

$$\ln \ln \frac{1}{1-v_c} = \delta \ln x_i - \delta \ln x_0 \quad (4)$$

where:

$$\ln \ln \left(\frac{1}{1-v_c} \right) = y \text{ in Equation 3}$$

$$x = \ln x_i$$

$$m = \delta$$

$$b = \delta \ln x_0$$

After having determined δ and x_0 , the Rosin-Rammler parameters, a theoretical commulative mass distribution can be calculated by inserting values of x_i , the upper size interval, and by determining the corresponding value of:

$$\ln \ln \frac{1}{1-v_c} \quad (5)$$

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TABLE I

Fragment-Size Distribution ROSIN-RAMMLER

<u>Parameters</u>	<u>PO-82</u>	<u>PO-76</u>	<u>PO-74</u>	<u>PO-64</u>	<u>PO-55</u>	<u>IASL R-1</u>
δ	0.526	1.86	1.07	2.50	1.43	0.576
x_o	1.97	9.99	15.6	8.94	14.3	0.73
D^*	0.0465	0.0727	0.0229	1.241	0.0004	Good

* D is an indication of the fit; PO-64 being the worst and PO-55 the best.

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Each of the five experiments has been plotted in Figures 20, 21, and 22; and, as a comparison, the plot of IASL Test R-1 is shown in Figure 23. Considering the difficult assessment method and the obvious related errors, the test data agree reasonably well with the Rosin-Rammler distribution function.

Considering the error that has necessarily been introduced into the basic data, subsequent treatment of the data, with the attendant accrue-ment of error, is not warranted during this initial investigation of concept basic feasibility. Such extreme scrutiny does not add significantly to the general analysis. Therefore, an attempt has been made to utilize other statistical techniques that will use the basic data in its simplest form, and at the same time, will provide a graphical presentation of the particle-size-distribution curve, which affords a better means of mentally picturing the conditions and extent of relative test deviations.

The technique evolved from an assessment of the various methods is the simple construction of the fragment-size-distribution curve, which is based upon a coordinate system of percent cumulative mass sample, as a function of screen mesh opening. Because the raw fragment-screening data indicate a range of particle sizes within a given screen-mesh-mass figure (such as, Equation 1), a statistically-correct presentation of the fragment-size distribution, utilizing the aforementioned coordinate system, would take the form of a star-stepped progression. This graphically indicates that a given percent of the cumulative mass sample is comprised of a range of fragment sizes, as retained by a given screen mesh. A typical construction of this type is illustrated in Figure 24. Although statistically correct, a construction of this form does not permit rapid visual comparison and evaluation of a number of test results. An extension of this form was therefore performed in which a best-fit curve is projected through the fragment distribution within a given screen-mesh range. With reference to Figure 24, it would appear that the screen mesh could intercept Line A-B at any point within Limits A-B, since by definition, the fragments are of a size A-B. Statistically, however, the fragment-size ordinate is represented by the upper limit of the screen mesh (Point B) and gives an unapparent conservative trend to the curve.

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Figure 20
Fragment-Distribution Comparison
Tests P0-55 and P0-76

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Figure 21
Fragment-Distribution Comparison
Tests PO-64 and PO-74

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Figure 22
Fragment Distribution
Test PO-82

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Figure 23
Fragment Distribution
IASL Test R-1

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Figure 24
Construction of Fragment-Size-Distribution Curve and MMD

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The MMD was established as a composite numerical index expressing gross concept efficiency, and therefore should be treated accordingly. Early attempts to define the intercept of this point with the 50% cumulative mass sample were subject to the same considerations as the particle-size-distribution curve generation. At that time, it was considered statistically valid to construct the fragment-size-distribution curve using the midpoint of the screen-size range (illustrated in Figure 24) by the dashed line passing through Points C, E, and D. In assigning an MMD for the curve generated in that fashion, it was considered commensurate with conservative data presentation to assume the curve as a straight line falling between midpoints (Line C-D). Subsequent consideration, however, has led to defining the MMD as the point at which the particle-size-distribution curve (through Points J, H, B) intercepts the 50% mass-sample line (Point G). It is felt that this method is more statistically correct, based on the conservative approach, and also, that it produces more valid and comparative MMD figures, since the MMD point becomes more dependent on the rate-of-change of line-slope. Further, it should be noted that using MMD figures for gross-concept-comparison seems to be particularly useful and valid in particle-size-distribution curves that display the same characteristic form.

An attempt was made to establish a PODS concept, explosive efficiency numerical index that would indicate, in terms of a composite number, the relationship between the percent increase of explosives and the percent reduction of MMD. However, this system was found inadequate after further examination, in that subsequent reduction of fragment sizes by increased amounts of explosives becomes increasingly less efficient as the MMD is reduced.

This relationship was known to be present during previous data analyses, but no valid quantitative formulation could be discovered. Concept efficiency has, therefore, been presented in the text by indicating the percent reduction in MMD and the corresponding percent increase in explosives.

b. Fragment-Velocity Distribution

This method of fragment-velocity-distribution data analysis would appear to be relatively straight-forward. However, here again, some qualification of the data presented is required.

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At the outset, the highspeed photographic technique of fragment-velocity determination indicated the short-comings of even the best available methods of velocity measurement. In general, the most difficult task associated with the highspeed photographic measurement techniques is that of obtaining adequate fragment-size and fragment-size/quantity-mass resolution. This short-coming is inherent in the subsequent presentation of data; to the degree that, little can be proved as to the actual, quantitative, fragment-size/quantity-velocity relationship.

The photographic data are therefore presented in the form of a fragment velocity/distance curve, generated on a coordinate system of fragment velocity versus radial distance from target exterior. The data are presented irrespective of the complementary fragment sizes and quantities (both being indeterminate). However, in view of the geometry of the fragment array on the sampling plane, the fragment-size/velocity/distance relationship can be postulated with some reasonable assurance of validity.

In reviewing the velocity/distance curve for Test PO 91 (Figure 25), which is generally typical of most reduced test data, it will be noted that a distinct drop in fragment-profile velocity occurs between 3 and 7 ft from the target. A dotted line has been arbitrarily positioned within this area to indicate the point at which the high-velocity gasses and dust particles lose the majority of their impetus and are overtaken by the larger fragments. This transition period is quite apparent in the high speed motion pictures, which display a rather jagged fragment mass emerging from the somewhat uniform explosive-gas profile. A typical fragment profile progression (Test PO 91) is presented in the selected sequence of motion picture frames appearing in Figure 26.

The dense black profile that first emerges from the target has, to this point, been described as explosive gas. However, it is theorized that the actual composition is a combination of extremely small ($\sim 1\text{-}\mu$ mesh) graphite particles with smoke and gas generated by the detonating explosives. This theory is strengthened by the observed presence of fine graphite dust and is deposited radially on the ground out to between 30 and 50 ft around the target zone, predominantly at the four points of pressure vessel failure for the four-projectile

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Figure 25
Fragment Velocity vs Distance
Test PO-91

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Figure 26
Typical Fragment Profile Progression
Test P0-91

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Mark D PODS. These small particles probably lose their velocity very rapidly once they escape the high-pressure gas "jet-stream"* that is a consequence of the combined internal hydrodynamic effects of the pressure-vessel rupture, the reflector bar mass-inertia, and the simulated target geometry (shadow shield, etc.). So, in evaluating or translating the fragment velocity photographic data into the graphical presentations of this report, the zone designated "explosive gas" actually indicates the velocity of the composite gas/fragment mixture. Under space environment, these particles would continue at the highest velocities attained instead of rapidly slowing down.

The technique used for determining velocity by photographic data reduction is common to the ordnance field. However, certain areas are peculiar to this specific application. It has been mentioned that the initial horizontal fragment profiles usually emanate from the four pressure-vessel failure points of the four-projectile Mark D PODS. Likewise, four vertical fragment "spikes" emanate from the top of the target at what appears to be the location of the four explosive charges. The data-recording cameras are positioned as nearly perpendicular as possible to both the horizontal and the vertical fragment planes to photograph radial expansion of the cloud profile. This film provides the means of determining maximum fragment velocities without subsequent correction of the data for nonplanar velocity effects.

It should be noted, that in preparing the horizontal fragment velocity/distance curves, two velocities were measured at each arbitrarily selected time interval, based upon the radial rather than on the diametrical cloud-profile expansion. By this method, maximum velocities were not minimized by the averaging process, in the event that the two velocities were not coincidental. The velocities of the vertical fragments were measured in a similar manner, and only the two "spikes" normal to the camera were considered to provide valid velocity profiles. Because of the questionable validity of the vertical fragment velocities, as a result of the simulated target and effects, vertical fragment velocities have been shown for Test PO-91 only. These are reasonably typical of the Mark D concept tests, in which the spikes might represent the material forced back out of the projectile entrance holes in the forward head structure.

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*Figure 27 clearly indicates the four heavily populated fragment regions resulting from test PO-91.

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Figure 27

Target/Explosives Orientation and Overall Post Test Dispersal
Test P0-91

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The influence of target simulation on fragment velocity is not well understood at present, and could conceivably require a separate and extensive research program of its own if investigated fully. The data are therefore presented for review in the light of this consideration, with the added comment that it has been empirically demonstrated that target-simulation accuracy effects appear to be reduced markedly as the c/m ratio increases above that represented by the four 105mm projectiles. However, even this statement must be qualified, considering the "jitter" effect produced by nonsimultaneous detonation of the charges. Induced jitter appears to result in a reduction of the effective c/m ratio by reducing peak pressures (as evidenced by the "abnormal" failure of the pressure vessel). This accomplishes the reduction or complete elimination (depending upon charge initiation jitter times) of shock-loading type stress-strain failures induced by the interface collision of primary or reflected shockwaves (or both) propagated from individual charges. This abnormal failure is illustrated in Figure 27a, to show the reassembled pressure vessel fragments from Test PO-91.

The failure points, which can be seen in Figure 27a, are from stress concentrations presented by the end-plate mounting holes. The stair-stepped failure geometries are indicative of the staggered hole patterns (top and bottom). This illustration is in direct contrast to the results of Tests PO-65 and PO-69, in which 105mm charges were used within similar targets and resulted in pressure-vessel failure at four points, each nearly midway between explosive charges, on the outer periphery.

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- INDICATES EXPLOSIVE CHARGE LOCATION AND FIRING SEQUENCE
- INDICATES BOLT HOLE - EITHER FULL OR PARTIAL

Figure 27a
Pressure Vessel Failure Points
Test P0-91

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G. EXPLOSIVES FEASIBILITY STUDY

The purpose of the explosives feasibility study was to evaluate the explosive performance of the candidate PODS concepts and thus determine feasibility. The scope of work was planned to cover a preliminary evaluation of explosives performance parameters (the type, shape, size, location, number, standoff, initiation, confinement, liner design, etc. of explosives) against one-, two-, and three-dimensional (FSSE) targets. The empirical data generated through this activity is utilized directly in the concurrent Mechanical Feasibility study (Section III.N) to analyze and evaluate both the performance of the total system and its relative feasibility.

Eight candidate explosive PODS concepts were directly investigated. Seven PODS tests were conducted against FSSE targets to investigate the feasibility of the candidate concepts. Of the seven tests, six involved concepts other than the implanted projectile (Mark D/J) type, and one (Test PO-55) studied the four-projectile Mark D/J concept. The remaining two concepts (Mark K and Mark L) were crudely tested, and being similar to others investigated did not warrant further study and testing involving FSSE targets. The tabulated results of these initial concept-feasibility tests appear in Table II. These data have also been presented in the graphical form of fragment-size-distribution curves (Subsection III.I.2).

1. Test Description

The following paragraphs outline the general setup and objectives of the various tests conducted during the PODS concept feasibility study.

a. Test AC-132

Test AC-132 was performed to investigate the Mark D/J internal burster charge concept for application to the ACDS. The test setup generally consisted of a single, cylindrical explosive charge (22.4 lb of Composition B) statically implanted (asymmetrically) within a Mod 2e FSSE target. The resultant fragment array was sampled to determine conformance to the ACDS criteria. The recovered samples were subsequently screened and weighed for fragment-size determination as applied to the PODS fragment-size objective.

TABLE II

Results of Initial Concept - Feasibility Tests

Test No.	Test Date	Target	PODS Concept	Explosive Form, and Type, and No. Used	Special Parameter Investigated	Total Explosive Weight (lb)	C/M ①	Percent Mass Sample Within Screen Size Range (%/in.)										MMD② (in.)
								>1,250	<1,250 >0.625	<0.625 >0.312	<0.312 >0.132	<0.132 >0.093	<0.093 >0.0394	<0.0394 >0.0197	<0.0394	<0.0197		
PO-36	20 September 62	Mod 5	Mark G	3/4-in.-thick sheet, Comp. B	Concept Feasibility	160.3	0.122	---	53.8	14.5	6.9	2.0	3.2	---	19.6	---	0.725	
PO-41	20 November 62	Mod 5	Mark G	1-in.-thick sheet, Comp. B	Increased explosives	274.0	0.212	---	48.4	22.0	10.8	---	7.8	2.7	---	8.3	0.595	
PO-45	5 December 62	Mod 1	Mark G	1-1/2-in.-thick sheet, Comp. B	Increased explosives and timing	655.0	0.312	---	51.7	13.2	8.1	0.9	2.4	---	23.7	---	0.683	
PO-46	4 December 62	Mod 5	Mark F	5-in.-dia CSC, Comp. B (12)	Concept feasibility	170.0	0.146											
PO-54	12 December 62	Mod 5	Mark H	2-1/4-in LSC, Octol (20)	Concept feasibility	332.9	0.333	---	74.2	20.1	4.5	0.4	0.4	---	0.4	---	1.140	
PO-55	17 December 62	Mod 5	Mark D/J	105mm, Comp B (4)	Concept feasibility	63.2	0.063		32.6	31.5	25.1	2.9	5.7	---	2.2	---	0.412	
PO-56	19 December 62	Mod 5	Mark M	105mm + 1/2-in.-thick sheet, Comp. B	Concept feasibility	138.3	0.136	---	49.3	26.6	19.8	0.6	1.3	---	2.4	---	0.615	
PO-57	Test cancelled	Mod 5	Mark H	2-1/2-in. LSC, Comp. B (20)	Concept feasibility and HE orientation													
PO-64	3 January 63	Mod 5	Mark D/J	155mm, Comp. B (4)	Increased explosives	147.9	0.182	---	9.8	26.1	52.7	4.5	6.7	---	0.2	---	0.280	
PO-65	3 January 63	Mod 5	Mark D/J	105mm, Comp. B (4)	HE initiation jitter	65.0	0.076	---	25.0	32.4	35.3	3.7	3.6	---	---	---	0.360	
PO-66	10 January 63	Mod 5	Mark D/J	155mm, TNT (4)	Explosives brisance	139.2	0.171	---	35.9	32.6	22.9	1.7	4.3	---	2.6	---	0.447	
PO-67	Test cancelled	Mod 5	Mark F	5-in.-dia CSC, Comp. B (48)	Increased energy transmission													
PO-69	15 May 63	Mod 5	Mark D/J	105mm, Comp. B (4)	Fragmenting HE liner	64.6	0.065	---	42.6	25.2	11.9	3.7	8.4	---	8.2	---	0.507	
PO-70	15 January 63	Mod 5	Mark D/J	95mm, Comp. B (6)	HE spatial distribution	72.8	0.086	---	33.2	32.2	25.5	2.3	5.8	---	1.0	---	0.415	
PO-74	17 January 63	Mod 5	Mark D/J	155mm, Comp. B (4)	Target effect - dense reflector	154.2	0.182	---	28.1	38.3	18.1	4.1	5.2	---	6.2	---	0.450	
PO-75	Test cancelled	Mod 2a	Mark E	7-in.-dia CSC, Comp B (30)	Concept feasibility													
PO-76	4 February 63	Mod 2	Mark D/J	155mm, Comp. B (4)	Target effect - FSSE vs Mod 5	309.0	0.163	---	9.7	25.5	54.0	3.5	5.6	---	1.7	---	0.282	
PO-77	24 April 63	Mod 5	Mark D/J	155mm, Comp. B (4)	HE liner thickness (1/4 in.)	162.6	0.180	---	19.1	44.8	31.0	2.8	1.4	---	1.0	---	0.345	
PO-78	24 January 63	Mod 5	Mark D/J	155mm, Comp. B (4)	HE liner thickness (3/16 in.)	170.3	0.209	---	19.3	39.5	28.6	2.9	6.5	---	3.2	---	0.355	
PO-82	21 February 63	Mod 5	Mark D/J	133mm, Comp. B (6)	HE spatial distribution	169.1	0.206	---	5.6	9.3	9.8	---	24.0	16.7	---	34.6	0.088	
PO-84	Test cancelled	Mod 2	Mark D/J	155mm, Comp. B (6)	Increased explosives													
PO-86	6 March 63	Mod 5	Mark D/J	155mm, Comp. B (4)	Fragment velocity measurement	143.9	0.155	---	25.9	32.7	25.6	5.5	8.7	---	1.6	---	0.368	
PO-91	20 June 63	Mod 5	Mark D/J	105mm, Comp. B (4)	HE initiation jitter	62.0	0.055	---	29.0	39.8	23.3	3.1	1.8	---	3.0	---	0.417	
PO-92	Test cancelled	Mod 1	Mark D/J	105mm, Comp. B (4)	Core module geometry - NERVA B-4													
PO-93	Test cancelled	Mod 13	Mark K	3-in -thick sheet, Comp. B	Concept feasibility													
PO-96	27 May 63	Mod 5	Mark D/J	222mm, Comp. B (1)	HE spatial distribution	61.5	0.056	---	28.6	41.8	22.1	2.0	4.6	---	0.9	---	0.420	
								>1,000	<1,000 >0.500	<0.500 >0.250	<0.250 >0.125	<0.125 >0.062	<0.062 >0.031	<0.0312				
APG-1	13 February 63	Mod 1	Mark D/J	105mm, Comp. B (4)	HE dynamic implant - Full-Core-Length Solid Rod	~130.0						17.60	---					
APG-2③	21 March 63	Mod 1	Mark D/J	105mm, Comp. B (4)	HE dynamic implant - 90° B-4 quadrant	~130.0	0.047⑤	0.50	4.10	16.60	25.10	17.60	---	36.10			0.090	
APG-2④	21 March 63	Mod 1	Mark D/J	105mm, Comp. B (4)	HE dynamic implant - 90° B-4 quadrant	~130.0	0.047⑤	0.03	1.13	10.02	20.73	12.46	3.74	51.89			0.055	
APG-2⑤	21 March 63	Mod 1	Mark D/J	105mm, Comp. B (4)	HE dynamic implant - FSSE (Solid-Core Modules)	~130.0	0.059⑤	---	23.00	37.50	26.50	7.00	5.20	0.80			0.280	
								>1,500	<1,500 >1,000	<1,000 >0.750	<0.750 >0.625	<0.625 >0.436	<0.436 >0.312	<0.312 >0.221	<0.221 >0.132	<0.132 >0.093	<0.093 >0.039	<0.039
AC-85	22 August 62	Mod 5	Mark D/J	90mm, Comp. B (4)	Reduced size explosives (diameter)	31.2	0.026											
AC-129	18 February 63	Mod 2d	Mark D/J	105mm, Comp. B (1)	Reduced size explosives (length)	23.2												
AC-132	4 March 63	Mod 2e	Mark D/J	133mm, Comp. B (1)	Reduced charge L/D ratio	22.4	0.011	36.8	19.6	4.7	2.1	7.8	5.2	4.7	6.0	3.0	4.9	5.2
AC-154	6 May 63	Mod 2e	Mark D/J	105mm, Octol (1)	Target refinement and HE brisance	25.1												

① Charge to mass ratio
② Mass median dimension - fragment particle screen size 50% mass (graphical approximation)
③ Data reduction by Los Alamos Scientific Laboratories (LASL)
④ Data reduction by Aberdeen Proving Ground (APG) extracted from APG Report No. DPS-1060, September 1963)
⑤ Solid rod portion of core (270°) - 0.059
B4 configuration module quadrant - 0.047
Cumulative c/m 0.056

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The test results are significant only to indicate order-of-magnitude efficiency for the particular c/m ratio as related to other Mark D/J tests (as well as to tests of other concepts). It is anticipated that the results of this test might best be used to determine the trend of energy-utilization efficiency for the Mark D/J concept when related to tests using higher c/m ratios.

b. Test PO-36

Test PO-36 was the initial investigation of the Mark G (implosive) concept and used a 3/4-inch-thick "sheet" of explosives (160.3 lb of cast Composition B) to completely cover the circumference of the Mod 5 FSSE target. A linear shaped charge (LSC) was positioned along the full-length exterior of the target at 90-degree intervals and parallel to its longitudinal axis. The LSC effectively removed the mechanical constraint by cutting through the pressure vessel and the magnesium outer reflector sections, and allowed the sheet charges to exert their full compressive loading on the core modules. The results were unsatisfactory in that an excess of large fragments were produced. The decision was made to increase the thickness and quantity of the implosion charges.

c. Test PO-41

Test PO-41 was basically the same as Test PO-36. It varied in that a 1-inch-thick sheet of explosives was used (274 lb of cast Composition B). The results, although slightly improved from Test PO-36, were still inadequate.

d. Test PO-45

Test PO-45 was a final attempt to produce adequate core pulverization with the Mark G concept. In review of the results of Tests PO-36 and PO-41, it was theorized that the target geometry or scaling effect was a critical factor in the function of the concept. Therefore, exaggerated charges (1-1/2-inch-thick sheet - 655 lb - Composition B) were used on a slightly shortened Mod 1 FSSE target. By initiating the LSC and the circumferential sheet implosive charges in a proper sequence so that both extreme ends of the target were being folded in while the center section of intermediate charges and LSC were

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being detonated, it was theorized that, rather than being extruded from either end of the target as had been previously observed, the core of the target would be almost completely retained and subjected to the applied forces of the entire implosive compression/rarefaction cycle.

The results of the test indicated that the implosive constraint technique had functioned properly. However, the solid-rod core modules had been grossly compacted and reshaped under plastic deformation. A large portion of the inner, rod-free void spacing was thus filled, and the core had practically formed a solid graphite cylinder. Additional graphite intergranular void volume decreases (densification) were also observed. The compression rarefaction release following this compression state was somewhat effective in producing additional quantities of small fragments. However, this was accomplished by the superficial stress release, or "elastic limit overshoot," of the rods in which the dynamic rebound caused by the sudden release of the compressive loads caused the intergranular structure of the graphite to exceed the maximum elastic tensile limits. Also, because of the sustained unidirectional loading, the core rods were subjected to a lesser degree of rod interaction which would normally reduce the length of the larger fragments. The net result was an increased quantity of smaller splinter-shaped and half-round fragments (resulting from the elastic limit overshoot effect), and an increased quantity of larger fragments (resulting from the splintering action). The larger fragments appeared to have the lesser structural integrity. Compressive loading tests conducted on post-test samples indicated at least half the lateral compression strength remained.

As a result of this test and the preceeding tests, it was concluded that the Mark G concept was not promising and did not warrant further development.

e. Test PO-46

Test PO-46 was an investigation of the Mark F concept in which conical shaped charges (CSC) are peripherally applied. The choice of CSC configuration was based upon the predictions of deep-penetration capability tests as applied to slab targets. Twelve charges of the chosen configuration (5-inch-diameter totalling 170 lbs of Composition B) were attached to the pressure vessel

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of a Mod 5 FSSE target. A staggered geometrical array was used in which each charge would penetrate the core normal to the target longitudinal axis, but not all charges were aimed to intersect this axis. The charges were initiated in a sequence that was calculated to produce maximum core-module interaction, and also, to make maximum use of the lateral forces imparted by the penetrating jet.

Although fragmentation was inadequate, it was felt that by modifying the concept to use a greater number of smaller charges having lesser penetration and greater lateral energy transmission characteristics, a greater degree of fragmentation might be achieved. However, subsequent detailed analysis of potential shaped charge characteristics and of the relative difficulty in mechanical transport and positioning led to the cancelling of the proposed Test (PO-67) and to the discontinuing of developmental efforts on the Mark F concept.

f. Test PO-54

Test PO-54 was an investigation of the Mark H concept which uses only LSC. Prior to conducting this test, a series of subscale tests were performed on slab targets to establish the general explosive-charge characteristics and geometrical charge array that would best produce the desired results. The slab targets used were flat, sandwich structures simulating the successive layers of the actual reactor, from pressure vessel to reactor core. Various sizes and types of LSC, both singularly and in parallel groups, were applied to the slab targets. The object was to produce the maximum core-rod pulverization by the combined action of deep jet penetration and the spalling action of the area of the outer reflector bars between parallel charges. Upon establishing the optimum charge size, configuration, standoff, geometrical array, and other companion considerations, charges of the recommended type were fabricated and attached to the pressure vessel of a Mod 5 FSSE target in the proper orientation.

Two functional modes were envisioned, both appearing to provide equal potential destruct capabilities. One mode was to orient the LSC perpendicular to the core rod modules; the other mode was to orient them parallel to the modules. Although, initially, one test was planned for investigating each mode, the perpendicular mode was chosen to be tested first, because of its expected performance advantage over the parallel type.

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Unforeseen, inclement weather conditions immediately following Test PO-54, prevented adequate fragment recovery. Therefore, there are no data (other than photographically obtained fragment velocity data) to support the test-result conclusions for this test. However, it can be said, as a result of casual observation and engineering estimates (by area/fragment population density approximations), that the results were somewhat like those of the Mark G concept tests (PO-36, PO-41, and PO-45), and were inadequate to the extent that several 8- to 9-inch-long fragments were observed.

The inadequacy of the resultant core breakup led to additional slab-target testing of the parallel mode concept. Insufficient improvement of general results then led to the subsequent cancellation of the second full-scale test (PO-57). The Mark H concept was not considered worthy of added investigation because, from analysis, it was concluded that the bulky system-translation subsystem requirements would not provide an optimum PODS design.

g. Test PO-55

Test PO-55 consisted of four 105mm cylindrical charges (1/4-inch-thick wall - 63.2 lbs of Composition B) statically emplaced within the core of a Mod 5 FSSE target.

The test results did not satisfy the fragment-size objective although the fragment-size distribution was several orders-of-magnitude improved over previous tests.

The improved results of the Mark D/J concept test led to the derivation of the Mark M concept, and a Mark D/J system of increased explosive charge size.

h. Test PO-56

Test PO-56 was an investigation of the Mark M concept. The test setup consisted of a single 105mm charge (15.3 lbs of Composition B) statically emplaced in the center of a Mod 5 FSSE target core, and an external 1/2-inch thick sheet of explosive (123 lbs of Composition B) covering the outer periphery of the pressure vessel. The Mark M concept was based upon the observed test results of the Mark D/J and the Mark G concepts and as a combination of two

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two held promise of solving the following basic inadequacies of both of these concepts:

(1) The restriction of adequately fragmented core to the area directly adjacent to the explosive charge, for the Mark D/J concept.

(2) The restriction of adequately fragmented core to the area directly adjacent to the graphite reflector shield, for the Mark G concept.

It was felt that sufficient energy could not be transmitted through the heterogeneous reactor members to achieve adequate core fragmentation by either concept alone. The integrated Mark M concept, might provide adequate breakup in the aforementioned areas. The external implosive charge might also (by sequential explosives initiation) retain the reactor geometry for a sufficient period after detonation of the internal burster charge to allow the maximum additional fracturing effect caused by core module interaction.

The test results, although indicating an improvement of the efficiency of the Mark G concept alone, did not achieve the anticipated fragmentation results. Improved results (and efficiency) of the subsequently tested, enlarged version of the Mark D/J concept during the parametric fragmentation-study prompted the decision to suspend further investigation or development of the Mark M concept.

i. Test PO-64

Test PO-64 was an investigation of the effect of increased explosives content (as related to Test PO-55) as applied to the Mark D/J concept. The test setup was basically the same as that for Test PO-55, with the exception that four 155mm charges (147.9 lbs of Composition B) were used in place of the four 105mm charges.

The test results indicated a substantial reduction of fragment sizes over those of Test PO-55. They also indicated that, unlike the Mark G concept, fulfillment of the PODS fragment-size objective might be met with the

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Mark D/J concept if the tolerable limit of explosives weight (because of flight weight penalty considerations) can be maintained commensurate with the steadily decreasing system efficiency as fragment sizes diminish.

j. Test PO-76

Test PO-76 was a full-scale version (Mod 2 FSSE target) of Test PO-64 and produced a nearly identical fragment-size distribution. The successful performance of this test indicated that, within the qualifications imposed by the choice of available reactor simulants, the Mark D/J concept appeared to be the most feasible PODS. Establishing this conclusion categorically completed the PODS concept feasibility study, and initiated a parametric development program for the further investigation and optimization of the Mark D/J concept.

2. Comparative Analysis

a. External Explosive Charge Relative Efficiency -
Mark G Concept

The fragment-size distribution curves for the three Mark G concept tests (PO-36, PO-41, and PO-45) appear in Figure 28. Tests PO-36 and PO-41 used Mod 5 FSSE targets, and Test PO-45 used a Mod 1 FSSE target. It can be noted that a 75% increase in c/m ratio from Test PO-36 to Test PO-41, resulted in a 12% reduction of the MMD. Test PO-45, in which the c/m ratio was increased 41%, produced a reverse trend, by increasing the MMD 15%.

The results of these tests clearly indicated both the diminishing efficiency to be anticipated by further increase of the c/m ratio (increased explosives) and the subsequent inability of the Mark G concept to meet the PODS fragment-size objective.

b. Internal Explosive Charge Relative Efficiency -
Mark D/J Concept

Figure 29 illustrates the characteristic Mark D/J fragment-size-distribution curves resulting from Tests PO-55, PO-64, and AC-132. These three curves are generally representative of the fragment-size distribution obtained in other Mark D/J concept tests, and were chosen for illustration because of the wide range of c/m ratios presented.

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Figure 28

External Explosive Charge Efficiency
Mark G Concept

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Figure 29
Internal Explosive Charge Efficiency
Mark D/J Concept

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In comparing Tests PO-55 with AC-132, it will be noted that a 182% increase in explosive weight resulted in a 63% reduction of MMD. In the case of Tests PO-55 vs PO-64, a 134% increase of explosive weight produced a 32.3% reduction of MMD. These data indicate a trend that substantiates the conclusion that the efficiency of the explosives to reduce the graphite fragment sizes, drops off rapidly as the fragment sizes diminish. In other words, increased reduction of the MMD becomes increasingly more difficult, and subsequently, the explosives become less effective.

c. Explosive Charge Energy Utilization Efficiency

The candidate PODS concepts tested were the Mark D (Test PO-64), Mark G (Test PO-41), Mark H (Test PO-54), Mark J (Test PO-64), and Mark M (Test PO-56). The particle-size distribution curves for these five candidate PODS concepts appear in Figure 30. The relatively high pulverization efficiency of the Mark D/J concepts is apparent. If consideration is given to the variation in cumulative mass ratios, the true differential between the Mark D/J and the Mark G and Mark H distribution curves is actually greater than indicated.

The fragment-size-distribution curves shown are typical of a number of similar tests and were picked because of their representative characteristics.

It will be noted that the Mark D/J concept produces a fragment-size-distribution curve unlike the other concepts tested, in that there are a greater quantity of fragments falling in the "midrange" sizes. As compared to the Mark G concept, Mark D/J produces less dust as well as fewer large fragments.

d. Explosives System Efficiency - Internal Contrasted with External

Figure 31 illustrates the comparison of fragment sizes resulting from Test PO-36 (Mark D concept) as opposed to Test AC-132 (Mark D concept).

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Figure 30
Explosive Energy Utilization Efficiency

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Figure 31
Results with Increased c/m Ratio
Mark D Concept

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It will be noted that an increase of cumulative mass ratio by a factor of nearly 10 for Test PO-36 produced only slightly improved results in the range of fragment sizes under consideration. However, Test AC-132 produced nearly comparable results in the larger fragment sizes (> 2.0 inch long).

3. Conclusions

In review of the test data derived from the PODS concept feasibility study, it can be concluded that the Mark D/J concept has not only demonstrated superior fragmentation capabilities, but also relatively efficient explosives utilization. It follows that the flight-weight PODS system will reflect both this weight saving and a general functional simplicity.

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H. FRAGMENTATION PARAMETRIC STUDY OF MARK D/J CONCEPT

The purpose of this study is to further investigate the performance characteristics of the Mark D/J concept to better define the parameters which affect and limit the functional operation. The study also includes investigation of methods to improve fragmentation performance. The empirical data derived from this activity will be used in the concurrent mechanical feasibility study to better define the imposed limitations and requirements necessary for successful functioning of the overall system.

Parametric investigation data for Mark D/J concept tests are tabulated in Table III. Test setup and objectives are discussed in the following section. Graphical comparisons of the fragment-size distributions for individual tests are discussed in Section III.H.2.

1. Test Description

The following paragraphs describe the general setup and objectives of the various tests conducted during the Mark D/J concept parametric fragmentation study. The fragment-size-distribution results of these tests have been entered in subsequent sections. Test descriptions have been grouped and presented in this section by technological advancement rather than chronological progression since the former method was used in the test program.

a. Test PO-74

Test PO-74 was conducted to determine the effects of the fragmented graphite inner-reflector simulant on the observed and recorded fragment samples. It was thought that the graphite fragments resulting from the shattering of the simulated inner reflector might affect the reduced fragment-size data. The similarity of the reflector graphite and the simulated core modules makes it impossible to distinguish between the two materials when adequately fractured and reduced so that physical geometries are not detectable. These materials would possibly be recognized through costly and involved liquid floatation/separation techniques and selective control of material density values. Since fragmentation of the inner reflector is not a condition of the PODS criteria, Test PO-74 was conducted to determine the general effect and magnitude of contribution of the reflector material to the overall fragment display.

TABLE III

Parametric Investigation
Mark D/J Concept

Percent Mass Sample Within Screen Size Range (%/in.)																	
Test No.	Test Date	Target	PODS Concept	Explosive Form, and Type, and No. Used	Special Parameter Investigated	Total Explosive Weight (lb)	C/M ①	>1,250	<1,250 >0,625	<0,625 >0,312	<0,312 >0,132	<0,132 >0,093	<0,093 >0,0394	<0,0394 >0,0197	<0,0394	<0,0197	MMD② (in.)
PO-36	20 September 62	Mod 5	Mark G	3/4-in.-thick sheet, Comp. B	Concept Feasibility	160.3	0.122	---	53.8	14.5	6.9	2.0	3.2	---	19.6	---	0.725
PO-41	20 November 62	Mod 5	Mark G	1-in.-thick sheet, Comp. B	Increased explosives	274.0	0.212	---	48.4	22.0	10.8	---	7.8	---	8.3	---	0.595
PO-45	5 December 62	Mod 1	Mark G	1-1/2-in.-thick sheet, Comp. B	Increased explosives and timing	655.0	0.312	---	51.7	13.2	8.1	0.9	2.4	---	23.7	---	0.683
PO-46	4 December 62	Mod 5	Mark F	5-in -dia CSC, Comp. B (12)	Concept feasibility	170.0	0.146										
PO-54	12 December 62	Mod 5	Mark H	2-1/2-in LSC, Octol (20)	Concept feasibility	332.9	0.333	---	74.2	20.1	4.5	0.4	0.4	---	0.4	---	1.140
PO-55	17 December 62	Mod 5	Mark D/J	105mm, Comp. B (4)	Concept feasibility	63.2	0.063		32.6	31.5	25.1	2.9	5.7	---	2.2	---	0.412
PO-56	19 December 62	Mod 5	Mark M	105mm + 1/2-in.-thick sheet, Comp. B	Concept feasibility	138.3	0.136	---	49.3	26.6	19.8	0.6	1.3	---	2.4	---	0.615
PO-57	Test cancelled	Mod 5	Mark H	2-1/2-in. LSC, Comp. B (20)	Concept feasibility and HE orientation												
PO-64	3 January 63	Mod 5	Mark D/J	155mm, Comp. B (4)	Increased explosives	147.9	0.182	---	9.8	26.1	52.7	4.5	6.7	---	0.2	---	0.280
PO-65	3 January 63	Mod 5	Mark D/J	105mm, Comp. B (4)	HE initiation jitter	65.0	0.076	---	25.0	32.4	35.3	3.7	3.6	---	---	---	0.360
PO-66	10 January 63	Mod 5	Mark D/J	155mm, TNT (4)	Explosives brisance	139.2	0.171	---	35.9	32.6	22.9	1.7	4.3	---	2.6	---	0.447
PO-67	Test cancelled	Mod 5	Mark F	5-in.-dia CSC, Comp. B (48)	Increased energy transmission												
PO-69	15 May 63	Mod 5	Mark D/J	105mm, Comp. B (4)	Fragmenting HE liner	64.6	0.065	---	42.6	25.2	11.9	3.7	8.4	---	8.2	---	0.507
PO-70	15 January 63	Mod 5	Mark D/J	95mm, Comp. B (6)	HE spatial distribution	72.8	0.086	---	33.2	32.2	25.5	2.3	5.8	---	1.0	---	0.415
PO-74	17 January 63	Mod 5	Mark D/J	155mm, Comp. B (4)	Target effect - dense reflector	154.2	0.182	---	28.1	38.3	18.1	4.1	5.2	---	6.2	---	0.450
PO-75	Test cancelled	Mod 2a	Mark E	7-in.-dia CSC, Comp B (30)	Concept feasibility												
PO-76	4 February 63	Mod 2	Mark D/J	155mm, Comp. B (4)	Target effect - FSSE vs Mod 5	309.0	0.163	---	9.7	25.5	54.0	3.5	5.6	---	1.7	---	0.282
PO-77	24 April 63	Mod 5	Mark D/J	155mm, Comp. B (4)	HE liner thickness (1/4 in.)	162.6	0.180	---	19.1	44.8	31.0	2.8	1.4	---	1.0	---	0.345
PO-78	24 January 63	Mod 5	Mark D/J	155mm, Comp. B (4)	HE liner thickness (3/16 in.)	170.3	0.209	---	19.3	39.5	28.6	2.9	6.5	---	3.2	---	0.355
PO-82	21 February 63	Mod 5	Mark D/J	133mm, Comp. B (6)	HE spatial distribution	169.1	0.206	---	5.6	9.3	9.8	---	24.0	16.7	---	34.6	0.088
PO-84	Test cancelled	Mod 2	Mark D/J	155mm, Comp. B (6)	Increased explosives												
PO-86	6 March 63	Mod 5	Mark D/J	155mm, Comp. B (4)	Fragment velocity measurement	143.9	0.155	---	25.9	32.7	25.6	5.5	8.7	---	1.6	---	0.368
PO-91	20 June 63	Mod 5	Mark D/J	105mm, Comp. B (4)	HE initiation jitter	62.0	0.055	---	29.0	39.8	23.3	3.1	1.8	---	3.0	---	0.417
PO-92	Test cancelled	Mod 1	Mark D/J	105mm, Comp B (4)	Core module geometry - NERVA B-4												
PO-93	Test cancelled	Mod 13	Mark K	3-in.-thick sheet, Comp. B	Concept feasibility												
PO-96	27 May 63	Mod 5	Mark D/J	222mm, Comp. B (1)	HE spatial distribution	61.5	0.056	---	28.6	41.8	22.1	2.0	4.6	---	0.9	---	0.420
								>1,000	<1,000 >0,500	<0,500 >0,250	<0,250 >0,125	<0,125 >0,062	<0,062 >0,031	<0,0312			
APG-1	13 February 63	Mod 1	Mark D/J	105mm, Comp. B (4)	HE dynamic implant - Full-Core-Length Solid Rod	~130.0											
APG-2③	21 March 63	Mod 1	Mark D/J	105mm, Comp. B (4)	HE dynamic implant - 90° B-4 quadrant	~130.0	0.047⑤	0.50	4.10	16.60	25.10	17.60	---	36.10			0.090
APG-2④	21 March 63	Mod 1	Mark D/J	105mm, Comp. B (4)	HE dynamic implant - 90° B-4 quadrant	~130.0	0.047⑤	0.03	1.13	10.02	20.73	12.46	3.74	51.89			0.055
APG-2④	21 March 63	Mod 1	Mark D/J	105mm, Comp. B (4)	HE dynamic implant - FSSE (Solid-Core Modules)	~130.0	0.059⑤	---	23.00	37.50	26.50	7.00	5.20	0.80			0.280
								>1,500	<1,500 >1,000	<1,000 >0,750	<0,750 >0,625	<0,625 >0,436	<0,436 >0,312	<0,312 >0,221	<0,221 >0,132	<0,132 >0,093	<0,093 >0,039
AC-85	22 August 62	Mod 5	Mark D/J	90mm, Comp. B (4)	Reduced size explosives (diameter)	31.2	0.026										
AC-129	18 February 63	Mod 2d	Mark D/J	105mm, Comp. B (1)	Reduced size explosives (length)	23.2											
AC-132	4 March 63	Mod 2e	Mark D/J	133mm, Comp. B (1)	Reduced charge L/D ratio	22.4	0.011	36.8	19.6	4.7	2.1	7.8	5.2	4.7	6.0	3.0	4.9
AC-154	6 May 63	Mod 2e	Mark D/J	105mm, Octol (1)	Target refinement and HE brisance	25.1											5.2

① Charge to mass ratio
② Mass median dimension - fragment particle screen size 50% mass (graphical approximation)
③ Data reduction by Los Alamos Scientific Laboratories (LASL)
④ Data reduction by Aberdeen Proving Ground (APG) extracted from APG Report No. DPS-1060, September 1963)
⑤ Solid rod portion of core (270°) - 0.059
B4 configuration module quadrant - 0.047
Cumulative c/m 0.056

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This problem was approached by replacing the graphite reflector with a density and dimensional simulant so that the mass inertia effect would not be altered, and the normal (unknown) fragment-size distribution would be produced. A solid annulus of Densite plaster (1.7 sp gr) was used in a Mod 5 target and four 155mm charges were statically emplaced within the target core. The results were to be directly correlatable to those of Test PO-64, and indirectly to those of Test PO-76.

The results of the test were somewhat inconclusive and subject to arbitrary interpretation. The Densite plaster failed to dynamically simulate the graphite under explosively induced compression loading rates. The overall result was an effective reduction of shock transmitted to the outer reflector and pressure vessel members, as a result of the shock attenuation and the energy absorbed in pulverizing the Densite annulus. This was apparent in the reduced amount of damage sustained by the outer structure of the target, of the target, as compared to previous Mark D/J concept tests. A further result was an increase in the plastically deformed core rods indicative of sustained intense pressure and temperature zones.

The fragment-size distribution resulting from the test was somewhat poorer than was indicated by Tests PO-64 and PO-76. A relative comparison rather than quantitative evaluation of fragmentation results was deemed adequate for the current phase of parametric investigation as warranted by the limitations of the fragment recovery system. Based on consideration of the results of this test, it was decided to continue the use of graphite inner-reflector simulant, until quantitative evaluation of reactor core mass balance might be required. When depleted fuel-loaded simulant core material is available, a feasible means would exist for the separation and differentiation of the fragments.

b. Test PO-76.

Test PO-76 utilized a Mod 2 FSSE target, and was conducted to determine the effects of controlled end conditions compared with a Mod 5 target in PO-64. Four full-core-length 155mm charges were used (309 lbs Composition B).

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The results indicated that the fragment-size distribution, although inadequate to meet the PODS fragmentation-size objective, was essentially the same as for Test PO-64. They thereby indicated that the use of the less expensive Mod t targets would provide adequate indication of Mark D/J concept gross destruct capabilities.

c. Test APG-1 and APG-2*

Test APG-1 and APG-2 (conducted by Aberdeen Proving Ground) were investigations of the effect of dynamic projectile (105mm) insertion. The two tests were essentially alike except that Test APG-2 used a single 90° quadrant of fuel depleted B-4 core modules rather than a complete core of solid rod simulants. The remainder of the core in Test APG-2 was constructed with solid graphite rods.

The tests basically consisted of the impact penetration and detonation of a single, full-core-length, explosive projectile (4 projectile total ~ 130 lbs Composition B) within the simulated core of a Mod 1 FSSE target. The projectile was gun launched. Three statically implaced charges of similar construction were positioned in the centers of the remaining three quadrants of the target core. The projectile was dynamically inserted into the center of a randomly chosen blank quadrant of the core in Test APG-1, and in the center of the B-4 element filled quadrant in Test APG-2. A recovery pit technique was used to recover fragments for both tests.

The projectile penetrated and detonated properly in Test APG-1 but the fragments could not be recovered adequately and the fragment-size-distribution data were not meaningful.

The projectile also functioned properly in Test APG-2 and fragment sampling was performed. Solid rod fragments and B-4 element fragments were separated by differential density flotation techniques and the respective fragment-size distribution was computed (APG).

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* Aberdeen Proving Ground Report DPS-1060, September 1963.

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The results indicated not only gross difference between solid and B-4 rod fragment-size distributions within Test APG-2, but also gross differences in results as compared to Test PO-55. These differences are presumably attributed to the variation in target geometries: Mod 1 opposed to Mod 5. The variations in basic test target geometries and test conduct procedure of APG-2 opposed to PO-55 present a difficult data interpretation and correlation problem. However, the retention of basic fragment-size-distribution-curve characteristics for the results of APG-2 as contrasted with PO-55, and the advancement of presumably conservative fragment-size data, would appear to justify the use of fragmentation data derived from tests using Mod 5 targets. This is particularly true in consideration of the "relative-variation-of-results" approach that has been taken for parametric test evaluation and the selection of Mod 5 targets for medium to high cumulative mass (c/m) ratio tests only where end effects are less significant compared with the low c/m ratio tests.

d. Test PO-70

Test PO-70 was conducted to study the resultant fragmentation effects caused by different spatial distribution of the explosives within a Mod 5 target. This test used six 95mm charges (one per each radial 60° of the core). The total amount of explosives used (72.8 lbs Composition B) was nearly comparable (within limits of available materials) to that of four 105mm charges. Test results should be compared to those of Test PO-55.

The test results indicated a fragment-size distribution nearly comparable to that of Test PO-55. Slightly less dust range fragments and fewer large fragments resulted. The validity of Test PO-70 was considered questionable because of the possibility that the charges were not initiated simultaneously, and because of difficulty in selecting a representative sample from the fragment array.

e. Test PO-96

Test PO-96 used a single 222mm charge (65.5 lbs Composition B) centrally emplaced in a Mod 5 target, and represented the opposite extreme in spatial distribution of explosives for "105mm equivalent class" charges. The

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test results indicated an improvement in the reduction of the larger fragments, but considerably poorer production of small-size fragments. The lower resultant dust production is a direct result of the reduced surface area of explosive incident upon surrounding core material.

f. Test PO-82

Test PO-82 was an investigation of the same explosive spatial distribution effects with regard to "155mm equivalent class" explosive charges, and was related to Test PO-64. This test used six 133mm charges (169.1 lbs Composition B) that were radially-spaced in the core (every 60°) of a Mod 5 target.

The results show considerable improvements over Test PO-64, with an 87.5% reduction of the MMD. Also, in relation to the 105mm equivalent class, this test indicated that the advantageous effect of spatial distribution is more pronounced as the c/m ratio increases.

It should be noted that because of the program limitations, it is impossible to determine the explosive casing wall thickness and metal condition that would produce maximum core breakup for each charge size (95mm, 105mm, 133mm, 155mm, and 222mm). Casing wall thickness was therefore "scaled" by engineering estimate based primarily upon similar military round designs. It is anticipated that the overall fragment size could be substantially reduced in each case by additional investigation of the tradeoff effects of direct explosive blast as functions of casing fragmentation.

g. Test PO-65 and PO-91

Tests PO-65 and PO-91 investigated the effects of non-simultaneous explosive charge initiation (launch gun "jitter"). Both tests utilized four 105mm charges statically emplaced in a Mod 5 target, and differed only in the charge sequencing patterns and firing delays. Test PO-65 had a charge delay 100μsec after the firing of the other three charges. Test PO-91 had a total firing time spread of 7.5msec (3.5msec each between first and second, and second and third charges and 0.5msec between third and fourth). The dissimilarity of firing

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delays was caused by firing panel premature discharge brought about by adjacent panel RF field. These delays of 100μsec and 10msec (programed but inadvertantly disrupted, total time span) represent the best available ROM estimate of the anticipated minimum and maximum allowable projectile launch jitter. This is as a result of radiation damage to early arriving projectile in dynamic insertion.

The results of both tests were compared to the results of Test PO-55 in which all four charges were fired simultaneously. The fragment-size-distribution curves from the two tests are difficult to interpret when compared to Test PO-55. Generally, Test PO-65 (100μsec delay) produced relatively better results in the overall range of fragment sizes, and Test PO-91 (7.5msec delay) produced a MMD nearly comparable to that of Test PO-55. Contrary to the somewhat misrepresentative comparison of MMD figures, Test PO-91 actually resulted in less dust and fewer large fragments than Test PO-55. This shift of fragment-size-distribution curves is the major problem of interpretation, since the relative rating of "better" or "poorer" results presumably entails flight mission operational analysis considerations that do not form a part of the present work program. However, interpretation based upon the tentative PODS objective (all fragments less than 1/32 inch) would indicate that, since less dust resulted, Test PO-91 produced slightly poorer results than Test PO-55.

h. Test PO-66

Test PO-66 investigated the effect of low brisance explosives on the fragment-size distribution. For comparison purposes, the test setup was the same as that for Test PO-64 (except for explosives type). Forecasts indicated that TNT would probably withstand radiation damage better than other explosives. For that reason, Test PO-66 was conducted to determine anticipated effects if the use of TNT becomes necessary. It was also theorized that lower brisance TNT (compared to Composition B or Octol) could produce superior fragmentation results because of the postulated larger duration of damage process time interval.

The results indicated that the fragment-size distribution was not only poorer than that for Test PO-64, but was worse than that of Test PO-55. In consideration of the known, primary, objectives of the PODS fragmentation

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criteria, TNT was discontinued pending the results of the forthcoming Explosives Radiation Research Program.

i. Tests PO-77 and PO-78

Tests PO-77 and PO-78 investigated the fragment-size-distribution effects produced by different explosive projectile casing wall thicknesses. Both tests used setups similar to that of Test PO-64, for comparison purposes. Test PO-64 used 3/8-inch-thick wall 1015 steel tubing. Test PO-77 used 1/4-inch-thick wall, and Test PO-78 used 3/16-inch-thick wall tubing of the same material and same physical condition.

The fragment-size distributions resulting from the tests (in relation to Test PO-64) generally indicate an increase in fragment-size reduction with an increase in explosive casing thickness, within the limitations of the wall thicknesses that were tested. Certain inconsistencies of distribution curve characteristics have been noted between the three tests. It is not precisely known if the increased core breakup is a function of the increased explosives confinement, as reflected by the additional bursting strength of the tube; the simple bulk mass (or a combination of the two), the increased quantity of fragmentable metal present, or the greater core penetration capabilities presented by the individual casing fragments as a function of greater impetus. All of these factors are considered to contribute to the degree of fragmentation. However, the performance tradeoffs for this specialized application remain unknown. Additional investigation of these parameters will be made during future development efforts.

j. Test PO-69

Test PO-69 used a test setup similar to that of Test PO-55 except that pregrooved explosive casings were used to determine the effects of controlled casing fragmentation. As normally associated with the fragmentation results of explosive loaded mild steel cylinders, detonation of the simulated projectiles in previous Mark D/J concept tests resulted in a number of full charge length, narrow (ribbon) fragments. It was anticipated that a substantial reduction of core fragment sizes would be realized by controlled fragmentation of the

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casing to produce a great number of small diamond shaped fragments. This reduction should be even more apparent in the case of the actual reactor, where (as demonstrated in Test APG-2) a great quantity of splinter-shaped core fragments resulted.

The casing fragment yield was less than expected by design and, although more small size fragments resulted (as compared to Test PO-55), a considerable quantity of larger fragments were produced also (with a subsequent 23% increase of MMD). However, improvement of the fragment-size reduction over the entire range of the distribution is anticipated with properly designed and fabricated explosive casing groove geometries.

2. Comparative Analysis

a. Effects of Graphite Reflector Slabs on Observed Fragment-Size Distribution

The fragment-size-distribution curves for Tests PO-64 and PO-74 are presented in Figure 32. Although the tests utilized similar explosive charges and c/m ratios, the resultant fragment-size-distribution curves are radically different.

As discussed in the preceeding section, the simulated inner reflector graphite slabs of a Mod 5 target were removed and replaced with a solid annulus of Densite plaster. The contribution of the graphite slabs to the recovered graphite sample (mixture of graphite core rods and graphite inner reflector slab fragments) was to be expected.

The modified target with the plaster simulated inner reflector failed to simulate the dynamic characteristics of the standard Mod 5 target. The resultant data are presented in Figure 32 to illustrate the variation and to emphasize the conclusion that the engine components must be accurately simulated.

b. Target Scaling Effects - Mod 5 Opposed to Mod 2

The fragment-size-distribution curves for Tests PO-64 and PO-76 are illustrated in Figure 33. The comparison of these curves indicates the effect of target scaling (full-scale opposing full-diameter, half-length) on the observed fragment-size distributions.

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Figure 32

Effect of Graphite Inner Reflector Fragments on
Core-Fragment-Size Distribution Data

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Figure 33

Simulated Engine Target-Scaling Effect
Mod 2 vs Mod 5

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As illustrated in Figure 33, the two curves are nearly coincidental, indicating the relative integrity of the results to be expected from a Mod 5 target (under the imposed conditions of c/m ratio, etc.). It should be noted that this comparison is for relatively high c/m ratios only and that the trend is not necessarily true for smaller c/m ratios (less explosives), as indicated by the comparison of Tests PO-55 and APG-2.

c. Target Scaling Effects - 105mm Charges

The fragment-size-distribution curves for Tests PO-55 and APG-2 are illustrated in Figure 34. Unlike the 155mm class charges a deviation was indicated between the results of the two types of targets (Mod 1 and 2 as opposed to Mod 5 FSSE targets).

The results shown for Test APG-2 are for the solid rod portion of the core and were obtained from APG data reduction.* The APG-2 test was the only full-scale test using 105mm charges, and therefore, is the only reference with which to assess the scaling effect. A number of differences in test conditions, were present in APG-2. These variations include: (1) The use of the early Mod 1 FSSE target design. (2) Preferential pressure vessel failure modes for medium to low c/m ratio tests when using grossly dissimilar core simulants. (3) Effects of dynamic insertion are functions static prepositioning of explosive charges, and different test attitude, fragment recovery, and sampling procedures used. Because of the "hybrid" introduction of charges in Test APG-2, (three static charges and one dynamically implanted charge) the validity of the indicated variation between the size-distribution curves of tests APG-2 as contrasted with PO-55 may be subject to question. However, at present, little can be said in the way of quantitative evaluation of this variation.

d. Core Material Simulant Effects

The fragment-size-distribution curves for Tests PO-55 and APG-2 are illustrated in Figure 35. Both LASL and APG data reductions appear for the B-4 geometry core-material fragments resulting from Test APG-2. The size-distribution of the solid rod core-simulant fragments from Test APG-2 is a result of APG data reduction.

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*Aberdeen Proving Ground Report DPS-1060, September 1963.

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Figure 34
Simulated Engine Target-Scaling Effects
Mod 1 vs Mod 5

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Figure 35
Effects of Dynamically Implanted High-Explosive Charge
and Core-Material Geometry

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Because of the unknown nature of the many variables introduced into Test APG-2 (that is partial static/partial dynamic charge insertion, part solid/part B-4 core, different recovery techniques, etc.), comparison with Test PO-55 on any level of quantitative evaluation would appear to be of little significance at the present time. The most meaningful significance that can be attached to the comparison is the order-of-magnitude variation to be expected between solid rod simulant in a Mod 5 target and Mod 1 target, and to actual B-4 configuration core modules in a Mod 1 target.

From this comparison, it would appear that a general indication of Mod 1 target performance, as loaded with B-4 core material might be obtained by using a considerably less expensive Mod 5 target loaded with solid rod core simulant. This would appear (in view of the results of Tests PO-64 vs PO-76, etc.) to become an increasingly more valid assumption as c/m ratios increase; and conversely, since target simulation becomes increasingly more critical as the internal explosive charges are reduced, it is assumed that the validity decreases as the c/m ratios are decreased.

The size-distribution curves illustrate the conservative indication presented by the Mod 5 target performance in relation to the Mod 1 target B-4 fragment-size distribution.

It will be noted that in the two reductions presented for the fragment-size distribution of the B-4 quadrant (one conducted by LASL and one at a later date by APG) a significant difference existed between the two curves. This difference is thought to be the result of two things:

- (1) The localized nature of the LASL sample
- (2) The variation of techniques used in fragment screening and data reduction

Sufficient information is not available at this time to allow a detailed error analysis, in either of the analyses performed in explanation of the size-distribution difference. However, the two curves have been shown to illustrate the variation that may be introduced by the sampling and subsequent treatment of fragments derived from the same test even when using the best NERVA

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core simulant available. For purposes of future comparison, it will be assumed that the IASL data is invalidated by the localized recovery of the sample, and that the APG data is more indicative of the test results. These data to, are perhaps, a bit optimistic especially when considering the conservative approach taken by Aerojet.

e. Explosive Charge Spatial Distribution Effects -
105mm Class Charges

Figure 36 illustrates the comparison of the fragment-size-distribution curves resulting from Tests P0-55, P0-70, and P0-96. These tests represent three distinct variations in the distribution of the same quantity of explosives (based upon the quantity of explosives in four 105mm charges) within the core of a Mod 5 target. Two extremes from the standard four 105mm charges were investigated. These were the six 95mm charges in Test P0-70, and a single 222 mm charge in Test P0-96.

Comparison of the results appear to indicate that little advantage is to be gained by the use of either extreme. However, of the two extremes the one with greater distribution of explosives (Test P0-70)* appeared to produce the better results. This improvement was more noticeable in the upper end of the fragment-size range, and, although appearing to be of little significance in the comparison of curves, actually resulted in a significant reduction in fragment maximum length. It also resulted in a reduction of structural integrity for the larger fragments.

f. Explosive Charge Spatial Distribution Effects -
155mm Class Charges

The fragment-size-distribution curves for Tests P0-64 and P0-82 are presented in Figure 37.

Based upon the slightly improved fragmentation indicated by Test P0-70 for "105mm class charges," Test P0-82 investigated the same distribution parameter with regard to 155mm class charges, and consisted of six 133mm charges

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* Recall that the data for P0-70 was considered extremely conservative.

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Figure 36

Large Explosive Charge vs Spatial Distribution Effects

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Figure 37
Explosive Charge Spatial Distribution Effects

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radially distributed within a Mod 5 target. The results are compared to those of Test PO-64 consisting of four 155mm charges.

The test results indicated an improvement for the distributed charges (87.5% reduction of MMD). Approximately 50% of the total sample mass achieved the 1/32-inch PODS fragment-size objective and represented the best performance obtained on the program.

g. Explosive Charge Initiation Jitter Effects

Figure 38 illustrates the fragment-size-distribution curve comparison of Tests PO-55, PO-65, and PO-91. These three tests were conducted to determine the core fragmentation effects produced by various conditions of simultaneous initiation of the explosive charges (jitter).

It is anticipated that some degree of jitter will occur by nonsimultaneous launch and insertion of the actual projectiles as a result of normal component variation, even under the most ideal conditions. Initial estimates of the time spread between early and late projectiles (inserted) indicate a maximum time span of 7-10msec. Using conventional point detonating (impact actuated) projectile fuzes, a maximum time span of 10msec is indicated between the detonation of the first and fourth projectiles. Estimates of other initiation systems (such as trailing wire, radio frequency, and shaped charge) indicated that near simultaneous initiation of the charges might be achieved within a maximum time span of 100μsec. (It should be noted that initial estimates of allowable exposure of explosives to irradiation indicated a 40-45 msec maximum; therefore, radiation damage does not constitute a limiting influence in this analysis.)

A test was conducted to investigate the extreme initiation-time spread for each case. Test PO-65 provided a 100μsec delay between the detonation of the first and fourth charges. Test PO-91 provided (because of inadvertant premature initiation of one charge) a 7.5msec initiation delay between the first and fourth chartes. In Test PO-55, all four charges were initiated simultaneously, and the fragment-size results therefore are used as a "relative effects" reference.

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Figure 38

Explosive Charge Initiation Jitter Effects

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Although the fragment-size-distribution curves resulting from these three tests are somewhat difficult to correlate, it appears that the effects of non-simultaneous detonation are relatively insignificant; and, rather than detrimental, they appear to somewhat improve fragment-size results. However, overall fragment velocity increases with jitter as well.

h. Explosives Brisance Effects

The fragment-size-distribution curves for Tests PO-64 and PO-66 are presented in Figure 39. As discussed in Section III.H.1, Test PO-66 used four 155mm TNT loaded charges within a Mod 5 target. Compared to the results of Test PO-64 (four 155mm charges loaded with Composition B) this indicates the relative effect of explosives brisance on the resultant fragment-size distribution.

In comparing the curves resulting from two tests, it should be noted that the lesser brisance TNT produced poorer results (60% increase in MMD) than Composition B.

This comparison points out two significant conclusions:

(1) The superior fragment-size distribution resulting from the more brisant explosive indicates that the shattering effect of direct explosive blast presents an important mechanism of core pulverization.

(2) Assuming (by previous experience) that the shattering effect is somewhat localized and restricted to the area immediately surrounding the explosive charges (because of the shock attenuative properties of the target). It would appear that greater distribution of the explosives within the core of the target, to effectively increase the area subjected to the localized shattering effect, would result in increased pulverization of the core material. The total mass of blast-affected core material is smaller than the mass of material involved in mechanical crushing action. The validity of these points would appear to be upheld by consideration of the results of the explosives spatial distribution tests (PO-64 as opposed to PO-82, and PO-96 opposed to PO-55).

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Figure 39
Explosives. Brisanse Effects

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i. Explosive Charge Casing Wall-Thickness Effects

Figure 40 illustrates the comparison of fragment-size-distribution curves resulting from Tests PO-64, PO-77, and PO-78. These three tests investigated the effects produced by various wall thicknesses of the explosives casing. All three tests used similar Mod 5 targets loaded with four 155mm explosive charges.

Test PO-64 used 3/8-inch-thick wall, Test PO-77 used 1/4-inch-thick wall, and Test PO-78 used 3/16-inch-thick wall explosive casing. The casing material in all Tests was 1015 carbon steel tubing and produced full-charge-length ribbon fragments (3/4-1-1/2 inch wide) when detonated.

The test results generally indicated improved core breakup with increased explosive projectile casing thickness. This trend deviated somewhat in Test PO-78 where the results indicate the opposite effect in the smaller fragment-size range. The upper end of the fragment-size distribution, however, follows the indicated trend. Although no precise explanation for this deviation is known at present, it does not seem likely that it is the product of some "threshold" condition. It is more likely to have been the result of some unknown error or variable introduced during the fragment recovery and data reduction process.

The assumption is that the extensive core breakup produced by the thicker casing is the result of the greater mass of the metal fragments (whose penetrating capability is accelerated by their greater kinetic energy) rather than by any form of increased explosives confinement, since the added constraint of the increased metal thickness is negligible in comparison to the constraint of the core material and the target structural mass.

j. Explosive Charge Casing, Controlled Fragmentation Effect

The fragment-size-distribution curves for Tests PO-55 and PO-69 are illustrated in Figure 41. Both tests used Mod 5 targets loaded with four 105mm explosive charges. However, the charge casing in Test PO-69 was internally grooved to produce a controlled fragment pattern.

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Figure 40

Explosives Confinement - Heavy vs Light walled Casings

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Figure 41
Explosives - Casing Controlled Fragmentation Effects

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As discussed in Section III.H.1, the groove design did not prove adequate and produced casing fragments 6 to 12-inches long by 1-inch wide, rather than the planned high yield of 1-inch square fragments. Generally, the results were considerably poorer than those of Test PO-55 although better in the smaller fragment-size range.

It is anticipated that properly designed controlled-fragmenting explosive casings of better design will produce an overall reduction of fragment sizes as opposed to non-controlled fragmenting casing.

3. Conclusions

From the information gained during the Mark D/J concept parametric fragmentation investigation, it can be generally concluded that:

- a. Because of the use of solid rod core simulants and Mod 5 targets, fragment-size-distribution results seem conservative in relation to actual B-4 core configuration fragmentation results, and are definitely affected in some manner (probably shifted to larger average fragment sizes) by the inclusion of simulated graphite inner reflector fragments.
- b. Increased distribution of the explosive charges within the core produces increased reactor pulverization (within the limits tested).
- c. Non-simultaneous initiation of explosive charges (simulated projectile launch jitter) does not necessarily adversely affect fragmentation performance (within the "jitter" limits tested) unless higher fragment velocity is considered undesirable.
- d. Core fragmentation results improve with more brisant explosives.

Core fragmentation results improve with increased explosive projectile casing thickness (within limits tested).

- e. Controlled fragmentation of projectile casings appears to hold promise as a means of further reducing core fragment sizes, particularly in the case of actual B-4 configuration core material. In addition, (should the requirement arise) it appears that by the choice and manipulation of these

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various parameters (that is, explosives brisance, initiation delay, casing configuration, etc.) the PODS can be made to produce fragments conforming to any specific fragment-size-distribution curve and range desired yielding high percentages of the core fragments into non-critical sizes, and minimizing the production of fragments within critical-size ranges.

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I. FRAGMENT-VELOCITY STUDY

The scope of this task did not include the investigation and analysis of core-fragment velocities and dispersion characteristics with regard to a potential, radioactive-fragment, prompt-reentry radiation safety hazard (during orbital flight reactor destruct).

It was not the intent of this program to obtain either an empirical or analytical relationship between the space-time distributions of fragment size (mass), shape, velocity, and angle (polar and longitudinal). An add-on program was planned to determine if generating such a complex relationship would be feasible. It will be determined under what conditions the data derived from this effort and from the fragmentation performance effort portion of Sub-Subtask 1.6.5 during Contract Year 1964, could be used to define a mathematical destruct model. These data, or the model, can then be applied to the reentry model, or code, being continuously upgraded by Westinghouse Astronuclear Laboratory (WANL) and to the Physiological model or dosage study being performed by Nuclear Utilities Services (NUS). The result of this combined study will be a Flight Safety Model, which will form a basis for the final safety criteria for postoperation destruct under which RIFT and future space missions employing the NERVA engine may be planned.

An attempt however, has been made to measure initial fragment-flight velocities, and to determine the fragment-velocity/fragment-mass/fragment-angular-dispersion/fragment-population-density relationships for the entry into operational analysis. As discussed previously, because of crude fragment recovery methods, target dynamic simulation problems, and photo-optical resolution, the relationships between these parameters has not as yet been resolved and might entail an extremely high cost.

The scope of activities conducted thus far has been limited to acquiring fragment-velocity data in support of initial AEC/SNPO operational analysis, and in anticipation of impending requirements for reduction or control of fragments constituting a prompt-reentry hazard.

1. Data Presentation

Fragment-velocity/distance curves for 14 PODS tests are illustrated in Figures 42 through 55. These curves are representative of fragment velocities obtained from Mark D, Mark F, Mark G, Mark H, and Mark M concept evaluation tests.

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Figure 42
Fragment Velocity Curves
Test PO-45

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Figure 43
Fragment Velocity Curves
Test P0-46

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Figure 44

Fragment Velocity Curves
Test PO-55

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Figure 45
Fragment Velocity Curves
Test P0-56

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Figure 46
Fragment Velocity Curves
Test PO-64

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Figure 47
Fragment Velocity Curves
Test PO-65

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Figure 48
Fragment Velocity Curves
Test PO-66

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Figure 49
Fragment Velocity Curves
Test P0-70

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Figure 50
Fragment Velocity Curves
Test PO-74

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Figure 51
Fragment Velocity Curves
Test PO-76

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Figure 52
Fragment Velocity Curves
Test P0-78

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Figure 53
 Fragment Velocity Curves
 Test PO-82

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Figure 54
Fragment Velocity Curves
Test P0-86 - North End

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Figure 55
Fragment Velocity Curves
Test PO-86 - South End

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As a result of difficulties in obtaining accurate fragment-velocity measurements, the presented data represent only the average velocities of the expanding fragment-cloud profile. Certain inconsistencies will be found within individual test plots. These are felt to be the result of poor illumination, erratic fragment flight and, in some cases, cloud oscillations induced by ground-reflected pressure waves. The plotted points do, however, indicate an overall trend of fragment-velocity decay that appears to be reasonably reproducible between FSSE targets having somewhat equal c/m ratios. It should be noted at this point, that although the Mark D concept target assemblies were oriented (based upon anticipated pressure-vessel failure points), so that high-velocity fragments would presumably be propelled normal to the camera line-of-sight, in certain instances the pressure vessel failed at points other than those anticipated. Because of this the recorded fragment velocities are those which resulted rather than those considered as maximums. The extent of these variations is not known, since the majority of the "questionable data" was recorded prior to discovering and identifying the origin of the initial high-velocity-gas/fragment loss. An example of this is presented in Test PO-64, which was one of the first investigations of the Mark D/J concept and which produced the first vivid evidence of the high-velocity fragment jets for the four-projectile design. It was assumed that the fragments of highest velocity emanated from the target either directly outward from or adjacent to the explosive charges, and the target was oriented accordingly with respect to the cameras. A maximum fragment-cloud-profile velocity of about 1600 fps was recorded. Subsequent analysis of the test data indicated that the pressure vessel had failed at points other than those anticipated (though not specifically identified prior to this test) and that the velocities recorded were therefore resultants. This is verified in review of subsequent tests using four 155 mm charges, where maximum velocities of 2100 to 2900 fps were recorded.

Test PO-86 was conducted to more accurately establish the velocities of fragments of given mass. The camera positions in this test were abnormally near the target. The target was turned on its side (with axis horizontal instead of the normal vertical position) on top of the 10-ft-high test stand (Figure 56). This was done in order that fragments might be seen at their highest velocity; that is, perpendicular to the camera line of sight.

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Figure 56

Test Setup
Test PO-86

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Two velocity profiles obtained from Test PO-86 (Figures 57 and 58) indicate the geometric shape and velocity profile of the expanding graphite fragment cloud. The two profiles indicate the target as viewed from either end. The shape of the image, correlated with the test setup orientation, indicates the pressure vessel typically failed at a point midway between the charges and produced the leading dust-cloud fronts at these locations. The fragment dispersion pattern on the dry lake bed for Mark D/J concept tests characteristically indicated that the dust lobes (areas of heaviest fragment population) are also oriented radially outward between respective charge centers. The magnesium reflector simulant material and aluminum pressure-vessel material are usually fractured into fairly small pieces and randomly scattered beyond the limits of the graphite-dispersion area.

The interpretation of one series of Test PO-86 film appears in Table IV. Although some of the velocity data appear to be rather erratic, the figures entered are currently the best available measurements of the velocities of fragments of established size and mass. Attempts to obtain additional fragment-velocity determinations, as well as clarification of existing data, were made and will be made during future test activity.

The empirical velocity determination indicated that graphite fragments comprising the expanding cloud profile from a Mark D/J PODS have an average maximum velocity of about 1200 fps for medium c/m ratios and 2500 fps for high c/m ratios. The true maximum limits have not been established, but should be less than 3000 to 3500 fps unless (as indicated by Test PO-91) nonsimultaneous charge-detonation phenomena produce fragments traveling at near hypervelocity speed by virtue of prolonged, or augmented, impetus. Under this condition, fragments appear to be capable of approaching velocities of 7000 to 8000 fps, however, presumably in a somewhat unidirectional mass.

2. Conclusions

There appear to be methods by which the higher velocity fragments might be controlled to reduce their velocity or to predict their directional dispersion (thus permitting harmful prompt reentry fragments to be minimized) if such a requirement becomes essential. These methods are suggested:

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Figure 57

Fragment Velocities
Test PO-86 (North)

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Figure 58

Fragment Velocities
Test PO-86 (South)

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TABLE IV

Data Interpretation
Test PO-86

Destruct Modes	Functional Probability			
	Excellent	Good	Fair	Poor
MARK D				
Control and Fire System				
Closure - Destruct Relay Contacts	x			
Response - Relay Impulse to Fire Pulse Generator	x			
Operation - Fire Pulse Generator	x			
Operation - Safe/Arm Switch	x			
Subsystem Reliability	x			
Operation (Function)				
Initiation - EBW Detonator, MDF Leads	x			
Propagation of MDF Leads	x			
Initiation - Propellant Igniter	x			
Ignition - Propellant Charge		x		
Propagation of Propellant Charge		x		
Dynamics of Projectile Launch		x		
Dynamics of Impacement		x		
Initiation - EBW Detonator, Shaped Initiator Charge	x			
Propagation of Shaped Initiator Charge	x			
Dynamics of Shaped Initiator Charge Jet	x			
Initiation of Burster Charge		x		
System Reliability		x		
Explosive Probability Rating				
Fragmentation and Dispersion (Demonstrated)	x			
MARK E				
Control and Fire System				
Closure - Destruct Relay Contacts	x			
Response - Relay Impulse to Fire Pulse Generator	x			
Operation - Fire Pulse Generator	x			
Operation - Firing Unit	x			
Operation - Safe/Arm Switch	x			
Subsystem Reliability	x			
Operation (Function)				
Initiation - EBW Detonator, MDF Leads	x			
Propagation of MDF Leads	x			
Initiation - Shaped Charge Initiator		x		
Initiation - Shaped Charge	x			
Propagation - Shaped Charge	x			
Dynamics of Shaped Charge Jet	x			
Penetration - Shaped Charge Jet		x		
System Reliability	x			
Explosive Probability Rating				
Fragmentation and Dispersion (Anticipated)		x		
MARK J				
Control and Fire System				
Closure - Destruct Relay Contacts	x			
Response - Relay Impulse to Fire Pulse Generator	x			
Operation - Fire Pulse Generator	x			
Operation - Firing Unit	x			
Operation - Safe/Arm Switch	x			
Subsystem Reliability	x			
Operation (Function)				
Initiation - EBW Detonator, MDF Leads	x			
Propagation of MDF Leads	x			
Initiation - Propellant Igniter	x			
Ignition - Propellant Charge		x		
Propagation of Propellant Charge		x		
Delay - Shaped Charge Initiator			x	
Dynamics of Projectile Launch		x		
Initiation of Shaped Charge		x		
Dynamics of Penetration			x	
Actuation of Firing Device for Burster Simultaneity				x
Initiation - Burster Charge			x	
System Reliability		x		
Explosive Probability Rating				
Fragmentation and Dispersion (Demonstrated)	x			

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- a. Select a Mark D PODS design of other than the four-projectile system (i.e., one, two, six).
- b. Use low-brisance explosives.
- c. Apply greater radial dispersion of projectiles in core.
- d. Use nonparallel positioning of projectiles in core.
- e. Enforce unequal penetration of full-core-length projectiles within the core.
- f. Use sub-core-length projectiles.
- g. Reduce interprojectile explosive charge initiation delay (jitter) to a low value (approach simultaneous action).

Items b through f appear to produce reduced graphite dust quantities as a consequence of these design selections. The first item tends to produce greater dust quantities as a function of greater explosive dispersion. The effect of the last item singly or in combination with the extremes of spatial distribution, is not clearly known. It may force more accurate jitter control upon the system characteristics to lower the high-fragment-velocity generating effects of the long duration destruct pulse.

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J. FRACTURE-MECHANISMS STUDY

The purpose of the fracture-mechanisms study was to investigate the complex explosive destruct processes in order to more systematically evaluate the PODS fragmentation problem. The prime effort was accomplished under Sub-Subtask 1.6.1 in support of the PODS program. Data from both the material correlation study and the fracture mechanisms study provide a better understanding of the problems associated with the PODS fragmentation performance.

1. Prime Damage Mechanism

The latter part of the PODS program for Contract Year 1963 was formulated on the hypothesis that, in the area near the Mark D projectile, the core elements are well fragmented by the strong explosive shockwave, but that the shock attenuates rapidly because of reflection at the multitudinous free surfaces (axial coolant holes) and element interfaces. After considerable testing in the supporting Fragmentation Research program, the prime fracture mechanism is understood to be largely caused by the elements being forced outward against neighboring elements. The fracture mechanisms study attempted to define the zones in the NERVA reactor core where shockwave effects predominate, and where core element fragmentation is predominately caused by impulsive loading. This relationship can then lead to an approximation of the total quantity of dust particles which would be produced by various explosive charge geometries. The four 105-mm projectile Mark D PODS can be considered as an example. The strong shock-induced fracture processes extend approximately three to four element thickness radially outward from the projectile casing for a PODS of this c/m ratio (this does not consider the elements being disturbed by penetration dynamics). Assuming the optimistic case of four undisturbed element thicknesses, the total diameter of the shock-affected zone surrounding each projectile is

$$D = 4.125 + 8 (0.75) = 10.125 \text{ in.} \quad (6)$$

The total cross-sectional area of four of these affected zones is

$$A = \pi (10.125^2 - 4.125^2) = 269 \text{ in.}^2 \quad (7)$$

The total cross-sectional area of the reactor core with projectiles in place is

$$A = \frac{\pi}{4} (35)^2 - \pi (4.125)^2 = 907 \text{ in.}^2 \quad (8)$$

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The ratio of the affected zones to that of the entire core is $\sim 30\%$, indicating that no more than this fraction of the core mass can be reduced to dust particles by explosive shock action when assuming the best case of undisturbed core integrity (that is, statically emplaced projectiles).

When considering the more realistic case of penetration disturbance of the core mass, it is postulated that the lateral precrushing of the displaced elements will increase the localized shock-attenuating properties of the mass in the immediate area of each projectile by at least 100%. Relating this change in attenuation properties to a generalized thickness value of half the four elements assumed to be the optimistic case (a linear attenuation relationship with radial distance), two element thicknesses are postulated. Further effects are expected as a result of this increased attenuant condition, which will be observed as reduced apparent c/m ratio performance. Disregarding the lowered c/m ratio performance effect, the dimensional changes in shock-affected core zones result in a new ratio of 12%. This indicates that only a fraction of the core mass can be expected to be reduced to dust particles by explosive shock action considering a postulated worst-case of predisturbed core integrity (that is, dynamically emplaced projectiles).

The corresponding best- and worst-case pulverization fractions brought about by the six 133-mm-projectile Mark D geometry is 58% and 15%, respectively, computed as in Equations 7 and 8. This larger, more distributed design configuration is capable of providing better performance than the four 105-mm-projectile concept. However, in doing so, the six 133-mm-type suffers a 2.3 increase in system weight.

Pulverization beyond these threshold values is probably produced by the repeated interaction between neighboring core elements and fragments traveling intersecting courses. The resultant inter-element impacts are generally thought to be of a grazing nature, producing little dust. The major contributor to the impact-generated dust fraction is the impact of metal projectile-casing fragments upon the core elements and the subsequent impact of the elements upon the structure comprising the reflectors and pressure vessel.

The brittle nature and grain structure of graphite produces dust upon simple fracture, even from blows with a hammer. This repetitious impact

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process becomes less efficient as the particle sizes become smaller. However, the duration of this process can be of a considerable length, allowing many direct and abrasive contacts. The total fraction of the core reduced to dust by this process is difficult to determine, but is definitely related to the c/m ratio of the specific test; this is, more dust results from the greater interaction-generating capabilities of the higher c/m tests.

Another process related to the mechanical pulverization process concerns reinforcing the individual projectile effects that occur between the distributed detonation centers. This reinforcement, observed in a well-developed state in the four-projectile designs, causes a high-velocity jetting that, in addition to severing the massive layered structure surrounding the core in a preferential fashion, also produces a region of concentrated fragment expulsion. This concentration produces further pulverization, along with a polishing of the fragment surface to a high, "metallic" luster.

The fragment-polishing condition is apparently caused by long-duration, intense pressure and temperature pulses and by the concentrated expulsion (with consequent increased gas and rubbing ablation) of the major portion of the core material as it is ejected through the severed core-confinement. The total core fraction involved in the concentrated jetting and ablation is also difficult to determine. The geometries which tend to produce the action (that is, four-projectile) have reduced impact effects upon the massive surrounding structure, which in some complex manner (probably a 45° shift in directional action) compensates for the increased effects brought about by the concentrated jetting.

2. Anisotropic Reactor Design

The NERVA engine design is completely anisotropic (unidirectional). This peculiarity extends from the pressure vessel radially inward to the core bundle in a concentric cylindrical arrangement. Within the core, all element interfaces are longitudinally aligned. The elements themselves are geometrically designed with the cooling hole pattern also longitudinally aligned. Further, the element extrusion process aligns the grain/void structure in a longitudinal pattern. The extrusion process produces a "skin" effect on the longitudinal surfaces of the element, which induces an additional anisotropic toughness.

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As an overall result, the NERVA reactor core should be overly sensitive to lateral attacks. This observation has been adequately demonstrated by numerous tests, from single elements up to large bundles of elements, and under a wide variety of explosive and mechanical loading conditions, rates of loading, and boundary conditions. The elements tested have varied in geometric design, in fabrication process, and in degree of support and constraint.

To provide laterally directed explosive loading, the engine structure either must be radially attacked in a well-distributed fashion through the pressure vessel, as by a number of the unsuccessful PODS concepts (Mark E, F, G, H, etc.), or it must be axially attacked by introducing long explosive projectiles that can provide the required lateral core loading internally over the full-core-length, as in the case of the successful Mark D/J concept.

Aft projectile attacks would be preferable to forward attacks, because of reduced penetration requirements. This is not possible because of the attendant radiation and structural support problems.

Axial core loading (as in the Mark K concept) is an extremely inefficient fracture mechanism, particularly when introduced from the front of the core because of the lack of a suitable confining effect at the nozzle end.

Although the lateral loading of the core material is much more desirable than any other type, the anisotropic characteristics of the NERVA engine design make it impossible to eliminate sliver-shaped core fragments, regardless of the element hole geometry, even under strong explosive shock and mechanical interaction conditions. This is extremely evident in the NERVA B-4 reactor element design, primarily as a result of the approximate 0.075-inch characteristic minimum structural web dimension (see Figures 59 and 60)* which is more than twice the 1/32-in. maximum size allowable after destruct action. The 0.075-inch dimension is an averaged value obtained from the maximum and minimum longitudinal breakage surface lengths inherent in the NERVA B-4 reactor element cross-sectional hole pattern. The NERVA B-1 design provides a larger characteristic web dimension (0.125-inch), and hence it is expected to be influenced in its fracture characteristics toward larger average fragment sizes when under strong impulsive loading.

* Figures 59 and 60 illustrate the geometric shape of the B-4 element.

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Figure 59
B-4 Element Configuration

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Figure 60
B-4 Element Plastic Deformation

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The difference in fragment size resulting from the hexagonal geometry (NERVA B-4) as opposed to the circular geometry (NERVA B-1 and crude rod) is felt to enhance the fragmentation performance of the former.

The element geometry, therefore, appears to have a more pronounced effect upon fragmentation than grain structure and other physical properties. However, it is not possible to obtain a quantitative evaluation of all these effects or to even separate them. However, if a rigorous treatment is desired, practically all properties (including elastic and plastic behavior relationships) must be considered because each appears to have some important bearing on the problem. The effects are neither directly proportional nor tending in the same direction.

The following observations are offered to exemplify the complexity of the problems which obscure and hinder a ready resolution of this anisotropic fracture mechanism.

a. Results of tests using solid rods indicated that the minimum characteristic fracture dimension was the $3/4$ -inch rod diameter, when the shock loading was below a certain threshold value. Shocks above this value produced longitudinal splinters originating from the tangential lines of concentrated cylindrical contact within the core bundle. Subsequent mechanical interaction reduced the splinter lengths considerably without reducing the thickness appreciably. This observation is based on the rough ends and smooth sides of the splinter fragments.

b. Extreme high-intensity shocks were attenuated so rapidly by the core material that a characteristic dimension, which influenced this mechanism, was not identified even though numerous ultra-high-speed photographic and microphotographic techniques were applied. Instrument data, relating the actual shock pressure values (kilobars) obtained by test (although absolute values in terms of the acquisition techniques used), can not be placed in proper relationship with the attendant test setup and fragmentation performance variables. Consequently, these data have been of little direct technical value to date.

c. If the noted thresholds exist in the NERVA B-4 element design much as they appear to in the crude material, it becomes almost futile to expect an exact definition relating each of the internal damage mechanisms to the production of graphite dust.

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3. Temperature Effects

Conclusive evidence indicating the extreme influence of temperature and pressure upon graphite fracture mechanisms has often been observed in testing. Under the extreme conditions involved in the application of the destruct task, intense pressure and temperature zones are created within the core. These zones either compact or plastically deform a significant portion of the normally fragile graphite material into large dense pieces instead of pulverizing the material into dust. This condition has been observed in the solid rod, round rod, in the NERVA B-1 (round and hexagonal element), and in the NERVA B-4 geometries (see Figure 60),* and has been produced by most destruct concepts (including the Mark D and specially noted in the Mark G) in both full- and small-scale tests. It was also observed in the depleted fuel-loaded NERVA B-4 elements used in Test APG-2.

Neither the temperature effects upon the physical properties of graphite nor the related effects upon its fragmentation properties are known. It appears that any tendency toward high-temperature conditions within the core, regardless of the source, will reduce the explosive fragmentation effectiveness. This is because graphite material, through its plastic behavior, tends to absorb impulsive loads at high strain rates under extremely high temperature. This characteristic behavior increases the possibility of creating localized zones of plastically-deformed elements instead of the desired dust.

4. Conclusion

The following are among the more important factors relating to damage mechanisms and to the degree of success in reducing the NERVA engine core to dust fragments.

- a. Detailed engine structure, core, and element design
- b. Graphite grain size and orientation
- c. Detailed fabrication processes
- d. Environmental status of the engine
- e. Primary direction of explosive attack.

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* Figure 60 indicates the deformation of B-4 material.

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The relationship of these factors to one another are extremely complex. Gross attempts have been successful in isolating the predominant parameters, which should aid in developing a successful PODS.

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K. MATERIAL CORRELATION STUDY

The twofold purpose of this study was to investigate means by which the response effects of the actual NERVA engine core material could be simulated by using low-cost materials, and to develop methods to correlate these effects. This study was performed under Sub-Subtask 1.6.1, in support of the ACDS and PODS programs.

1. Graphite-Property Considerations

Graphite, as a structural material, has many peculiar characteristics. It is a high-incident energy-absorbing material and, as previously discussed, pulverizing a large quantity into fine dust presents a difficult problem. The basic material has a complex and highly variable physical nature which is difficult to determine, reproduce, and extrapolate to new and more critical environmental and operational conditions. Its physical behavior at ambient temperatures and at low strain-rates is well known. Its characteristic properties are presently being investigated over a wide thermal spectrum. However, no data are available on the fracture characteristics of graphite at any temperature under extremely high (explosively induced) strain-rate loading conditions. Such data would be invaluable to understanding and accurately applying explosives to the post-operation destruct task. A thorough presentation of graphite properties and their possible effects upon the correlation of simulative materials is in Report RN-S-0021.

2. Geometric Effects

Sufficient material correlation data are not available for a quantitative correlation between PODS performance utilizing extruded 3/4-inch-diameter solid, round AGSX (National Carbon Co.) graphite electrode rod and that utilizing enriched fuel-loaded graphite elements of NERVA B-4 configuration. The 3/4-inch-diameter rod geometry was selected because of its commercial availability, low cost, and similarity to the NERVA B-4 configuration, with respect to total void volume (inter-element and cooling hole) and approximate ambient strength. The material correlation experiments have been directed toward isolating the effect of each of the various fracture processes on different types of simulated core elements rather than toward obtaining direct correlation between fragmentation

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properties of the actual and simulated core elements, since actual NERVA B-4 core material was not available to this program. The experiments conducted to date indicate that the geometric difference between the actual and the simulated elements is of major importance.

The subscale test results indicated that in the immediate vicinity of the projectile, the core elements are well fragmented by the strong explosive shockwave. However, the shockwave is attenuated in a short distance, because of the many interfaces and inhomogenities in the core. This leaves the elements near the periphery of the core to be fragmented by being forced against neighboring elements and the constraining pressure vessel/reflector structure. Because of this mechanism, the fracturing occurring at the core periphery results in much larger fragments. Fracturing of the 3/4-inch-diameter rods into short lengths without a reduction of diameter has been observed in PODS tests in which internal explosive charges were used. In two subscale tests where the extruded 3/4-inch-diameter rod fragmentation was compared with the fragmentation of NERVA B-4 elements machined from extruded reactor grade graphite bars, results indicated that the latter elements are considerably more fragile, and will fracture easily at the webs between the longitudinal holes. If B-4 type elements were used, therefore, the large number of 3/4-inch-diameter short-length fragments always obtained from both full-scale and subscale tests with the crude rods might be reduced.

In the explosive destruct configuration used in Test PO-82, the maximum projectile-casing-to-core-element distance was approximately 7 inch, and the subscale test using machined NERVA B-4 geometry elements (MC-56) had a maximum projectile-casing-to-core-element distance of 2.6 inch. The c/m ratios were increased by a factor of twenty from Test MC-56 to Test PO-82.

Therefore, it seems reasonable to assume that the destruct system of Test PO-82 would have fractured the elements furthest from the projectile casing if the core elements used in the test were machined from extruded graphite bar in the NERVA B-4 geometry. The degree of fragmentation depends upon the location of the explosive within the core and the localized damage mechanisms prevailing.

In one test, an extruded unloaded NERVA B-1 element was laterally deformed to the extent that the holes were completely closed, but the element

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had not fractured at the webs. This is not as likely to occur in the NERVA B-4 element design because of the greater number of holes (19 opposed to 7), the thinner structural webs (0.075 inch opposed to 0.125 inch) and the edge stress concentrations caused by the geometrical shape (hexagonal as opposed to circular). However, Test APG-2 results clearly indicate that the depleted fuel-loaded NERVA B-4 elements can be laterally compacted to completely close all holes (Figure 60), regardless of its fragility. These fragments were undeformed elements of approximately 1-inch maximum lengths. Plastic flow in the round rods generally results in a larger quantity of pieces of 6 to 10 inch long. The plastic behavior of graphite (a normally brittle material) presents a problem, and the solid, round rod configuration exaggerates its magnitude compared to the more fragile NERVA B-4 elements. At elevated temperatures and at conventional strain rates, graphite becomes more ductile. This may complicate the problem by causing the NERVA B-4 configuration to deform to a greater extent instead of easily fracturing under lateral loads.

If the NERVA B-4 elements can be fractured at each of the webs between the longitudinal holes, the maximum dimension of the fragment cross-section would be approximately 0.075 inch, assuming that there is no abrasion during the fracture process. That is, if only a single cleavage were created between neighboring holes, the fragments would resemble slivers with a maximum cross-sectional dimension of approximately 0.075 inch. The length of these slivers would be somewhat random, but controlled fragmentation of the projectile casing (the previously discussed serrated, diamond-shaped design) might be a means of limiting the fragment length to only short dimensions. The sub-scale test employing machined NERVA B-4 geometry elements produced several slivers that were approximately 1.5 inch long. Lateral mechanical impact in a drop-weight apparatus, with an impact energy of 14.95 j, fractured a 2-inch-long element into slivers, except at the two side corners (Figure 61). But, it is anticipated that extruded NERVA B-4 geometry elements will be more resistant to this type of lateral impact than the machined simulant because of the different kind of residual stresses imposed on the material during the fabrication process.

The largest recovered fragment from Test APG-2 was 80 gm (~6.4 inch of the length of a whole element) indicating that the problem of fracturing

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Figure 61
Results of Graphite Fragmentation
Under Impact

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depleted fuel-loaded NERVA B-4 elements at all of (or most of) the webs was not completely solved. Figure 62 illustrates a range of shapes resulting from Test APG-2.

Reducing the fragment cross-section below the 0.075-inch sliver dimension has not been systematically studied. The results of the two subscale comparison tests of the 3/4-inch-diameter solid rods and the machined NERVA B-4 geometry elements (Tests MC-32 and MC-56) however indicated that the proportion of fragments in sizes varying between 0.039¹/₄ inch and dust was doubled by using NERVA B-4 geometry. Extrapolation of this result to full-scale conditions is somewhat questionable because the dust fragments are produced primarily near the projectile, and the shock-propagation process is a function of too many complex variables to be scaled with confidence at this time.

3. Fabrication Effects

The effects of fabrication upon the fracture characteristics of graphite structural core elements has been noted. The NERVA B-4 geometry machined into extruded graphite bars was determined by numerous tests to be considerably weaker than similar graphite material extruded in the same geometry. Small differences probably exist because of the manufacture's batch tolerances, but the overall indication is that the extrusion process produces an extremely tough skin effect on the longitudinal surfaces of the graphite element, and that this skin effect greatly influences the detailed fragmentation properties of the element. Basic geometric differences govern the degree to which the skin effect is noticed and is the major parameter of concern. For instance, in the 19-hole NERVA B-4 design the extrusion process produces significant geometric and skin effects as compared to the process of the 7-hole NERVA B-1 design, and the effects of solid rod simulant are hardly noticeable. Specifically, the NERVA B-4 design provides a well-distributed, toughening effect because of the thin web design that increases the skin effect. Yet, even this toughness does not compensate for the basic geometric induced fragmentation weaknesses inherent to that design. It was determined that both the BFE unloaded NERVA B-4 simulant and the GFE depleted fuel-loaded NERVA B-4 simulant fractured more easily, produced smaller average fragment sizes, and transmitted less incident energy under all types of loading conditions than did the solid, rough graphite rods. Further, it was determined that the

Figure 62
Fragmentation Resulting from Test APG-2

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larger grained graphite material is more susceptible to incident energy attenuation than is the finer grained graphite material. It also produced considerably more data scatter. This scatter is probably a result of both an increased production process control tolerance and the larger range in basic grain sizes used in the mix process. Reactor-grade graphite is typically fine grained and is rigidly controlled in the fabrication process. The large-grained graphite provides increased void volume and therefore is less dense than the fine-grained material. The finer grained graphite is affected more by the extrusion process than is the large-grained material by way of increased tendency toward grain and void alignment and skin toughening.

4. Fuel-Loading Effects

The lack of data upon which predictions can be made, makes it difficult to anticipate what detailed localized effects exist between the presence of the heavy fuel particles and the unloaded graphite material constituting the core. The observations to date indicate that no apparent differences exist, but this may be because of an unknown threshold condition. It would seem that the presence of well-distributed, minute - yet dense - masses would assist the fracture process at the matrix/fuel particle interfaces, especially under strong shock conditions. If this is true, greater dust production might be possible for the loaded fuel elements. A carefully prepared FSSE test should be conducted to investigate this condition. If the influence of fuel loading is found insignificant compared with the basic primary variables relating to graphite material, geometry, and fabrication process, future FSSE tests could be conducted with the lower cost GFE unloaded NERVA B-4 simulant. No comments can be made regarding the influence of either the new encapsulated fuel or the fission product status on the localized fracture mechanisms of the NERVA B-4 design. It is important, however, to correlate the anticipated responses of the actual core material to those of the best suitable simulant material available.

It is expected that the new element fabrication process will aid the fragmentation performance (increase dust fraction) because of the better fuel-dispersion and size-control. This should reduce the tendency toward random fragment-size production. Also, any reduction in basic element strength or grain-structure damage, as a result of the fission product buildup during engine operation,

will produce better fragmentation performance for low to medium c/m ratio Mark D systems, which depend to a great extent upon repetitious mechanical impact for dust generation.

5. Conclusions

As previously stated, the task of correlating the physical characteristics of a low-cost commercially available material and design with that of a high-cost GFE material and design is difficult. This is particularly true when this material is graphite and when the design is as complex as the NERVA engine. However, sufficient interrelating bits of data have been obtained to permit generation of a coherent PODS design based upon, and verified by, a large number of relatively inexpensive tests. The correlations have been indirect, but have indicated data-substantiated trends which, in combination with engineering judgment, could provide reasonable solutions.

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L. NERVA ENGINE SIMULATION ADEQUACY

The NERVA engine simulation study indicated that destruct concepts of low to medium c/m ratios which rely primarily upon internal pressure generating mechanisms must be tested against FSSE targets designed to reflect the overall response characteristics of the actual NERVA engine under the same dynamic conditions of pressure-vessel failure. The load-transmission properties of the simulated core must be closely compatible with the fracture characteristics, or overall toughness of the simulated pressure vessel so that the test data obtained will not be misleadingly optimistic or overly conservative. If, because of the lack of a suitable material, the core simulated to be used has higher load-transmitting properties than the actual NERVA B-4 core, then the simulated pressure-vessel design must also reflect a higher toughness factor than the actual NERVA pressure vessel. Otherwise, the test will produce fragmentation results that are overly pessimistic because of an early release of the massive confinement surrounding the core. These dynamic effects are not believed to be as significant as those affecting ACDS dispersion performance, but are nevertheless believed to be important enough to warrant careful design and analysis considerations prior to conducting further FSSE tests. Thorough analyses of the ACDS FSSE test simulation adequacy are presented in Reports RN-S-0020 and RN-S-0022.

1. Load Transmission

The FSSE target cores were constructed using solid, round 3/4-inch-diameter, extruded electrode stock. The bulk-mean-density of the test cores is similar to that of the actual core (81 lb/ft³ as opposed to 95 lb/ft³). The graphite material selected to represent the actual core elements also had similar physical properties except that uranium loaded fuel was not involved. The detailed anisotropic design characteristics were not the same, since the actual NERVA core is considerably more complex. Because of this predominate factor, the crudely-simulated core would not respond to dynamic loading in the same manner or to the same degree as the actual core.

All of the explosive destruct concepts depend, to a degree, upon transmitting great forces through the core material to accomplish the functions of fragmentation, confinement release, and subsequent fragment dispersion. The

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NERVA B-4 elements are much weaker than the solid rods under all types and directions of incident loading because of the thin matrix webs between the numerous cooling holes inherent to that design. These elements collapse more easily, and consequently do not transmit as great a mechanical load as do the solid rods. This load-attenuation condition would be magnified even further when precrushing occurs as a result of the dynamic penetration of projectiles in the core mass. To compensate for this lack of accurate core simulation during testing activities, the other related engine components and structures upon which these transmitted loads act must be designed to be compatible with this artificial core condition.

Experiments were conducted to compare the related load-transmission properties of the various core-simulant-material geometries available for use, since no absolute values could be obtained with the unavailable actual core material. Mild-steel cylinders (6 in. ID x 0.25 in. wall thickness x 6 in. long) were filled with core elements, and a selected 5/8-inch-diameter, Composition B explosive charge was detonated in the center of each cylinder.* The damage contour of the deformed cylinders was measured and the energy for deformation was obtained by numerically integrating the conventional stress-strain curve along the length of the cylinder. Good integration accuracy was obtained because the strains were not large enough to cause appreciable thinning of the cylinder wall. The effects of strain rate (including radial distance magnitudes from the source of loading) and of exact confinement conditions were neglected.

The ratios of deformation, or load transmission, energies for a hexagonal NERVA B-1 hole configuration (machined from extruded bars of HLM Grade graphite - Great Lakes Carbon Co.) compared with the solid 3/4-inch-diameter, extruded rods (made from AGSC Grade graphite) were found, by the above method, to be

$$\frac{3/4\text{-in. Hex NERVA B-1}}{3/4\text{-in.-dia Round Rod}} = 0.75 \quad (9)$$

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* Figure 63 indicates the test cylinder.

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Figure 63

Test Model: Load-Transmission Energy Ratios Test

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Subsequently some extruded NERVA B-4 geometric simulant, with an unknown fabrication history, was received as GFE. An experiment was conducted to determine the ratio of load-transmission energies between this unfueled configuration and the solid rods. It was found to be:

$$\frac{3/4\text{-in. Hex NERVA B-4}}{3/4\text{-in.-dia Round Rod}} = 0.4 \quad (10)$$

This indicates a relative measure of the lateral attenuating properties of the design-geometry-induced effects. It also indicates some similar relationships with respect to the fragmentation performance. This postulated relationship between attenuation and fragmentation is probably not linear, but is most certainly an inverse function based on numerous test observations.

2. Pressure-Vessel Toughness

Program limitations forced the use of low-cost commercially available, material simulants for all engine components. Despite efforted to realistically simulate components, some major inconsistencies existed. Generally, the pressure vessel, the forward head structure, the nozzle convergent section, and the outer and inner reflector assembly designs (as applied to the FSSE targets) accurately represented the actual engine, as far as obtaining engineering-trend information regarding destruct charge performance was concerned. At least the differences and their effects on destruct performance were accountable from close inspection of the post-test debris and, in some cases, can be easily changed by design to accommodate desired test objectives. However, when a large simulation inconsistency exists because of using a low-cost material in the core, which then disturbs the overall dynamic response of the FSSE, it becomes extremely important to closely examine the remaining, controllable, design factors to some extent. The major control over a compatible match between the load-transmission properties of the core and the failure characteristics of the pressure vessel is that of both pressure vessel toughness and thickness since outside diameter, length and material are well defined by the engine design requirements. The NERVA pressure vessel is constructed of 6061-T6 Aluminum alloy with a minimum wall thickness of

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0.67 inch. Since FSSE pressure-vessel thickness was established by the commercially available value selected at an earlier time and based on previous engine design information because of load lead mill run purchases, toughness provided the only remaining controllable variable. In general, the two most useful heat treat conditions are the -0 and -T6. The ratio of failure energies (toughness) of 6061-T6 to 6061-0 is 0.78. This value is obtained by comparing measured areas under the stress-strain curves for the respective materials, while assuming strain-rate effects are negligible.

Taking thickness variations into account, the pressure-vessel fracture energy ratios are:

a. 6061-0 Aluminum Alloy

$$\frac{\text{NERVA Pressure Vessel}}{\text{Mod 1 FSSE}} = 0.78 \left(\frac{0.67}{1.00} \right) = 0.52 \quad (11)$$

$$\frac{\text{NERVA Pressure Vessel}}{\text{Mod 2 and Mod 5 FSSE}} = 0.78 \left(\frac{0.67}{1.13} \right) = 0.46 \quad (12)$$

$$\frac{\text{NERVA Pressure Vessel}}{\text{Mod 2 FSSE}} = 0.78 \left(\frac{0.67}{0.80} \right) = 0.65 \quad (13)$$

b. 6061-T6 Aluminum Alloy

$$\frac{\text{NERVA Pressure Vessel}}{\text{Mod 1 FSSE}} = 1.00 \left(\frac{0.67}{1.00} \right) = 0.67 \quad (14)$$

$$\frac{\text{NERVA Pressure Vessel}}{\text{Mod 2 FSSE and Mod 5}} = 1.00 \left(\frac{0.67}{1.13} \right) = 0.59 \quad (15)$$

$$\frac{\text{NERVA Pressure Vessel}}{\text{Mod 2 FSSE}} = 1.00 \left(\frac{0.67}{0.80} \right) = 0.84 \quad (16)$$

Combining the pressure-vessel and core-material simulation ratios, an overall correlation between the anticipated results of an actual NERVA engine destruct test and the performance of the specific Mark D tests conducted to date, or planned for the future, is obtained for different core-material simulants

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A desirable resultant product should be either ≥ 1.00 to represent test conditions which would provide conservative results. Overly optimistic fragmentation results caused by late confinement release from too tough a pressure vessel (a number less than 1) during early development testing, might lead to an inadequate fragmentation performance under actual conditions. Conversely, an overly conservative design based on fragmentation performance affected by early confinement release from too weak a pressure vessel (a number much greater than 1) would effect the payloads of third- or fourth-stage rocket vehicles by forcing the use of an overly heavy PODS to obtain a given fragment-size distribution. The simulation adequacy product is:

$$\frac{\text{NERVA Engine (Core Type)}}{\text{Simulated Engine Material}} = \frac{\text{Pressure Vessel}}{\text{Fracture Energy Ratio}} \div \frac{\text{Core Load}}{\text{Transmission Ratio}} \quad (17)$$

For the FSSE targets containing the crude solid-rod cores used in the PODS development program, the following relationships hold:

a. Mod 1 FSSE (1.00-in.-thick)

$$\frac{\text{NERVA Engine (B-4)}}{6061-0} = 0.52 \div 0.4 = 1.30 \quad (18)$$

$$\frac{\text{NERVA Engine (B-4)}}{6061-T6} = 0.67 \div 0.4 = 1.68 \quad (19)$$

b. Mod 2 and Mod 5 FSSE (1.13-in.-thick)

$$\frac{\text{NERVA Engine (B-4)}}{6061-0} = 0.46 \div 0.4 = 1.15 \quad (20)$$

$$\frac{\text{NERVA Engine (B-4)}}{6061-T6} = 0.59 \div 0.4 = 1.48 \quad (21)$$

c. Mod 2 FSSE (0.80-in.-thick)

$$\frac{\text{NERVA Engine (B-4)}}{6061-0} = 0.65 \div 0.4 = 1.62 \quad (22)$$

$$\frac{\text{NERVA Engine (B-4)}}{6061-T6} = 0.84 \div 0.4 = 2.10 \quad (23)$$

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From these results it appears that all existing FSSE pressure-vessel designs used were not conducive to obtaining conservative data. The best matches are the Mod 2 and Mod 5 FSSE targets, with factors of 1.15. Fortunately all Aerojet PODS tests utilized this design during Contract Year 1963. However, in the interests of better individual component simulation, the Mod 2 FSSE designs and fabricated pressure vessels presently on hand are of 0.80-inch thickness in the -T6 condition which can be annealed back to the -O condition). These were provided in anticipation of the four cores of unloaded NERVA B-4 simulant and of the one core of depleted fuel-loaded NERVA B-4 simulant expected as GFE during early Contract Year 1963. From the factors presented above, use of the available pressure vessels (0.80-inch thickness) in either the -O or -T6 condition in combination with the available crude round-rod core material would not be desirable. The resultant data would be overly conservative (that is, early release of internal destruct mechanisms) unless some other core-load-attenuating mechanism could be included in the design.

In order to increase the pressure-vessel-toughness effect and to obtain a better match (~ 1.00) it would be necessary to place more attenuating material between the core and the pressure vessel (that is, change the inner and outer reflector simulant designs). The present double concentric ring of wide flat HLM-Grade graphite slabs comprizing the simulated inner reflectors should be retained because they present a greater void volume than the actual NERVA design and can assist in increasing the pressure-vessel toughness. In addition, magnesium outer reflector simulant sectors have been cast recently with cored holes that represent the central control drum holes. This configuration, with simulated control drum (extruded magnesium bar stock) rigidly installed, would tend to attenuate the impulsive loading effects more than has the solid magnesium design (structurally disconnected in the Mod 1 and Mod 5 FSSE targets) and will also aid in increasing the pressure-vessel toughness. These factors will assist in reducing the simulation adequacy product from a value of 1.62 (representing the case of using the available 0.80-inch-thick pressure vessels in the -O condition) to perhaps 1.50, but probably not much closer to the desired value of 1.00. If either the unloaded or the depleted fuel-loaded NERVA B-4 simulant core elements are available to the

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program as GFE in the required quantities (four unloaded and one depleted fuel-loaded), the following relationships would be involved. (Note that no difference in load-transmission characteristics between the loaded and unloaded state is known at this time, since no correlative tests were possible, they will be assumed to be the same.)

a. Mod 1 FSSE (1.00-in.-thick)

$$\frac{\text{NERVA Engine (B-4)}}{6061-0} = 0.52 \div 1.00 = 0.52 \quad (24)$$

$$\frac{\text{NERVA Engine (B-4)}}{6061-T6} = 0.67 \div 1.00 = 0.67 \quad (25)$$

b. Mod 2 and Mod 5 FSSE (1.13-in.-thick)

$$\frac{\text{NERVA Engine (B-4)}}{6061-0} = 0.46 \div 1.00 = 0.46 \quad (26)$$

$$\frac{\text{NERVA Engine (B-4)}}{6061-T6} = 0.59 \div 1.00 = 0.59 \quad (27)$$

c. Mod 2 FSSE (0.80-inch-thick)

$$\frac{\text{NERVA Engine (B-4)}}{6061-0} = 0.65 \div 1.00 = 0.65 \quad (28)$$

$$\frac{\text{NERVA Engine (B-4)}}{6061-T6} = 0.84 \div 1.00 = 0.84 \quad (29)$$

These values indicate the reverse trend of simulation results; that is, all data would be overly optimistic. The best match would be the use of the present version of the Mod 2 FSSE (0.80-inch thickness) in the 6061-T6 condition. One method of reducing the apparent pressure-vessel toughness effect and obtaining a better match (≥ 1.00) would be to place less attenuating material between the core and the pressure vessel (for example, change the inner and outer reflector simulant designs for better load transmission). The present flat graphite slabs that compose the inner reflectors should be replaced with a single layer of square-section slabs to reduce the void volume in the zone. This in effect, would increase the load-transmission properties of the layers, and would

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consequently reduce the effective toughness of the pressure vessel. The old design solid-magnesium simulated outer reflector segments used in place of the new segments (which are cored for installing simulated control drums) would assist transmitting incident impulsive loads into the pressure vessel, by decreased void volume, thereby tending to reduce the pressure vessel toughness.

By their application, these factors may assist in raising the simulation adequacy product from 0.84 to perhaps 0.90, but certainly not beyond 1.00. However, if by test, it is found that the response to impulsive loading of the unloaded NERVA B-4 simulant is not dynamically similar to that of depleted fuel-loaded NERVA B-4 simulant, but rather represents the enriched and fission product case reasonably well, then the simulation adequacy relationship will shift from the stated position. It is expected that the presence of the dense fuel material dispersed within a light matrix of graphite is more attenuant than a plain matrix (without fuel). Also, the effects of dynamic projectile insertion are expected to produce a condition surrounding the explosive charges which will effectively increase the attenuation even further. If these statements are true, then the relationships will tend to be as follows:

$$\frac{3/4\text{-inch Hex B-4 (loaded)}}{3/4\text{-inch-dia Round Rod}} \leq 0.4 \quad (30)$$

$$\frac{3/4\text{-inch Hex B-4 (loaded)}}{3/4\text{-inch Hex F-4 (unloaded)}} \leq 1.00 \quad (31)$$

These values produce a positive shift in the simulation adequacy product that is detrimental to the unloaded NERVA B-4 simulant with the available 0.80-inch-thick pressure-vessel material in the -T6 condition.

The failure characteristics of the inner reflector assembly barrel are known to strongly affect the dispersion performance of the ACDS concepts using shaped charge jet generated internal burster mechanisms. It is also believed to present some recognizable effects upon the fragmentation and dispersion performance of low c/m ratio Mark D (one 105 mm) FSSE tests. However, for the medium c/m ratio Mark D (four 105 mm) tests, the characteristics of the inner barrel, are overpowered by the increased explosive yield. Another condition,

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which was not observed in the smaller c/m ratio tests, also begins to take effect. This concerns the means by which the design of the inner barrel spacer strips provide a mechanical load-bearing connection to the outer reflector segments. In the simplified FSSE design, three circumferential strips provide this bearing area, while in the actual engine design approximately 48 core-length longitudinal strips are used as flow spacers. It would seem that a FSSE design change to incorporate this increase in bearing area would provide a proportional increase to the load transmission of incident impulses of high strain rates. But, based upon numerous tests in the medium to high c/m ratio range, the presence of the spacer strips served to not only transmit energy but also caused the magnesium reflector simulant to absorb a large portion of the incident energy that resulted in the formation of new fracture surfaces coincident with the points of spacer strip contact. This fracture mechanism is felt to be a function of the size, shape, and location of the spacer strips because of the stress-riser condition that they induce. Hence, a somewhat equalized transmission as a function of attenuation condition exists, regardless of the spacer design. This condition will persist so long as extremely wide variations in symmetry, larger bearing surface areas, and high efficiency stress-risers are not employed.

Spacer bearing conditions between the outer reflectors and the pressure vessel must be carefully simulated so that no unexpected stress concentrations are generated.

The results of this deductive analysis indicate that a problem exists when selecting the best compatibility between the respective simulative components. The best solution rests with using GFE core material for all remaining PODS tests if adequate testing control is to be exercised in combination with using available pressure vessels already heat treated to the -T6 condition. If the GFE material is not available and the 0.800 pressure vessels and crude rod cores must be used then the data obtained will not represent the best possible conditions. If better data is required despite use of the crude rod cores, then additional pressure vessels should be constructed using, at least, the 1.13-inch thickness in the -0 condition of the early Contract Year 1963 Mod 2 FSSE design. By solving the problem backward from a simulation adequacy product of 1.0: the pressure vessel should be constructed of approximately 1.3-inch-thick 6061-0 or 1.675-inch-thick 6061-T6

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Aluminum alloy taking into account the compensating simulation adequacy product shift effects previously presented.

3. C/M Ratio Effects

The effects of c/m ratios upon the NERVA engine simulation adequacy have been mentioned in previous sections as being extremely important. All test evidence indicates that care should be exercised in designing FSSE's and in selecting suitable material simulants to maintain the obtainment of conservative test results. The low c/m ratio tests must be designed to incorporate the closest compatibility between the core load transmission factor and the pressure-vessel toughness. The medium c/m ratio tests are also of concern because of the obvious signs of pressure-vessel failure observed in the post-test debris in all tests of the four 105 mm Mark D system. Since static projectiles were used in all Aerojet tests, the FSSE cores were lighter (73%) than the actual core because of the volume displaced by the projectiles and the lack of heavy metal fuel in the graphite. This causes the test results to be somewhat optimistic because of the higher c/m ratio than would be applied in the actual case. This effect would seemingly tend to counteract the effect of the overly conservative NERVA engine simulation adequacy values for all tests utilizing the crude rod material.

However, it does tend to negate the optimistic overall effects of the simulation adequacy values for all tests utilizing the GFE NERVA B-4 core simulant. This suggests the need for dynamic projectile insertion to obtain the most realistic results when using the more accurate core simulant (as in AFG-2).

4. Preferential Failure

Various modes of preferential FSSE failure exist in the PCDS test program. The most important consideration is the use of partial cores in a single FSSE, which combine simulative material of large differences in load-transmission ratios, thereby inducing a condition of preferential failure that is capable of completely masking the fragment-size-distribution and velocity-distribution data in an asymmetrical fashion. It is suggested, therefore, that the crude rod material not be combined with either the unloaded or loaded NERVA B-4 simulant in any further single tests using low to medium c/m ratio PODS because of the possibility of obtaining useless data. This condition is particularly critical in

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the special PODS case of the four-projectile Mark D for sizes of less than and including 105 mm.

The variance in load-transmission characteristics between the kinds of unloaded and loaded NERVA B-4 simulants is not known, but is suspected as being less than the wide variations produced by element geometry. Therefore, partial cores of unloaded and loaded NERVA B-4 simulant can be used together with little anticipated error. If single projectile dynamic launches are used, then it is suggested that the loaded NERVA B-4 simulant portion of the core be oriented to receive the penetration-derived precrushing process. This should minimize the preferential failure modes as much as possible.

5. Conclusions

Detailed conclusions and recommendations have been made in each of the preceding sections. An overall summation of these conclusions would indicate that a great design flexibility exists with respect to adequately simulating the NERVA engine.

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M. EXTRAPOLATED PODS PERFORMANCE

The Mark D concept produced the best fragmentation test results of the numerous PODS concept that were investigated to date and indicated the most promise of achieving the present fragmentation-size objective of $1/32$ inch. Since it was not possible to achieve complete conversion of the fueled core elements to particles within this size range, the development objectives then are:

- (1) To manipulate the explosive system design parameters
- (2) To correlate the differences brought about by the necessary use of low cost simulant materials
- (3) To predict the eventual PODS fragmentation performance (for comparison with establishable criteria) to which the actual flight version of the NERVA engine must be destructed.

1. Six 133 mm-Projectile Configuration

Various Mark D configurations were tested using full-scale configurations. The best performance potential was demonstrated in Test P0-82. The explosive array of this test was dynamically equivalent to the PODS consisting of approximately 340 lb of high-explosives contained in six 133 mm-diameter full-core-length projectiles inserted in an equally distributed parallel fashion within the core at positions measuring 0.6 the core radius. The total system weight, including extra radiation shielding and thermal conditioning devices, is estimated to be about 3500-lb for this configuration. The particle-size distribution results of this test conservatively indicated that 50% of the crudely simulated core material could be reduced to fragments of less than $1/32$ inch in size. Figure 64 represents this performance prediction. The core simulant used in all Aerojet tests was $3/4$ -inch-diameter solid round commercial grade (AGSC) graphite electrode stock.

Only $\sim 85\%$ of the actual fueled NERVA core mass could be expected to be reduced to fragment sizes of less than $1/32$ inch under the best conditions available to date. This holds true despite the encouraging results of Test P0-82 being extruded to those expected if depleted fuel-loaded NERVA B-4 material were

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Figure 64

Data Extrapolation to Theoretical PODS Maximum Achievement
Test PO-82

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used and if the combined results of all fragmentation studies were applied in a manner to increase dust production. It is also estimated that no more than 99% of the core can be reduced to fragments of less than $1/4$ inch in size with this large system.

2. Four 105 mm-Projectile Configuration

The best pulverization fraction actually demonstrated by test thus far was obtained with the depleted fuel-loaded NERVA B-4 simulant in the Aberdeen Proving Ground Test APG-2, in which it was reported, that between $1/3$ and $1/2$ of the quadrant of this core material was reduced to fragments of less than $1/32$ inch. However, considering the data acquisition methods applied to the test setup and the data analysis compared with those used at Aerojet, it would appear that the Aberdeen results tend to be optimistic while the Aerojet data has been proved to be overly conservative. Considering the relative capability of this system (consisting of four 105 mm full-core-length projectiles containing 120-lbs of high-explosives) it is felt that the true dust conversion factor is between the $1/3$ and $1/2$ values. The major advantage of this smaller four 105 mm-projectile system is the lower system weight, if the lowered fragmentation performance potential can be accepted. The total system weight of this configuration, including radiation and thermal protection devices, is estimated to be about 1500 lbs.

From all of the test observations and deductive analyses applied to the problem of extending the performance of the four 105 mm-projectile Mark D system beyond the present status of knowledge, it is believed that no more than about 35 to 40% of the fueled NERVA B-4 configuration core mass can be expected to be reduced to sizes less than $1/32$ inch.

Figure 65 represents the combined application of all controllable methods tending to produce greater dust fractions. If the high velocity dust jets are objectionable, because of prompt re-entry modes, then application of a number of known system variables capable of counteracting this effect will certainly downgrade the dust-producing efficiency as well. Explosive initiation timing and projectile spatial jitter produce different effects on the relationship between dust and velocity, since they tend to reduce the dust fraction and to increase the overall fragment-mass velocity.

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Figure 65
Theoretical Maximum Achievement
Four 105mm Projectiles (Mark D/J)

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It is also estimated that no better than 90% of the core can be reduced to fragments of less than 1/4 inch with this configuration.

3. Conclusions

From these estimates it is evident that the performance gain (1.3 times) is not commensurate with the increase in system weight from the four 105 mm to the six 133 mm system (2.3 times). Because no exact relationship exists between weight and performance, the predictions presented herein were based on linear approximations when, in fact, some type of exponential function applies. The only positive statement that can be made is that, because of the linear function applied, the extrapolated performances indicated are truly limiting cases and the actual performance will always be less because of the anticipated exponential function effects.

These performance estimates must be verified by further full-scale testing before complete faith can be placed in the conclusion that the tentative fragment-size objective cannot be achieved, and can only be partially approached by an explosive system of reasonable weight. To approach the size objective more closely will force the system weights into ranges where either a better means of achieving the goal must be determined or the stringent size objective must be relaxed to permit accomplishment by a lesser powered, and consequently lighter PODS.

It is evident that, while the results obtained thus far do not adequately satisfy the objectives of this concentrated effort, the general trend of test, analysis, and design data supports the engineering ability to control the fragment-size distribution over a wide range of conditions in a systematic fashion, despite the complexity of the related problems. This provides the desirable capability of a quick response to any future changes in Flight Safety criteria, NERVA engine evolution and operational flight modifications.

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N. MECHANICAL FEASIBILITY STUDY

The purpose of this study is to evaluate the mechanical feasibility of the various proposed explosive destruct system concepts. A reserve of design criteria will be established from which the design of the most feasible system can be formulated. Prototype devices will then be fabricated and tested to substantiate analytical and empirical performance predictions for the most promising destruct systems in order to evaluate, select, and develop the final destruct system, and to provide for subsequent system integration. Formulation of the final system configuration and its location will be based upon a comparative system evaluation of functional characteristics which can be readily integrated into the NERVA engine complex.

1. Design Criteria

a. General System Design Criteria

The explosive requirements for achieving the desired fragmentation can be determined from empirical data obtained from the explosive feasibility study. In addition to satisfying the basic fragmentation requirements, an optimized explosive destruct system should possess the following inherent characteristics:

- (1) Fast response.
- (2) Ultimate reliability.
- (3) Operational capability in any static, dynamic.
- (4) Radiation environment.
- (5) Minimum system weight.
- (6) Ready integration into the reactor complex.
- (7) Minimum mechanical translation of the explosive array prior to initiation.
- (8) "Fail-safe" initiation.
- (9) Possible employment as a bifunctional destruct system.

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Preliminary information available to date indicates that these requirements can best be met by the internal-burster projectile, either of the impact core penetration (Mark D concept: Figure 2) or shaped charge follow-through (Mark J concept: Figure 8) configurations.

The demonstration of explosive application by any implosion or multiple jet interaction device employed for primary fragmentation has not been promising. The Mark F, G, H, I, K, L, and M concepts were not actively pursued beyond the preliminary stage. Weight, reliability, and response time requirements further justified reduction of the list of investigated concepts. Additional discussion and a comparative evaluation of all candidate concepts are presented in Sections III.G and III.H.

It can be postulated, from evaluation of the explosive feasibility experiments conducted to date, that maximum fragmentation effects can be derived from multiple, internal, and burster projectiles with:

- (1) Parallel orientation to the longitudinal axis of the reactor.
- (2) Simultaneous initiation.
- (3) Relatively high entrance velocity.
- (4) Minimum displacement of core material.
- (5) Small deviation in the relative emplacement of the multiple projectiles.
- (6) Increased distribution of full-core-length charges.
- (7) Possible controlled fragmentation of thick projectile casing.
- (8) Selection of higher brisance explosives.

It is probable that a large (10 to 50 millisec) jitter in the initiation system would be detrimental to fragmentation performance. Additional experiments are planned to study the effects of longer delays and relative placement of several projectile configurations. Some of the problems of system integration involve requirements of initiation, communication, and extreme dynamic loading to which these devices are subjected. Projectile components may experience

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dynamic loads of the order of 4,000 to 15,000 g, through impact velocity, penetration requirements, and stringent space limitations. The determining parameters, however, will be those associated with penetration, since setback loads are anticipated to be relatively low. Assuming the radiation sensitivity problem is solved, the exploding bridgewire (EBW) type appears to be the most promising of the various initiators considered for assuring simultaneous reproducibility of controlled initiation. However, dynamic limitations will be contingent upon the inherent physical properties of the various materials employed in these devices. Based upon the present state-of-the-art, it is anticipated that a functional EBW actuator can be developed to withstand acceleration in the order of 10,000 g.

Projectile geometry will be dependent upon the listed considerations and designs that will ensure minimum deflection during insertion.

b. Package Criteria

Significant experimental accomplishments are presented in Tables V and VI. The following innovations were demonstrated to be feasible:

- (1) Penetration through a simulated forward head structure by a conical shaped charge to permit unobstructed insertion of the PODS Mark J concept projectile.
- (2) Competitive performance of lead-lined conical shaped charge for the same application.
- (3) Jet formation diameters conducive to shaped charge initiation application of the implanted projectile explosive charge.
- (4) Promising performance of T8 mortar propellant using a Pyrocore igniter implemented by an Si-119 flash charge and a confining screen membrane.

Refinements developed in the optimization of the PODS shaped charge design have suggested that a significant reduction of weight could be realized without sacrificing performance. Evaluation of the results of conical shaped charge experiments conducted to date has further indicated the possibility of employing these charges in a PODS using the Mark E concept to achieve the fragmentation over a wide range of particle sizes. For this concept, an array of

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TABLE V

Significant Experimental Accomplishments in Explosives

Test	Target Configuration	Explosive Charge Configuration	Explosive Net Weight (lb)	Penetration Performance
MF-10	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° aluminum cone	Octol 63.44	Fired at a 10-in. standoff; produced a 9-1/2-in.-dia hole through the target.
MF-12	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° aluminum cone	Octol 63.44	Fired at a 12-in. standoff; produced a 5-1/2-in.-dia hole through the target.
MF-83	Simulated Forward Head Structure and Shadow Shield Mounted on a Simulated Core	8-in.-dia conical shaped charge containing a 90° aluminum cone	Octol 62.88	Fired at a 10-in. standoff; produced a 4-1/2-in.-dia hole 24 in. deep in the simulated core.
MF-84	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° aluminum cone	Octol 24.10	Fired at a 12-in. standoff; produced a 5-1/2-in.-dia hole through the target.
MF-85	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° aluminum cone	Octol 24.9	Fired at a 14-in. standoff; produced a 4-1/2-in.-dia hole through the target.
MF-86	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° lead cone	Composition B 61.0	Fired at zero standoff; produced a 2-in.-dia hole through the target.
MF-87	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° lead cone	Composition B 60.4	Fired at a 10-in. standoff; produced a 2-1/2-in.-dia hole through the target.
MF-88	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° lead cone	Composition B 60.3	Fired at a 6-in. standoff; produced a 2-3/4-in.-dia hole through the target.
MF-89	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° lead cone	Composition B 59.10	Fired at a 16-in. standoff; produced a 2-1/4-in.-dia hole through the target.
MF-106	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° aluminum cone	Octol 24.9	Fired at a 6-in. standoff; produced a 3-1/2-in.-dia hole through the target.
MF-107	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° aluminum cone	Composition B 22.14	Fired at a 10-in. standoff; produced a 3-1/2-in.-dia hole through the target.
MF-112	Simulated Forward Head Structure and Shadow Shield	8-in.-dia conical shaped charge containing a 90° lead cone	Octol 63.11	Fired at a 6-in. standoff; produced a 3-1/2-in.-dia hole through the target.

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TABLE VI

Configurations and Usage

Test	Test Description	Results
MF-93	Type 424 Pyrocore and M-9 propellant used in igniter. Base charge: 3-in. and 40mm propellant. Cardboard flash holder	Partially ignited base charge only
MF-94	Same as Test MF-93	Partially ignited base charge only
MF-95	Pyrocore changed to Type 1224	Good ignition - slow burning
MF-96	Same as Test MF-95	Incomplete ignition
MF-97	Flash holder changed to No. 80 screen	Incomplete ignition
MF-98	Flash holder changed to No. 40 screen	Incomplete ignition
MF-99	Pyrocore changed to Type 2024. SI-119 flash mixture substituted for the M-9 propellant	75% ignition
MF-100	Base charge changed to 100% 0.040-in.-web propellant	86% ignition
MF-101	Base charge changed to 100% 0.025-in.-web propellant	98% ignition
MF-102	Base charge changed to 100% T-8 propellant	100% ignition
MF-103	Same as Test MF-102	100% ignition
MF-104	Flash holder changed to No. 80 screen	99% ignition
MF-105	Same as Test MF-104	99% ignition

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these shaped charges would be mounted, on standoffs, above the forward closure and directed to fire down into the engine. The entrance angles could be varied to allow jet interaction within the reactor core. By using various standoffs and simultaneous initiation, the jets would enter the engine at staggered intervals and create a chain-reaction effect. Inasmuch as this system represents the most desirable concept from a feasibility and integration standpoint, additional experiments should be conducted to evaluate its explosive application.

These empirically derived innovations will be evaluated for parametric trade-off and system integration to ensure an optimum destruct system.

2. System Weight Analysis

Preliminary analysis was initiated to determine an order-of-magnitude of subsystem and system weights for the various candidate destruct systems. A tabulation of this analysis and a qualitative summary of response time and reliability of these systems is presented in Table VII. The wide range of total system weights for the Mark F, G, K, L, and M concepts can be attributed to variations in the mounting and translation modes employed; that is, emplaced, ready to fire, translation of the entire explosive array, and explosive and initiation system transfer.

Although the emplaced array is the heaviest installation because of shielding requirements, systems that require translation or transfer (including liquid-explosive storage) will inherently exhibit complications in reliability and response time that would outweigh their comparative weight advantage.

a. Mark D and Mark J System Considerations

Typical conceptual methods and alternates of the Mark D and Mark J systems are illustrated in Figures 66 and 67. Analyses of the Mark D and Mark J systems are based upon the following assumptions:

- (1) Six core-length projectiles of 105mm to 173mm diameter (Figure 68).
- (2) Muzzle velocity: 1000 fps, minimum (Mark D)
400 to 600 fps (Mark J).

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TABLE VII
System/Subsystem Weight Analysis

Concept Designation (Refer to Figure 1)	Application	Explosive Application To Date	Explosive Weight* (lb)	Linear or Projectile Weight* (lb)	Actuation and Launch Mechanism Weight* (lb)		Initiation Subsystem Weight* (lb)	Shielding Weight* (lb)	Cryogenic Cooling System Weight* (lb)	Control and Fire System Weight* (lb)	Support Structure Weight* (lb)	Total System Weight* (lb)	Response Time - Fire Pulse to Main-Charge Initiation (msec)	Preliminary Reliability Evaluation
					Explosive or Propellant (lb)	Mechanism (lb)								
Mark D	Anticriticality and Postoperation (bifunctional)	Promising - requires further development	198-480 (based on PO-70,76,78,82)	141-650	6-144	600-1800	3-60		30-200	231-370	120-260	1639-4684	20-34	Good
Mark E	Postoperation	Inadequate - pending further tests	600-900 (based on PO-75, Test Pending)	30-120	None	None	10-40	290-850	21-178	385-1850	8-32	1350-3970	μsec range - may require sequenced initiation	Good
Mark F	Postoperation	Inadequate - additional experiments planned	1200-2500 (based on PO-40,43,45,51, and 52)	130-240	0-162 (If translation is required)	20-480 (If translation is required)	2-90 (Requires additional development)	200-7850	20-560 (If explosive array is emplaced)	92-3120	400-1240	2044-16242	μsec to msec range	Poor
Mark G	Postoperation	Inadequate - inefficient explosive application	118-270 (based on PO-60,61,71,72, and 73)	75-200	0-62 (If translation is required)	12-190 (If translation is required)	4-80	200-7850	20-480	308-493	243-940	968-10565	μsec to msec range	Fair
Mark H	Postoperation	Inadequate - inefficient explosive application	1860-2000 (based on PO-67,68,71,72 and 73)	375-800	0-150 (If translation is required)	16-400 (If translation is required)	12-144	200-7850	20-420	69-2320	340-1100	2876-15184	μsec to msec range	Fair
Mark I	Anticriticality and Postoperation (bifunctional)	Poor - inefficient explosive application	140-200	40-120	0-18 (If translation is required)	2-92 (If translation is required)	4-18	380-684	24-110	120-246	60-370	768-1858	μsec to msec range	Fair
Mark J	Anticriticality and Postoperation (bifunctional)	Promising - requires further development	300-601** (based on PO-82,MF-12,82, and 83)	182-389**	3-120	210-1500	3-60	-	-	360-480	100-230	1498-4160	27-47	Good
Mark K	Postoperation	Poor - inefficient explosive application	715-2100 (based on PO-85, Test pending)	***	None	60-780 (Transfer system weight)	2-48	200-640	60-320 (Controlled heating system)	30-480	333-1975 (Includes storage container)	1400-6343	msec to sec range	Poor
Mark L	Postoperation	Inadequate	110-2500	75-800	None	90-890 (Transfer system weight)	2-144	200-1200	90-400 (Controlled heating system)	30-3120	160-2090 (Includes storage container)	757-11204	msec to sec range	Fair
Mark M	Anticriticality and Postoperation (bifunctional)	Marginal - additional tests required	250-750 (based on PO-70)	100-50	2-150	115-490	7-140	360-8570	39-530	146-553	43-1230	1283-12863	μsec to msec range	Fair

* Estimated.
** Includes Shaped Charge and Liner Weights.
*** Excluding Reactor Components.

Figure 66
Typical Mark J Concept

Figure 67
ernate Mark D or Mark J Concept

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SIZE (MM)	EXPLOSIVE COLUMN LENGTH (IN.)	PROJECTILE LENGTH (IN.)	OVERALL LENGTH (IN.)	BODY WALL THICKNESS (IN.)	EXPLOSIVE WEIGHT (LB)	PROJECTILE WEIGHT (LB)	TOTAL PROJECTILE ASSEMBLY WEIGHT (LB)
105 (4.125 IN.)	52.0	62.0	80.0	0.375	32.12	86.25	93.5
135 (5.250 IN.)	52.0	62.5	82.5	0.375	57.50	113.37	123.6
155 (6.250 IN.)	52.0	64.0	88.0	0.500	74.20	178.00	191.5
173 (6.812 IN.)	52.0	65.5	91.0	0.500	92.30	216.80	230.0

Figure 68
Internal Burster Projectile

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- (3) Titanium launch mechanism of either closed breech or recoilless geometry.
- (4) Aluminum or titanium projectile casing for the Mark J concept.
- (5) Redundancy in the initiation system only.
- (6) Maximum allowable radiation: 5×10^{17} nvt (neutron)
 5×10^8 R (gamma).
- (7) Vibration loads: 5 g at 2000 cps (transient)
2.5 g at 2000 cps (steady-state).
- (8) Linear acceleration: +6 g, -1.2 g parallel to thrust axis
+1 g perpendicular to thrust axis.
- (9) Spin load: 1 rad/sec² (acceleration)
25 degrees/sec (velocity).
- (10) Thermal environment: -130°F to +103°F.

The techniques applied for the initiation of the explosive devices as a portion of the Control and Fire System (CFS) would introduce a number of factors that would affect the overall system weight.

(1) Trail-Cable and Sliding Contacts Technique

One solution to the projectile initiation and communication problem is the use of a trail-cable device consisting of a wire, or sliding contact (sabot or telescoping tube), to maintain electrical continuity between the projectiles and a common CFS. A block diagram of a typical channel of the CFS for this application is presented in Figure 69. Component breakdown of the preliminary CFS and the anticipated weights and response times are presented in Tables VIII and IX, respectively. Earlier investigators have successfully employed an unraveling trail-cable device for maximum velocities of 900 fps. However, orifices on the back plate can be sized to limit the relative velocity between the projectile and plate within permissible limits. The cable that is employed consists of a music-wire core, plated with copper, and an outer shell of plated aluminum anodized to provide electrical insulation from the environment.

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Figure 69
Block Diagram of Typical
Control Fire System Channel

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Table VIII
Control Fire System Weights

<u>Quantity per Channel</u>	<u>Component</u>	<u>Unit Weight (lb)</u>	<u>Weight for Channel (lb)</u>
2	AGX-2010 Detonator (Propulsion) (includes end connectors and squib)	0.47	0.94
3	42-007 Triax Cable (100 ft)	6.25	18.75
3	AGX-4403 Firing Unit	0.63	1.89
3	AGX-4403 Input Cable (10 ft)	0.50	1.50
3	AGX-4403 Connectors	0.10	0.30
3	AGX-4405-40 Firing Pulse Generator	0.10	0.30
3	Cable Mounting Brackets	1.00	3.00
3	Output Monitor Cable (200 ft)	6.00	18.00
1	Trigger Pulse Cable (100 ft)	2.00	2.00
Total Weight per Channel			46.68

Supplementary Components for the Common CFS

Logic Box	1 lb
Launch Tube Hardware (6)	7.5 lb

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TABLE IX

Control and Fire System - Response Times

Response Time - Destruct Relay Closure to Propellant Initiation

	Time (μ sec)
AGX-4405-40-1 Firing Pulse Generator	2.5
AGX-4403 Firing Unit	3 (± 0.4)
42-007, 7 Ω cable, 100 ft (Firing unit to EBW)	0.15
Propellant Detonator (EBW) initiation	1
TOTAL Delay:	6.65 (± 0.4)

Response Time - Arm to Projectile Detonation Initiation

100-ft low-voltage control line	0.15
AGX-4405-40-1 Firing Pulse Generator	2.5
AGX-4403 Firing Unit	3 (± 0.4)
42-007, 7 Ω cable, 100 ft	0.15
EBW Burster Detonator	1
TOTAL Delay:	6.8 (± 0.4)

Assumptions:

	Time (sec)
Sensor Response:	0.1 - 1
Logic Operation:	1 - 3
Destruct Relay Response	0.010 (± 0.005)

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Since the time-of-arrival of the initial projectile in a multicharge salvo will be random, simultaneous initiation of all charges can be augmented by the impact of the initial projectile against the forward head, closing the circuit to the firing panel network. Mechanical contact devices can be strategically deployed in a low-pressure region of the launch mechanism to provide sequential arming and electrical contact to each projectile. Filament-wound or flock-filled high-strength dielectric material will provide electrical insulation to the power terminals until the system is armed. Electronic delay (L-C circuit) devices incorporated into the CFS should be superior to any pyrotechnic or mechanical device in providing solutions to the basic problem areas previously discussed.

(2) Shaped Charge Technique

An alternate method using a followup shaped charge to initiating the projectile explosives was also investigated. For this concept a conical shaped charge is mounted on the outside of each launch tube (recoilless) breech vent. The shaped charge consists of a 45° copper liner, an ogive to deflect exhaust gases, an EBW detonator, and Octol- or Composition B-type high explosive.

The propellant-initiators and the shaped charge detonators are connected to a time-delay sequencer. The propellant initiators are fired simultaneously upon command. After a predetermined delay, and after arming by impact against a witness plate (forward closure), high voltage is applied simultaneously to the EBW detonators of the shaped charges, sending the jet particles down the tube into the detonators or boosters mounted in the aft end of the projectiles. It is anticipated that the high-temperature, high-velocity jets (28,000 to 35,000 fps) would be sufficient to detonate the burster charges.

Based upon hypervelocity experiments previously conducted by the Ordnance Engineering Division, it has been demonstrated that this concept will minimize the problems of system jitter, since simultaneous initiation of the shaped charges will produce simultaneous detonation of the burster charges within a few microseconds for the range of distances anticipated for this application. This system may be affected by alignment problems resulting from nonsymmetrical projectile deflection or shaped charge jet formation irregularities.

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(3) Radio Frequency Technique

A radio frequency (RF) initiation concept was also investigated. This initiation concept employs an RF coil as an integral portion of the launch tube nearest the engine closure and is supplied from a high-energy RF transmitter through a closed loop. Each projectile would contain an RF-activated delay fuze. The initiators and transmitters would be activated through a time-delay sequencer. To prevent projectile initiation of the RF detonators by spurious RF from the telemetry signals and from plasma generated within the reactor core, the transmitter is designed to emit three separate RF signals on three special VHF frequencies before the coil will energize. The signal is timed to reach its peak as the projectile enters the coil field. The RF delay fuzes would be activated and the burster charges fired simultaneously at the proper insertion depth.

Although some degree of transmission complication is anticipated because of the ionized environment, the problems of communications may be minimized by the close proximity of the energizing coil and the RF-activated delay fuse near the point of termination of projectile acceleration.

b. Summary

Design formulation and analysis will be contingent upon continually changing reactor configuration and empirical interpretation of experiments conducted with simulated cores. Nonhomogeneous materials and voids employed in shielding and support structures will contribute the greatest disturbance to the shaped charge jet, and thus affect penetration and insertion of the Mark J projectile. The feasibility of integrating the required shielding into the basic shaped charge and projectile components will require evaluation to minimize parasitic weight. Experiments are planned to investigate lead shaped charge liners and microballoon standoffs seeded with shielding materials. This should aid in providing an additional basis for evaluating the various parameters involved in achieving minimum weight for the selected system.

3. System Response Analysis

Design of a preliminary CFS, initiation devices, and an explosive train was accomplished to evaluate the effects of system jitter, relative spatial distribution, and emplacement of the multicharge internal burster destruct systems.

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A survey indicated a few existing devices are applicable to the proposed systems. Additional discussion of these devices is presented in Section III.N.4.

a. System Vibrations and Response Time

A summary of anticipated delays and jitters for the Mark D system, from fire pulse to initiation of the projectile charge, is presented in the following list.

	<u>Delay, msec</u>
(1) Control and Fire System	0.007 - 0.014
(2) Initiation Jitter	3 - 5
(3) Acceleration Time	5 - 10
(4) Penetration Time	11 - 18
(5) Initiation Jitter of Main Charge	0.9 - 1.2

Although the summation of these times appears to be excessive for an ordnance destruct system, the duration from "destruct signal" to logic circuit to destruct command is anticipated to be several seconds. Thus, the delays indicated are an insignificant portion of the overall duration in the event of a premature counter-measure requirement. It is anticipated that, although component jitter can be diminished to reasonable levels, the predominant portion of destruct package response time will be attributable to acceleration, penetration, and inherent deviations in explosive properties through manufacturing tolerances.

The tabulated delay-times are based upon separate initiation of six standard electro-explosive devices. Initiation jitter can be reduced from 5 msec to less than 10 μ sec by using separate exploding bridgewire systems, or through the use of mild detonating fuze (MDF) explosive train interlinks. A combination of EBW and MDF interlinks is illustrated in Figure 70. By employing this combination of EBW and MDF concepts the initiation jitter for the large number of electro-explosive devices used in a complete destruct system can be reduced to less than 100 μ sec. The factors which contribute most to total system jitter are, therefore: projectile acceleration time (3 to 5 msec), and projectile target

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Figure 70
Redundant Initiation System

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penetration time (11 to 18 msec). If future testing indicates a need for reduction of total system jitter, then a development effort directed toward reducing those errors caused by delivery of separate projectiles into the target would be indicated. Factors governing the simultaneous detonation of projectiles after they are in the target, are discussed in the detailed description of candidate destruct systems (Section III,E).

It should be noted that the acceleration and penetration times given are for one projectile. Although some degree of jitter is inherent to projectile response, this can be held to a minimum by maintaining high quality standards in both hardware manufacturing and explosive loading, and stringent lot control of explosives and pyrotechnics. Response time can be further reduced by using the shaped charge initiation concept. This is the concept (Mark J) in which a conical shaped charge is mounted on the nozzle end of the launch tube and is oriented so that the hypervelocity jet particles will strike the aft end of the internal burster charge and cause detonation. These initiator shaped charges will also be initiated with MDF interlinks from a single CFS source.

b. Explosive Materials

Explosives and pyrotechnic compositions (that is, Magteflon, boron, and potassium nitrate, etc.) are being considered as a supplant for the conventional black powder that is employed to ensure a rapid-response, high-reliability system compatible with the radiation environment.

4. System Reliability Considerations

Inasmuch as the proposed concepts are still in an embryonic stage, because of the unique nature of the devices which will require additional

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development, reliability discussions will be limited to qualitative discussions of anticipated system performance. The major components in the initiation train, which need to be carefully considered for evaluation of the reliability of either the Mark D or Mark J destruct systems, are as follows:

- (1) EBW Firing Unit
  - (2) Propellant Initiator
  - (3) Propelling Charge
  - (4) Burster Explosive
  - (5) Shaped Charge
- a. EBW Firing Unit

The EBW system consists of two principal parts: the firing units and the EBW initiator (squib or detonator). One device which has been qualified for use in non-nuclear environments is the Aerojet Model AGX-4403 firing unit consisting of three basic components: a high-voltage converter, an energy-storing capacitor bank, and a trigger circuit. The components provide rugged construction, and assembled units have undergone hundreds of firings without deterioration in performance. The unit is designed for a 28-volt-dc input and supplies 2 j of energy to the EBW initiator.

When an arm command is given, a 28 (+4)-volt-dc input is converted to 2000 volts and is stored in a 1- μ f capacitor. When a firing-command is given a 28-volt-dc signal is supplied to a discriminating network, where the signal activates an energy gate and discharges the stored energy through the EBW detonator. The detonator converts the 2 j output of the firing unit to shock waves, heat, and incandescent particles of sufficient magnitude to initiate the explosive charge. Two units are normally used in each system to obtain redundancy and provide reliability.

For the firing unit, a reliability of 99.5 at a 95% confidence level has been demonstrated using a single firing unit for each system. When two firing units are used in a system (to obtain redundancy), the reliability can be calculated as 99.9975 at a 95% confidence level. This calculation is

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based upon an operating time of 1 hr for the charging circuitry of the firing unit. Operational characteristics for the Model AGX-4403 EBW unit are listed in Table X.

b. Propellant Initiator

The propellant initiator consists of three explosive components: an EBW detonator, a Pyrocore lead, and a pyrotechnic igniting charge. To ensure proper emplacement of the destruct charges into the engine core prior to initiation of the main explosive burster charge, it is necessary to keep system jitter to a minimum. The primary requirement then would be to obtain simultaneous initiation of the propelling charges and to assure uniform charge burning. To realize these objectives in a conventional gun chamber, two requirements should be met: (1) a linear source of ignition should be used, and (2) the burning velocity of this source of ignition should be as high as practical. These criteria can probably be met using the Pyrocore igniter concept. Considerable research has been done by Frankford Arsenal on Pyrocore ignition for the XM 28 and XM 29 weapon ignition system.* It was determined that higher projectile velocities and lesser velocity dispersions are obtained when the Pyrocore igniter is used, as compared to a standard military igniter. Further work is being done by the Aerojet Ordnance Division to refine the Pyrocore igniter. The design goal for the igniter is a reliability of 99.5 at a 95% confidence level.

c. Propelling Charge

At the present time, subject to the results of the radiation tests on explosives, a military propellant compositions M2, M5, and M9 are being considered as the propelling charge for the burster projectile. All three of these propellants are of nitrocellulose-nitroglycerin composition. The reliability of these propellants is extremely high when used in the planned application.

d. Shaped Charge

Initiation of the projectiles and the shaped charges will probably be accomplished by using the EBW system previously discussed.

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* Frankford Arsenal Technical Reports R-1543 and R-1543A.

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TABLE X

Model AGX-4403 EBW
Operational Characteristics

Operational Characteristics of the Model AGX 4403 EBW Unit.

Weight	10 oz
Volume	8.25 cu in. (2-in.-dia x 2.62-in.-long)
Temperature Limits	-67 to +212°F Indefinitely
Surge Current	120 ma
Indling Current	60 ma
Output Energy	2000 v, 2j for 2 μ sec
Arming Time	4 sec
Safe-ing Time	20 sec
Function Time	3 μ sec
Function Altitude	∞

Operation Characteristics of EBW Detonator

Detonator Type	EBW
Detonator Bridge	Explodable Wire
Bridge Resistance	1.0 (± 0.2) Ohms
Max No-fire	250 v ac at 1 μ f and 60 or 400 cps for 5 min 500 v at 1 μ f 900 v at 500 μ f
Min All-fire Current	1700 v at 1 μ f
Recommended Fire Output	2000 v dc at 1 μ f
No. of Detonators	1
Explosives	600 mg of RDX
Autoignition Temperature	386°F

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The base charge will be either Composition B or Octol, depending upon the results of the irradiation study being conducted on high explosives. Statically positioned charges of cast TNT (Mark D/J concept) demonstrated reduced fragmentation performance (Test PO-66) compared to Composition B explosive (Test PO-64). The reliability of either explosive can be demonstrated to be extremely high, based upon the quantity of tests with no failures, conducted by Aerojet as well as by military organizations.

e. Reliability and Confidence Level

The reliability and confidence level of the initiation system from the EBW unit through the propellant charge can be predicted to be quite promising. The overall system reliability goal, including the burster charges, is 99.5 at a 95% confidence level. Although explosive and pyrotechnic devices compatible with the radiation environment are under consideration, selection of the ultimate explosive employed may be a secondary choice that is dictated by explosive performance. Therefore, shielding and supplementary cryogenic cooling requirements may be formulated to implement the destruct package. A spherical combustion chamber is being considered in lieu of the conventional cylindrical geometry in an effort to assure optimum system performance and minimum interface complications because of the extension of the destruct system beyond Station O-O. Other system considerations will be incorporated wherever practical to the functional characteristics of the destruct package to ensure a high degree of system reliability.

5. Operational Analysis

While it is anticipated that problems will arise in the candidate PODS, a parametric evaluation and analysis of these systems will result in the elimination of the least promising concepts and in the selection of one system as the most promising, along with one backup system. Although final selection of the PODS might be made on the basis of the explosive feasibility test results, the following analysis was made to assist in system selection.

a. Infeasible Concepts

A qualitative summary of operation, malfunction and safety probability ratings of the various systems is given in Table XI. Inasmuch as the

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TABLE XI

Operation, Malfunction, and Safety
Probability Ratings of Various Systems

DESTRUCT MODES								
ESTIMATED PROBABILITY RATING								
	Mark D	Mark E	Mark F	Mark G	Mark H	Mark J	Mark K	Mark M
DESTRUCT ON COMMAND (OPERATIONAL)								
a. Functional Probability	Good	Very Good	Good	Good	Good	Good	Good	Good
b. Explosive Probability	Excellent	Excellent	Good	Good	Good	Excellent	Good	Good
Overall System Rating	Very Good	Very Good	Good	Good	Good	Very Good	Good	Good
NO DESTRUCT ON COMMAND (MALFUNCTION)								
a. Short Circuit	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable
b. Open Circuit	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable
c. Loss of Power	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable
d. Extreme Cold - Explosive Dud	Possible	Possible	Probable	Probable	Probable	Possible	Probable	Probable
e. Radiation - Explosive Decomposition	Possible	Possible	Probable	Probable	Probable	Possible	Probable	Probable
f. Loss of Explosive Continuity	Improbable	Improbable	Possible	Possible	Possible	Improbable	Possible	Possible
DESTRUCT ON NO COMMAND (MALFUNCTION)								
a. Transient Voltage	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable
b. RF Signal	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable	Improbable
c. Shock	Possible	Possible	Possible	Possible	Possible	Possible	Possible	Possible
d. Vibration	Improbable	Improbable	Possible	Possible	Possible	Improbable	Possible	Possible
e. Extreme Heat - Fire	Probable	Probable	Probable	Probable	Probable	Probable	Probable	Probable
NO DESTRUCT ON NO COMMAND (SAFETY)	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent

SYSTEMS IN ORDER OF DEMONSTRATED OR ANTICIPATED CAPABILITIES:

1. Mark D	5. Mark F
2. Mark J	6. Mark G
3. Mark E	7. Mark H
4. Mark M	8. Mark K

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explosive application of the Mark I and Mark L concepts has not demonstrated feasible application (even on a gross comparative basis), these concepts were abandoned and are omitted from the list. Although the phenomenon of liquid-explosive transfer employed in the Mark L concept has not been completely defined, complications are anticipated because of the inherent mechanical properties effected by the thermal environment of the NERVA reactor. Shrinkage associated with phase change (transition from liquid to solid state) of the transferred explosive will cause interruptions and voids within the explosive train and will impair transmission of the detonation front. Since the environment of the injection region for the Mark K concept will be approximately 226°R at 680 psia, the transfer mechanism (expulsion or pumps) required to ensure a rapid uniform displacement of the cryogenic fluid would be extreme. The complexities of transfer associated with the Mark K concept are quite severe in comparison to the Mark L concept.

The Mark F, G, and H concepts, which employ explosives for implosion or an implosion reaction to derive the necessary fragmentation and dispersion, have been demonstrated to be inadequate. Mounting, initiation, and support equipment associated with these concepts makes the total system weight prohibitive. Because of the excessive number of initiation points, reliability requirements would impose an excessive amount of redundancy in the destruct command circuit, resulting in weight increase and unjustified complexity.

b. Feasible Concepts

Based upon the explosive performance and the preliminary analysis of system evaluation, the most feasible concepts are the Mark D, J, and E. The candidate destruct systems are listed in Table XII in the order of operational preference. The detailed breakdown of the events and operational probability for the most promising concepts is presented in Table XII. Additional discussion of these concepts is presented in the following paragraphs.

(1.) Mark D Concept

The Mark D system employs multiple impact-penetration internal burster charges. Four sizes, ranging from 105 to 173mm, are under consideration although sufficient testing has not been completed to determine the

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TABLE XIICandidate Destruct Systems
in the Order of Operational Preference

<u>Fastax</u> <u>Frame No.</u>		<u>Velocity</u> <u>(ft/sec)</u>
1	Fire Flash	No Data
2	Fire Flash	No Data
3	Gas Front	4650
4	Gas Front	3580
5	Gas Front	3500
6	Gas Front	3200
7	Gas Front	2850

Fragment No. 1 - Graphite reflector slab simulant
Estimated size - 12.96 in.³ or 212 cm³
Estimated mass - 359 gm

8	1090
9	875
10	985
11	1180
12	1060
13	1300
14	1030

Fragment No. 2 - Magnesium Reflector Bar Simulant
Estimated size - 11.6 in.³ or 190 cm³
Estimated mass - 332 gm

8	710
9	885
10	915
11	1050
12	1060
13	1090
14	1090
15	1060
16	1110

Fragment No. 3 - Magnesium Reflector Simulant
Estimated size - 18.9 in.³ or 310 cm³
Estimated mass - 543 gm

11	424
12	768
13	424
14	473
15	531
16	651
17	708
18	738
19	708

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quantity of explosives required for each size. Mechanical feasibility on this system is concerned with the method of implanting the internal burster charges in the engine core. This will probably be accomplished through the use of a recoilless launch tube design. Each burster charge would be fabricated in a projectile configuration with an armor-piercing head fitted on the forward end and a propelling charge in a cartridge case fitted to the aft end. Launch tubes for the projectiles would be fitted on the forward end of the engine structure passing down adjacent to the outer periphery of the pump housing. The required length of these launch tubes has not been determined. However, it is possible that the nozzle end may extend through the lower thrust structure. It should be relatively simple to integrate the launch tubes of recoilless geometry with the plumbing on the forward engine structure since the assembly requires external support only to the extent of maintaining launch-tube rigidity. Based upon preliminary investigations, the Mark D system appears to be the most favorable, especially from the standpoint of compactness and fewer mounting problems resulting from the relatively small quantity of components.

(2) Mark J Concept

The Mark J system is similar to the Mark D system except that this system employs a conical shaped charge ahead of the projectile. This charge is designed to open an entrance hole through the forward engine section and into the core for insertion of the burster projectile. Lower projectile velocities are possible, thus resulting in smaller propellant quantities. However, the shaped charge would add components to the system which would result in greater initiation problems. All other system considerations provide competitive qualifications.

(3) Mark E Concept

The Mark E system employs an array of conical shaped charges mounted forward of the engine structure and directed to fire down into the core through the shadow shield. Mechanical feasibility on this concept is primarily concerned with mounting the shaped charge array on the structure. It is estimated that total system fitter on this system can be held to a lower level than on any of the other multicharge concepts. There is a probability that a large quantity of

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charges will be required to accomplish the desired fragmentation. However, the simplicity of integration and remote location will alleviate structural, interference, and shielding problems sufficiently to justify a competitive system.

6. Shielding Geometry

Preliminary calculations were made for an order-of-magnitude determination of shielding geometry. Inasmuch as the permissible limits of radiation rates and total dosage on the various proposed explosives are still undetermined, shielding analysis was based over a range of five orders of magnitude reduction to encompass any anticipated allowable limit. Since changes are anticipated to the existing flux profile that will dictate the ultimate shielding geometry employed, the first-order approximation was based upon a worst-case analysis that was, in turn, based upon minimum capture cross-sections.

7. Cryogenic Loop

A cryogenic loop may be necessary to implement the shielding because of the following:

- (1) The irradiated shielding material presents a potential heat sink.
- (2) The ultimate explosives and pyrotechnic devices employed may not be the most compatible with the radiation environment.
- (3) Cryogenic fluid may supplant the conventional organic or dielectric material required in electrical devices.

A preliminary design was made of a cryogenic loop to establish interface and operational modes of the system (Figure 71).

A controlled thermal environment is required in the explosive-load loop since temperatures as low as -80°F are known to affect the function time of explosives and as a result the subsequent fragmentation performance would be effected. The heater network for the pneumatic pressurization system offers one source of heat input. Inasmuch as coolant input to the explosive loop may be predominantly in the gas phase, expansion and control devices may be made optimum by utilizing the shielding loop to preheat the coolant and so offer minimum disturbance to the pressurization system. However, provisions would be made to bypass

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Figure 71
 System Cryogenic Loop

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the shield loop on demand, to ensure an adequate heat sink to dissipate absorbed energy. An effort would be made to either minimize the quantity of electrical control components, or to deploy their location within the engine complex, to maintain a compatible radiation environment. These devices will present additional problem areas.

8. Emplacement and Integration

A typical installation of the Mark D concept is recoilless gun geometry and shaped charge initiation arrangement is presented in Figure 72. The concept illustrated is a departure from the conventional recoilless gun, since a frangible cartridge case and an additional central breech vent are employed to provide accessibility to the initiation shaped charge.

Two methods of attachment are illustrated in Figure 72. Rigid attachment requires relief in the existing upper and lower thrust structures; however, the latter offers less structural complications since the terminal end of the launch tube can be segmented and will form an integral portion of the structural member. The structural integrity of the muzzle end of the launch tube for a rapid-response rapid-decay system may be primarily dependent upon flight (dynamic) loading rather than upon operational loads induced by propellant pressure. Since rigidity is a function of the product of the modulus of elasticity and the moment of inertia, for a given barrel weight, aluminum may be a more suitable material than steel or titanium in the muzzle end of the gun.

The effects of angular displacement of the destruct system from the longitudinal axis of the NERVA engine (ϕ) as opposed to explosive column length for lower thrust structure attachment are plotted in Figure 73. The following restrict unobstructed acceleration and insertion accessibility:

- (1) A major structural flange at Station 0-0
- (2) Servo actuators
- (3) Pumps
- (4) Accumulators
- (5) The relatively hard target offered by the reflectors.

Figure 72 (Left Half)
Installation
Mark D PODS Concept

Figure 72 (Right Half)
Installation
Mark D PODS Concept

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Figure 73
Effects of Angular Displacement vs Explosive Column Length

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It is apparent that the angular displacement for an optimized system lies within the range of 5 to 10°, since an increase in ϕ beyond the structural interference zone rapidly diminishes the effective explosive column length exposed to the reactor core. A destruct system for large values of ϕ ($< 21^\circ$) would require a multitude of shorter projectiles, would be inherently less reliable, and would entail excessive weight.

A similar plot of ϕ as opposed to permissible gimbal displacement (α) and explosive column length, is given in Figure 74 for upper thrust structure attachment. It should be noted that preferential insertion is not possible for small values of ϕ for any gimballed displacement. Destruct command would then be retarded by gimbal response until the permissible envelope described by the allowable values of α are reached. Thus, achieving the desired fragmentation of the core would entail response times on the order of several seconds, depending upon the value of ϕ existing at that time.

Systems that employ linkage devices or those totally encapsulated within the LH₂ tank (to minimize the problems of interference) would not be superior to the installation previously discussed, since the same limitations of accessibility apply. Although some degree of weight reduction can be realized by installing the destruct system within the LH₂ tank, the additional complexities of interface and assembly, and extent of the nuclear incident, may not warrant justification of these installations. The most desirable installation for an optimum destruct system would be to have it rigidly attached to the lower thrust structure. However, problems of interface and integration would still need be resolved. Although partial relief from structural interference might be derived by replacing the spherical accumulators with a vessel of toroidal design, considerations of the integrity of the upper thrust structure and of disturbances in the suction conditions (NPSP) of the circulating pumps because of protrusion within the LH₂ tank may be of prime concern. To partially remedy this condition, an extension of the suction connection would be in order. It is anticipated that the volumetric loss of usable propellant because of this extension would be minimal. Insulation would need to be provided to minimize the problems of thermal gradient induced by the casing protrusion.

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Figure 74

Effects of Angular Displacement vs Gimbal Displacement and Explosive Column Length

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9. Parametric Trade-Off

a. System Evaluation

Based upon data derived from the postoperation explosive feasibility tests, it is concluded that the Mark D and the Mark J concepts are the only two that have produced promising fragmentation results. Therefore, the mechanical feasibility investigations have been limited to these two concepts. Should any of the remaining concepts produce substantial performance gains after subsequent verification tests, a secondary (backup) PODS design would be initiated.

Basically, the Mark D and the Mark J destruct systems are the same, and differ only in the implanting mode. While both systems have advantages and disadvantages, sufficient tests have not been conducted to date with these concepts to allow a complete analysis on the selection of one as the prime system.

(1) Propellant Methods

Two methods of propelling the projectile are being investigated. These are: (1) a closed breech gun, and (2) a recoilless gun. Both methods are effective. However, tests conducted to date indicate that the recoilless concept is probably the more practical from the standpoint of design simplicity and total system weight.

(2) Propellants

Investigations must be conducted to determine the propellant composition required to obtain necessary projectile velocities consistent with the gun design. For ease of initiation and fast rise-times, it has been found that mortar propellant is probably the best. However, because of the high brisance of this pyrotechnic composition, the quantity required to propel the projectile at the required velocity may not be compatible with either existing or conceptual gun designs.

(3) Ignition

Tests indicated that a Pyrocore igniter is feasible (Section III.N.1.b). The use of this type of igniter, instead of a separate electrical device for each projectile, is particularly advantageous where it is imperative that system jitter be kept to a minimum, (that is, where several leads can be fed from a single initiation system component).

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(4) Shaped Charges

Consideration of the possibly deleterious effect of radiation on the Mark J shaped charge explosive motivated a limited program to determine the feasibility of using lead cones in the shaped charges preceding the burster projectile. Inasmuch as the use of lead cones has been demonstrated to be feasible (Subsection III.N.1.b), it should be possible to reduce the additional shielding requirements and increase the effectiveness of the shaped charge.

Investigations were made on the ability of shaped charges to open a hole in simulated forward engine sections (including the shadow shield) of sufficient diameter to implant a large projectile. The shaped charge configuration has been established and certain refinements have shown that a significant reduction in explosive quantity is possible without sacrificing performance.

(5) Internal Burster Projectiles

Impact-penetration internal burster projectile designs will require empirical substantiation. The nose geometry of such a projectile will be contingent upon a parametric trade-off evaluation considering such factors as:

- (1) Inclination of target impact, targets encountered.
- (2) Penetration depth and modes.
- (3) Permissible deflection during insertion.
- (4) Relative spatial distribution of the multiple-projectile array within the reactor core at the time of initiating the primary fragmentation charge.

Of these factors, impact inclination and deflection considerations will be of primary concern to ensure a high degree of reliability for shaped charge initiation of the projectile explosive charge. A blunt-nose configuration might be employed in lieu of the conventional armor-piercing head to minimize the effects of deflection.

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It is anticipated that a relative, maximum, longitudinal displacement of one-foot within the reactor core, between the initial and final projectiles, will not produce excessively deleterious effects upon fragmentation performance, assuming use of core-length projectiles as a minimum condition. Since the major portion of readily controllable function-time affecting spatial distribution can be attributed to initiation jitter and acceleration time, parameters will be held to the ultimate permissible limits. Aberdeen Proving Ground has found that they can be held to the following tolerances:

Total system initiation and acceleration jitter	5 msec

Array muzzle velocity variation	<u>+1%</u>

b. Launch Modes

In conducting the following parametric analytical study on methods of launching the Mark D or Mark J destruct charges, concepts have been considered using a closed breech gun, and a recoilless rifle. For the closed breech concept, data are available for both standard military towed weapons and howitzers. These were given first consideration because a large amount of empirical data are available. For the recoilless rifle concept, standard designs were used. However, the data provided should permit design modifications of these concepts to be made with no sacrifice of performance.

(1) Closed Breech Guns

In studies conducted on field artillery weapons at BRL some years ago,* it was found that the weight of a closed breech weapon was roughly proportional to the muzzle energy. Since these studies were made, advances in weight reducing techniques have resulted in new, lighter-weight weapon concepts. The data presented in Figure 75 are an estimate of what can be accomplished by use of these techniques.

The plot of Figure 75 is of the form

$$W_L = C_1 E \quad (52)$$

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* Ballistic Research Laboratory Report R-771, September 1951 (Secret).

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Figure 75
Weight of Weapon as a Function of Initial Energy
of Projectile-Towed Artillery Weapons

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where

W_L = weight of weapon (launcher)

C_1 = a constant of proportionality

E = initial energy of the projectile

Note that

$$E = \frac{1}{2g} W_P V_P^2 \quad (53)$$

where

V_P = muzzle velocity of projectile

W_P = weight of projectile

For the curve shown,

$C_1 = 1.8 \times 10^{-3}$ lb/ft-lb compared to

$C_1 = 2.9 \times 10^{-3}$ lb/ft-lb for World War II weapons, and

$C_1 = 2.3 \times 10^{-3}$ lb/ft-lb for post World War II weapons.

In any weapon system, the weight of ammunition is an important consideration. While the Mark D or J PODS will probably employ ammunition quite different from standard rounds, for this preliminary analysis only standard rounds were considered. Figure 76 illustrates the weight of a complete round, minus the weight of the projectile, plotted against the initial energy of the projectile. The lower line is for separately loaded ammunition and represents the weight of the propelling charge, W_c . The relation is given by:

$$W_c = C_2 E \quad (54)$$

or

$$W_c = 2.7 \times 10^{-6} E \quad (55)$$

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Figure 76

Weight of Initial Energy of Projectile

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To determine whether or not this empirical equation is reasonable, consider:

$$\text{ballistic efficiency} = \frac{(\gamma-1) W_P V_P^2}{2g W_c} \quad (56)$$

where

γ = the "gun gamma" (roughly 1.3)

λ = specific force of propellant (λ) = 3.14×10^5 ft-lb/lb for M1 propellant, 3.9×10^5 for M13. (The average value is about 3.6×10^5 .)

and,

$$\text{ballistic efficiency} = \frac{(1.3-1) W_P V_P^2}{2g (3.6 \times 10^5) 2.7 \left[\frac{10^{-6}}{2g} W_P V_P^2 \right]} \approx 0.3 \quad (57)$$

In practice this is roughly one-third.

The upper line of Figure 76 represents the weight of charge plus the weight of the cartridge case, W_{cc} , or

$$W_c + W_{cc} = C_3 E = 7.1 \times 10^{-6} E \quad (58)$$

Now, assume that for a moderately high performance gun, W_P is approximately $3W_c$, then the weight of separately loaded ammunition, W_r , for this weapon is:

$$W_r = (3 + 1) 2.7 \times 10^{-6} E = 1.08 \times 10^{-5} E \quad (59)$$

and the weight of a complete round (including the metal cartridge case) is:

$$W_r = (3 \times 2.7 + 7.1) \times 10^{-6} E = 1.52 \times 10^{-5} E \quad (60)$$

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The specific force of combustible cartridge-case material is about 3×10^5 ft-lb/lb. Therefore, the combustible case round weighs only a little more than separately loaded ammunition. If a combustible case is used instead of a metal case, the weight of ammunition is reduced by the factor.

$$\frac{1.52 - 1.08}{1.52} \approx 1/3 \quad (61)$$

for this weapon. This is a significant reduction in ammunition weight.

To provide an indication of weapon weight, the weight of the gun (tube and breech) is plotted as a function of the energy of the projectile in Figure 77. The three lines clearly show the result of improved design and materials in the newer guns.

Now, if all guns (and howitzers) had the same parameters, the three lines of Figure 77 would coincide if the proper parameters are used in a graph. These parameters can be established as follows: the maximum equivalent tangential stress σ , in a thick-walled gun tube is given by:

$$\sigma = \frac{P}{R^2 - 1} \sqrt{3R^4 + 1}^* \quad (62)$$

where,

P = maximum powder pressure

$R = \frac{b}{a}$, the wall ratio

a = inside radius

b = outside radius

The weight of the tube, W_t , is:

$$W_t = \pi(b^2 - a^2) w l \quad (63)$$

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*Based on distortion energy (or Mises-Hencky) theory of yielding.

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Figure 77

Weight of Gun as a Function of Initial Energy of Projectile

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where,

w = specific weight of material employed

l = length of tube

Combining the two relations:

$$\sigma = \frac{\pi a^2 P l w}{W_t} \sqrt{3R^4 + 1} \quad (64)$$

if the pressure at any point along the tube is some function of the maximum pressure, P , then,

$$\pi a^2 P l = C_\alpha W_P V_P^2 = C_\alpha E \quad (65)$$

where,

C_α = a constant of proportionality

Also, if R is proportional to pressure (i.e., the same factor of safety is used along the tube), then from the formula for σ is:

$$\sigma = \frac{C_\beta E}{W_t} \quad (66)$$

If the weight of the gun, W_g , is proportional to the weight of the tube, and if $f \geq 1$ is the factor of safety relating σ to σ_y , the yield stress of steel, then:

$$W_g = \frac{C_\gamma E}{\sigma_y / f} \quad (67)$$

or,

$$C = \frac{W_g}{E f / \sigma_y} \quad (68)$$

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The above relation is plotted in Figure 78. Note that the scatter between the points representing the different weapons is considerably less than in Figure 77. This indicates that the guns and howitzers are reasonably homologous according to the assumptions.

(2) Recoilless Rifles

Because a recoilless rifle is a combination of a gun and a rocket, it might be expected that its weight might be proportional to some combination of energy and momentum. In fact, the total weight of the rifle is proportional to the initial energy of the projectile as shown in Figure 79. The data fall into three general classes: conventional towed weapons, conventional tripod-mounted weapons, and newer weapons using high-strength, lighter weight materials.

Because the recoilless weapon is light, and an appreciable part of its weight consists of sights, brackets, cables, etc. (the weights of which are arbitrary), better correlations are obtained if the weight of the bare rifle only is considered. The curve on the left side of Figure 80 includes energy as one of the parameters in the abscissa. The correlation is reasonably good, but the slope of the line is less than 1, possibly indicating that energy is too strong a parameter. The graph on the right uses momentum as a parameter in the abscissa. The correlation is reasonably good (the slope is approximately 1), and the rifles fall into classes of conventional and newer rifles.

The ratio of charge to the projectile weight of recoilless weapons is plotted as a function of the normal muzzle velocity in Figure 81. The normalizing factor, $\sqrt{\lambda g}$, is used to compensate for the different specific force, λ , of different propellants.

The weight of the cartridge case is plotted in comparison to the charge weight in Figure 82. Note that the new frangible cases are much lighter than the conventional perforated steel cases.

It should be noted that since the recoilless rifle is a combination of a gun and a rocket, a simple rocket system should weigh less than a conventional restrained closed breech gun.

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Figure 78
 Weight of Gun as a Function of $\frac{Ef}{\sigma_y}$

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Figure 79
Weight of Weapon as a Function of Initial Energy
of Projectile-Recoilless Weapons

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Figure 80
Weight Comparison,
Bare Recoilless Rifle Tubes

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Figure 81

Recoilless Rifle Charge:
 Projectile Weight Ratio as a Function of Nozzle Velocity

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Figure 82
Cartridge-Case Weight vs Charge Weight

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During the delivery of a projectile to a target, the two forces, gravity and air resistance, oppose its motion. While these two forces may be negligible in the function of the PODS, they must be considered for purposes of generating a workable gun design. The requirements of a gun for the PODS may be visualized in this manner: it must impart to the projectile a velocity sufficient to defeat the target, and it must simultaneously provide the projectile with sufficient energy to overcome the opposing air resistance. At the lower velocities (less than 800 fps) the air drag is comparatively small even at sea level, and for free flight, the shape of the projectile is not important. The PODS will probably be used at altitudes where air drag will not be a factor, so the main design requirements for the projectile would be that it be structurally capable of withstanding the impact-g forces with no deleterious effects, and that it be designed to penetrate the engine with a minimum of restrictive drag.

The comparatively low velocity requirements anticipated for the PODS projectiles ($\cong 1000$ to 1300 fps), make it advisable to consider the use of a simple mortar-type device as the launch mode.

10. Operational Interrelationships

The purpose of this study was to identify, define, and evaluate the technical and operational relationships between a typical PODS and the various related and supporting components, systems, vehicles, facilities, and safety programs. Since the RIFT ballistic flights provide the only opportunity (without greatly increased dollar expenditure) of demonstrating the performance of the PODS either during or after NERVA engine operation, it is desirable to continue development of a functioning system and provide full integration with the RIFT program.

This coordination should be achieved by a close working relationship established between the cognizant representatives of the various project groups. This activity is extremely important during the initial phases of this program where the chances of omission of technical effort on a critical problem area or, conversely, the excessive overlap of effort in some other area, is great.

a. NERVA Engine

Preferential orientation for forward-closure insertion of the internal burster projectiles may necessitate placement of the launch tubes

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through the upper thrust structure to ensure reliable destruct of the reactor core in any gimbaled position. This will require radical modifications in the superstructure and entail protrusion of the system beyond Station O-O. Angular displacement of the destruct package to clear the existing superstructure will increase total system weight because of the following factors.

- (1) Decreased fragmentation performance.
- (2) Increased requirements in the structural integrity of the destruct package support members.
- (3) Additional shielding requirements for the higher radiation environment.
- (4) Excessive resisting torque on the gimbaled assembly during reactor operation.

Limitations on the additional mass attached to the reactor pressure-vessel casing, to diminish the effects of disruption of the thermal gradient and induced thermal stresses, and the hard targets offered in the reactor reflector assembly further restrain the angular displacement by affecting system weight. Modifications derived from relaxation of the tentative destruct criteria may partially relieve this condition.

Destruction initiated by the Range Safety officer signal would not ensure a fail-safe system inasmuch as the duration from indicated malfunctions to destruct signal relay may be in the order of several seconds. It is also questionable whether the present state-of-the-art of sensors can justify an automatic fail-safe malfunction sensor subsystem. However, a CFS and initiation train is being considered to provide as rapid a response as practicable to ensure an optimized destruct system independent of the source of destruct command.

Flight-test instrumentation to monitor diagnostic and control inputs from the PODS are required for proper performance evaluation during ground and flight operation. A preliminary analysis of the PODS was conducted to establish the parameters affecting successful operation. A summary of the sensor inputs derived is given in Table XIII

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TABLE XIII

Summary of Sensor Inputs

- Assumptions: a. Diagnostic and Control Inputs Only
 b. Minimum Redundancy

<u>Parameter</u>	<u>Quantity</u>	<u>Use</u>
Temperature Sensor	12	Explosive or Casing Temperature
	2 - 4	Cryogenic Loop and Shielding
	24 (max)	Electronic Components
Pressure Sensor	6	Combustion Chamber - Gun
	6 - 12	Shaped Charge
	2	Cryogenic Loop
Strain Sensor	6	Projectile Casing
	12	Launch Tube and Support Structure
	8	Cable Conduit or Harness
Position or Event Sensor	6	Projectile Position in Launch Tube
	6	Launch-Tube Translation if Aligned with Linkage
	24 (max)	SAFE and ARMED
	24	Continuity
	24	Monitor Capacitor Charge

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b. RIFT Vehicle

The PODS, physically attached to the NERVA engine structure, is also connected to an electrical contact on the Destruct Relay. This relay is now envisioned as comprising the output of an "OR" logic circuit receiving inputs from malfunction sensors and destruct commands. The primary input is the command-destruct signal transmitted from the Range Safety officer over the radio command/control link. This signal is received by antennas and communications equipment carried by the vehicle.

A simplified block diagram of one channel (one launch tube) of a typical Mark D or Mark J concept is illustrated in Figure 70. Figures 83 and 84 indicate examples of launch-tube destruct systems to which this system may be applied.

The destruct relay may provide the nucleus for destruct of both the RIFT vehicle and the booster stages (Saturn), the objective being that a command for destruct of any vehicle shall destroy all hazardous components either simultaneously or in preferential sequence beginning with the NERVA engine. This complex situation exists through launch to NERVA engine setup transient, and concerns actuation of the ACDS, which may exist as a single channel of a bifunctional, multi-unit PODS. However, for postoperation destruct, the common destruct relay will only serve a useful function for the remaining attached vehicles.

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Figure 83

Concept
Mark D Destruct Charge

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Figure 84

Concept
Mark J Destruct Charge

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The destruct power supply will consist of at least one 28-volt independent and unregulated bus (probably battery powered). From this source will be obtained safe and arming (S/A) voltage for the firing units as well as the destruct pulse.

Since postoperation destruct is designed for operation after separation of the RIFT stage from the booster, a possible mechanical S/A device would be a set of normally open electrical contacts in the interstage area, closing on staging to arm the destruct firing units.

To provide on-pad destruct system safety and still ensure that destruct function can be achieved when required, it is necessary to incorporate several S/A devices throughout the explosive system. Because it is anticipated that EBW firing units will be used as the fire system, the S/A devices can be electrical and must be installed in the system between the EBW firing unit and the EBW detonator.

The desired status, either SAFE or ARMED, of this type of unit may be achieved by either of two methods: the unit is SAFE until armed mechanically on missile lift-off or stage separation, or is SAFE until armed electrically by a telemetry signal. For the PODS, the latter method is most desirable. Standard safety practice requires that electrical feed lines to explosive devices be shorted until just prior to firing. Therefore, inadvertent firing from stray electrical pulses is most practically precluded by the use of a rotary switch or a spring-loaded switch that will keep the explosive-electrical system shorted until it receives the telemetry ARM signal. This type of unit would not have to be "one-shot," but could be safed again by an electrical signal, provided it becomes necessary to delay destruct.

As presently designed, the S/A switches are all energized simultaneously upon command. The three destruct systems are supplied independently from the command receiver. The theory of operation is:

Upon command, a specific signal will close the destruct relay allowing the charging voltage to build up the capacitor storage bands in the EBW firing units. As soon as indication is received that the EBW units are

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fully charged, the S/A switches are activated to complete the firing line circuits. A third signal discharges the capacitor into the EBW initiators, which initiates destruct. The follow-through shaped charge initiators are timed to fire as soon as projectile insertion is complete as determined by feed-back signals routed from the projectiles back through an OR logic circuit and another S/A device.

c. Saturn Booster Vehicle

Figure 85 is a simplified diagram illustrating a minimum CFS on RIFT and Saturn, assuming utilization of a common integrated explosive destruct system. Depending upon the type of destruct system finally selected, some variations in command receiver location may be expected. However, the most important consideration is that the nuclear stage may best serve as receiving center for all destruct commands. The diagnostic and control monitoring circuits required for either the bifunctional PODS or an alternate type are not shown in the figure.

d. Launch Facilities

Safety rules of the Atlantic Missile Range (AMR) require that special packaging, transportation, and installation procedures be followed with respect to the PODS ordnance items. For example, it will be necessary to ship all initiators and engine explosive charges separately in ICC-approved containers for storage in facilities operated by the Range Contractor. The Range Safety Plan further specifies that installation and electrical connection of ordnance items are to be performed as late as possible in the launch countdown, and must be coordinated with the Missile Handling Branch at Patrick Air Force Base (PAFB).

On systems presently launched from AMR, arming of the destruct system is accomplished by energizing the electronic dc/dc stepup converters in the destruct firing units, through a relay or a switch that will probably be controlled by the staging functions.

The Range Safety Plan specifies use of either arming rotors or arming firing plugs (or both), and safe/open plugs for use during checkout and launch countdown, so that circuit additions will probably have to be made with regard to applicable range safety requirements.

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* MDF LEADS

Figure 85
General Layout Diagram
PODS Control Fire System

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The RIFT/Saturn complex is to be assembled vertically and the launch facility will include the usual elevating catwalks for access around the vehicle at any level. This accessibility requirement for cable and destruct system component installation is important since some of these assemblies extend the complete length of the vehicle.

Installation check of the firing capability of each channel (launch tube) would be accomplished as follows:

- (1) Terminate the cable output of the channel to be checked, with a 1-ohm, 5-w wire-wound dummy-load resistor, shunted with a 100-ohm, 100/1 voltage divider.
- (2) Connect the output of the above divider to the vertical input terminals of a high-grade oscilloscope.
- (3) Arm firing units, allowing at least 30 sec for voltage buildup as indicated by the monitor and, on closure of the destruct relay contacts, check for acceptable amplitude and waveform of the firing pulse appearing on the oscilloscope.
- (4) All checks should be repeated while exercising the RIFT/NERVA gimbal system, to ascertain solid continuity of destruct circuits through such manipulation.
- (5) With all destruct equipment in place, but using dummy loads, an RF sweep check should be made over the frequency range and power level specified by Range Safety to ascertain that under no conditions does a significant RF output appear at the termination of any firing cable as determined with a demodulation probe on the input to the above oscilloscope.

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Close liaison with the various stage contractors will be maintained to integrate the PODS checkout tests with destruct circuit tests on the booster vehicles.

e. Space Vehicle Missions

In the event of future modification of the RIFT/NERVA design for use as either a manned or a delicately instrumented space vehicle, consideration must be given to the following from the standpoint of postoperation destruct:

- (1) After decision for postoperation destruct by any of the possible sources, the initiation signal will have to be delayed sufficiently to permit ejection and subsequent adequate clearance for the manned or instrumented capsule.
- (2) The transmission of energy by the directioned jet particles of high-energy shaped charges is believed to be of a high order of magnitude. The high-velocity jet particles generated by the various types of shaped charges which might be used on an ordnance-type destruct system might be expected to travel a considerable distance (possibly in the order of miles in a space environment) before suffering any appreciable loss of energy. The clearance requirements necessary from the time of ejection of personnel in a manned flight until the initiation of an ordnance destruct system, would therefore be an important consideration, and a factor which would need to be determined. A reliable method of measuring ejection distance will be required over this distance. The possibility of utilizing a small ranging radar, carried by the capsule and the RIFT vehicle, should be considered. A coded interrogation signal from the radar, or a command signal from a separate radio transmitter on the capsule

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could be used to initiate destruct of the NERVA engine and, subsequently, RIFT. Destruct backup in the event of malfunction of the capsule equipment, would be mandatory and could be provided by a timer on the RIFT stage.

- (3) Delay of the destruct signal, as described in (1), would hardly improve the safety aspects of the overall system, since a reactor power excursion could conceivably progress to the point of rendering the destruct system inoperative before reception of the destruct command from the capsule. Engine data indicate that no presently conceived destruct system (ordnance included) is capable of sufficiently rapid response to stop a power excursion, as well as to provide enough time for safe departure of a manned or instrumented capsule. The problem should be made the subject of a thorough investigation as one of the initial phases of the feasibility study for use of the NERVA engine for manned space missions. Better information on the mechanics of reactor power excursions; and the development of aster-acting engine performance sensors and allied logic equipment may allow this problem to be partially if not completely solved.

The method of installation of the CFS on the combined vehicles would be generally as follows:

- (a) Install firing pulse generators, firing units, etc., in designated electronics compartment above LH₂ tank.
- (b) Install intercables to control box in electronics compartment.

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- (c) Install Triax (firing) and LV (pulse) cables, approximately grouped, from the control box down around the LH₂ tank, across the gimbal system to the NERVA destruct launch-tube area.
- (d) Install launch tubes, mounting brackets, inter-projectile communication initiation link components, etc., in the engine compartment.
- (e) Install firing-unit monitor cables from control box to vehicle checkout receptacles.
- (f) Install launch propellant igniters in breech receptacles and attach connectors. Attach PODS-CFS to 28-v destruct power-supply bus.

Facilities and instrumentation for at least the following checks would be required:

- (a) Check continuity of all firing and monitoring cables and launch-tube contacts using dummy contact plugs as required.
- (b) Check continuity of capacitor monitoring circuits to checkout console voltmeters.
- (c) Check continuity of destruct relay to firing pulse generator inputs.
- (d) After closing the S/A relay or switch, check buildup of firing circuit capacitor voltages as indicated on console voltmeters.