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ROCKET ENGINE OPERATIONS - NUCLEAR

EVALUATION OF ANTICRITICALITY DESTRUCT SYSTEM CONCEPTS (U)

A REPORT TO

AEC-NASA SPACE NUCLEAR
PROPULSION OFFICE

REPORT NUMBER RN-S-0020 / DECEMBER 1963 / COPY 1

NERVA PROGRAM
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REPORT NO. 0020
TO
AEC-NASA SPACE NUCLEAR PROPULSION OFFICE
EVALUATION OF ANTICRITICALITY
DESTRUCT SYSTEM CONCEPTS

ROCKET ENGINE OPERATIONS - NUCLEAR

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ABSTRACT

The candidate explosive type NERVA engine anticriticality destruct systems have been preliminarily tested and studied. This report summarizes the status resulting from work accomplished through 15 June 1963.

The Mark A concept and small ejectable Mark D concepts have demonstrated achievement of the ACDS dispersion criterion and indicated superiority over all other ejectable ACDS concepts considered.

The multiple projectile Mark D concept has demonstrated superiority over all PODS concepts considered for bifunctional destruct application (capable of being used for either phase of operation).

The work described herein, and the material upon which this report was based, was performed by the Nuclear Engine Destruct Systems group of the Ordnance Research Division at the Downey Plant under the direction of REON.

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SECTION I

INTRODUCTION

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I. INTRODUCTION

This special report is submitted to AEC-NASA Space Nuclear Propulsion Office (SNPO) to detail the preliminary technical evaluation of candidate anticriticality destruct systems (ACDS). The publishing of this report denotes the completion of Milestone 19 of Task Item 1.6 under SNPO Contract SNP-1, Mod 8. The work was accomplished by the Aerojet-General Corporation, Ordnance Research Division under the provisions of Sub-Subtask 1.6.4 (AGC IWA A00785) during CY 1963.

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

The evaluation of candidate postoperation destruct systems (PODS) was reported in REON Report RN-S-0033, "Special Summary Report for Milestone 30," CY 1963.

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

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SECTION II

SUMMARY

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II. SUMMARY

The ACDS is required to render the reactor essentially harmless in the event an accident to, or malfunction of, the NERVA engine occurs prior to its operation. The purpose of the ordnance-type Anticriticality Safety System (ACSS) is to divide the reactor core into subcritical fragments, and to disperse these fragments so that none of the portions can combine in a geometry that could become critical in a moderating environment.

A tentative criterion was established for assessing the effectiveness of an ACDS based upon critical concentrations of fueled core material when immersed in a moderating environment such as water. This criterion, in terms of practical test techniques, established that the maximum quantity of fueled core material allowed to fall within any surface area represented by a circle 25 in. in dia, should be less than 12.5 lb.

A number of different ACDS concepts have been evaluated by performing tests of the various explosive systems against full-scale, simulated engine (FSSE) targets positioned on top of 10-ft-high test stands and oriented with the engine axis vertical. The 10-ft height was arbitrarily established for the test stands. The maximum core-fragment concentrations resulting from preliminary tests of the various concepts have been compared and evaluated. The vertical attitude was selected to assist in interpretation of fragment pattern symmetry and distribution. A greater test altitude or different attitude would affect the dispersion pattern by altering concentrations on the sampling plane. In addition to economic considerations, the use of this particular test height and orientation produced results which were sufficiently valid and comprehensive for comparative purposes.

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The maximum core-fragment concentrations resulting from preliminary tests of the various concepts were compared and evaluated. From this, a series of tests for each of three destruct system concepts were conducted in an effort to further demonstrate the explosive feasibility. The three concepts were the Mark A, the Mark C, and the single-projectile Mark D/J, all of which are described in detail in the technical discussion portion of this report. Component tests were conducted in support of these concept tests to develop and evaluate the functional capabilities of the individual explosive components so that the competing concepts would have an equal chance for success. No attempts were made to optimize the systems studied; rather, the emphasis was placed on demonstrations of explosive charge configuration feasibility.

The Mark A concept (in Test AC-155) demonstrated successful achievement of the anticriticality dispersion criterion against a full-scale, semi-accurate target. Although several tests of the Mark C concept were conducted, none were successful in attaining the necessary dispersion against a reasonably simulated engine. Two tests (AC-129 and AC-154) of the internally emplaced explosive projectile concept (Mark D/J) met the dispersion criterion. Tests of this concept were conducted by assembling the test model with the simulated projectile statically in place within the core.

The feasibility of propelling an explosively loaded projectile into a full-scale, simulated engine target in support of the Mark D/J concept was demonstrated in two concurrent PODS program (Sub-Subtask 1.6.5) tests conducted at the Aberdeen Proving Grounds.

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The explosive feasibility development has been necessarily conducted against crude NERVA engine material simulants. This was due to the unavailability and excessive costs of actual engine material. The simulants were selected for characteristics that represent as near as possible those of the engine, yet are compatible with test objectives (within the funding limitations); however, the variations from the actual material did impose differences of considerable consequence as recognized during interpretation of test results. One objective of the concurrent Fragmentation Research program (Sub-Subtask 1.6.1) has been to develop a correlation between pertinent physical properties of the crude material used for testing and the actual engine materials. Little is known of the response characteristics of these materials under the extreme conditions imposed by the use of explosives to render the NERVA engine safe.

For example, the core material used in the test models consisted of solid 3/4-in.-dia commercial-graphite electrodes. When compared with the geometry of the fuel elements intended for use in the NERVA engine, the solid rod possesses a much greater load-transmitting capability. All of the ACDS concepts depend, to some degree, upon the ability of the core material to transmit confinement-rupture loads and core fragmenting and dispersion forces; consequently, the correlation of material characteristics established by the Fragmentation Research program is important to the success and basic understanding of the various destruct mechanisms. Based on this material correlation study and on the evaluation of the effects of simulated materials on the test results, the Mark A and Mark D/J concepts are expected to be adequate for destructing the actual engine within certain limiting conditions involving detail selection of simulant material and target engine design.

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The selection of the Mark A system (Figure 1) for use as the primary, ejectable ACDS was essentially based on a comparative analysis of the Mark A and the ejectable Mark D/J concepts. The major considerations were:

Total system weight

System response time

Initiation reliability

Ejectability

Integration and emplacement

Although the aft-mounted, single projectile Mark D/J concept is the more efficient system, as far as the amount of explosive needed to accomplish the anticriticality destruct task, the Mark A concept is more desirable from all important feasibility aspects considered during selection of the ejectable ACDS. The Mark A concept will, then, receive a concentrated design and physical property determination effort to be completed and presented in the Milestone 25 report.*

Selection of the forward-mounted Mark D/J concept for the bifunctional destruct system was determined by a different set of considerations, since some of the above are not applicable to a bifunctional system. The main consideration is dictated by the postoperation destruct criteria. PODS concept feasibility and development progress to date, as described in the Milestone 30 report,** has indicated that the Mark D/J concept, installed above the NERVA engine shadow shield, will be the proposed explosive destruct system on which further development work should proceed during CY 1964.

* Milestone 25 report - REON report RN-S-0022

**Milestone 30 report - REON report RN-S-0033

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Figure 1
Mark A, Mod 2, ACDS Concept

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Comparison of all Mark D/J PODS test results with the anticriticality destruct criterion indicated that excessive fragment dispersion or a condition of "overkill" exists. The PODS test program incorporated multiple explosive charges statically simulating launched projectiles, each of a size considered adequate for accomplishment of the anticriticality dispersion criterion. Selection of the required number of bifunctional projectiles to satisfy this criterion is then solely dependent upon whether the RIFT interstage structure is to be defeated also by ACDS action or is to be removed independently by systems furnished by the RIFT contractor. It may not be technically feasible to defeat the confining effects of the interstage structure by any method other than fragment penetration produced by massive overkill.

Integration of the Mark D/J concept into a bifunctional capability becomes merely a modification of the control and fire system (CFS). There is little weight penalty involved and no ejection requirement, which makes the selection of this concept for the bifunctional destruct system appear most advantageous. Further design and analysis work will proceed on the bifunctional Mark D/J concept; the cumulative results of this effort will be presented in the Milestone 25 report.*

* Milestone 25 report - REON report RN-S-0022

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SECTION III

TECHNICAL DISCUSSION

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III. TECHNICAL DISCUSSION

The long range objectives of this program are to develop an explosive destruct system that will render the reactor core harmless in the event either an accident to, or malfunction of, the NERVA engine should occur prior to its operation in the RIFT and subsequent missions.

The immediate objectives were: (1) to determine the feasibility of achieving the tentative ACDS performance criteria, and (2) to select the ejectable ACDS concepts best suited for further studies and preliminary design. This discussion presents preliminary descriptions of several explosive concepts that have been studied, tested, and show promise of meeting the tentative ACDS performance criteria. The conclusions presented are based upon the results of tests performed with full-scale simulated NERVA engines and design studies reflecting presently available NERVA engine data.

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A. ANTICRITICALITY DESTRUCT CRITERIA

A power excursion, with the associated release of contaminating fission products, could result if the nonoperating NERVA engine were placed by accident, or a result of malfunction, into a highly moderating environment such as water or liquid hydrogen. A concurrent chemical explosion of the propellant could widely disperse the nuclear material, creating a difficult (if not impossible) problem of decontaminating the surrounding launch facilities. Should a similar malfunction occur during traverse of the shallow Atlantic Ocean shelf, the resulting nuclear excursion would produce fission contamination that could be spread by strong tides to inhabited shores. However, should the NERVA engine fall into deep water beyond the Atlantic shelf wide dispersion of fission products could occur without producing a hazardous situation.

To preclude these hazards prior to NERVA engine start-up, the destruct system must: fracture the reactor core into subcritical fragments, and disperse these fragments so that none of the portions could combine in a geometry which could become critical in a moderating environment.

Criticality studies* have evolved a literal interpretation of the three-dimensional geometric dispersion criterion for submerged nuclear material. The tentative ACDS criterion evolved from these studies, incorporating a factor of safety, established an approximate quantity of 12.5 lb of the fragmented fuel-element material (or test simulant) as the maximum amount which can be allowed to fall within a 25-in.-dia flat circular area for a successful destruct operation. Post-test sampling for such a criterion,

*REON Report 2421 to AEC-NASA SNPO

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on flat terrain, can be accomplished by moving 25-in.-dia circles randomly over the concentrated areas of fragmented mass within the total dispersion zone.

The height of the test target above the ground and its attitude with reference to the vertical axis will affect the dispersal pattern. It is anticipated that the actual minimum elevation of the NERVA engine above ground level during probable ACDS operation will be many times greater than the distance (10 ft) used during all empirical efforts and on which the performance of ACDS and PODS* concepts are presently being compared and evaluated. The proximity to the ground reduces the dispersion of fragments produced in explosive tests and thus produces conservation data. Any attempts to minimize this effect would greatly increase testing and analysis costs.

*PODS is designed for use at any time after engine operation.

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B. NERVA ENGINE SAFETY METHODS

Two types of countermeasure techniques are being actively considered for application to the NERVA engine program. These are: (1) poison wire, and (2) explosive destruct.

The poison wire system involves insertion of a number of wires containing a material of high neutron cross-section into the coolant-channels of the reactor core. These wires would be inserted prior to completion of engine installation. Prior to engine startup the wires would be withdrawn from the core and disposed of outside of the nozzle structure.

Several conceptual methods were suggested for the use of high explosives to accomplish the anticriticality destruct task. The concepts employ various types of charges such as linear shaped, curvilinear shaped, conical shaped, and explosive projectiles. Some utilize only one charge configuration while others employ different configurations in their most promising combinations.

Externally placed high explosive destruct systems are designed to convert chemical energy into kinetic energy which is transmitted through the engine pressure vessel and associated internal components rupturing the outer structures and fragmenting the core material. Under such circumstances, the breakup and dispersion of the core material is a combination of the effects of: (1) explosive jet action produced by the impact of minute particles of matter moving at extremely high velocities, causing cutting and external separation of structural material; (2) intense shockwaves produced by the detonation of high explosives, causing further fracturing and spalling of the cut material; (3) intense localized pressure and temperature regions near the engine pressure vessel, produced by great volumes of hot expanding

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explosives gases; (4) mechanical impact by structural members that have been accelerated to high velocity by the action of explosive gas pressures; and (5) collision and interaction between neighboring fragments traveling along intersecting courses at high velocities.

The internal burster type explosive projectile concepts are designed to carry the high explosive into the reactor core prior to initiation. These concepts create a highly confined, rapidly attenuated explosion within the core which causes the graphite elements to be crushed against the massive engine pressure vessel and reflector structures. The confinement structure tends to fail in a predictable manner determined by the explosive charge parameters and the manner by which the structure is loaded, thereby allowing the contained high-pressure gases and fractured core material to be released and dispersed through the rupture zones. The inserted projectile explosive charge effects contribution to core breakup and dispersion are somewhat different from those systems using externally placed explosive components. The primary effects are a combination of: (1) intense, localized explosive shockwaves, produced by the detonation of high explosives; (2) intense, localized pressure and temperature region, produced by great volumes of hot, expanding explosive gases momentarily confined by the massive pressure vessel and reflector structure; (3) mechanical impact by small projectile-casing fragments that are propelled at high velocity through the core material by the action of explosive gas pressure; and (4) collision and interaction between neighboring fragments at high velocities.

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Accurate physical property simulation of the reactor core material and associated NERVA engine structure is extremely important to performance evaluations because of the relatively small explosive energy level involved and the controlled dispersion nature of the ACDS concepts. *

*Further discussion in Milestone 25 report - REON Report RN-S-0022.

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C. EXPLOSIVE DESTRUCT CONCEPTS

Various explosive destruct concepts are depicted in Figures 2A and 2B and are discussed below.

1. Mark A

The Mark A configuration consists of an external linear cutting charge array, distributed over the pressure vessel, combined with an aft entry conical shaped charges. In this concept, a configuration of curvilinear and linear shaped charges are attached to the engine pressure vessel in such a manner that sections can be ejected from the engine prior to its startup if the ACDS is not required to function. The placement of the charges is such that, at initiation, the major structural integrity of the engine is destroyed by the curvilinear and linear shaped charges. The conical shaped charges, located to fire through the engine aft closure into the core mass accomplish the core fragmentation and dispersion. Provisions for ejection of the explosive charges are incorporated in the mounting attachments,

2. Mark C

The Mark C concept consists of multiple conical shaped charges installed externally on the engine, directed to fire into the core mass. Upon initiation, the resulting jets penetrate the engine and disperse the core as required by the destruct criteria. Radial forces developed by the jet interaction with the core were expected to rupture the pressure vessel. This concept is considered ejectable.

Figure 2a
ACDS Concepts

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Figure 2b
ACDS Concepts

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3. Mark D

The Mark D concept consists of internal burster projectile(s) launched from tube(s) located either aft of the nozzle closure or forward of the shadow shield (bifunctional system: ACDS/PODS). In this concept, the projectile, having an armor-piercing ogive, is propelled from a gun or launcher at a velocity sufficient to permit adequate core penetration prior to delayed initiation of the contained high-explosive charge. Ejection provisions are possible for this concept. The bifunctional projectile design (required to achieve the critically small PODS fragment-size criterion) is larger than the optimum size required to satisfy the present ACDS dispersion criterion, hence, an "over-kill" condition is produced. No ejection capability is required for the bifunctional design.

4. Mark J

The Mark J concept consists of a single deep-penetrating shaped charge combined with a follow-through internal burster projectile. This concept is similar to the Mark D concept, including its capability of bifunctional operation as either an ACDS or a PODS. The aft-entry-type Mark J concept also can be ejected from the engine prior to startup if the ACDS is not required to function. As in the Mark D concept, a projectile is launched into the core where it is detonated to produce fragmentation and dispersion effects. However, in this concept, a path of entry is opened for the projectile by the hypervelocity jet of a conical shaped charge placed in front of the projectile launch tube. Reduced projectile velocities can be used with this concept, but the launcher and projectile design criteria would be changed somewhat. However it appears that there is no significant change in total system weight between the two internal burster concepts.

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5. Other Concepts

Other ACDS concepts were studied and tested. They were determined to be infeasible after preliminary study or failed during test to produce adequate fragmentation or dispersion. As a result, such concepts are no longer being considered. However, should significant changes be made, either in the NERVA engine design and operation, or in the anticriticality safety criteria, certain concepts now discarded might deserve further consideration.

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D. DEVELOPMENT STUDY PROGRESS

1. Purpose of Study

The purpose of this study is to investigate a number of parameters relating to the various proposed explosive destruct systems and to generate conceptual methods to satisfy the existing anticriticality destruct criterion. The scope of work was planned to cover a preliminary evaluation of the performance effects of explosive type, shape, location, size, number, charge standoff, initiation, confinement, and charge liner design. This was accomplished through testing against simulated reactor and pressure vessel sections, and FSSE models. The empirical data generated through this activity was utilized in the concurrent Mechanical Feasibility study to permit technical performance tradeoff analyses of the other complex aspects of overall system feasibility.

2. Development Procedure

The development procedure followed to date has been to test explosive components against slab targets simulating NERVA engine sections followed by tests against crude full-scale targets for gross evaluation and determination of explosive interaction. Successful tests with the crude engine simulant are followed by tests against more accurately simulated engine targets.

Twenty-eight development tests of various conical shaped charges were conducted in support of the Mark A and Mark C destruct system concepts before the charges were tested on more accurate engine models. These tests investigated the effects of variations in liners (configuration,

material, and thickness, etc.) and in explosives (column length, fabrication flaws, standoff distance, and type).

A total of 79 tests were conducted against specific targets in the development of linear shaped charges for the Mark A destruct system concept. If a particular application required severance of the engine pressure vessel, similar material, fabricated in flat plate geometry, was used as the component-test target. A witness plate was used to measure the degree of effectiveness. A complex "sandwich" target was assembled for this type of cutting charge test, if the full-scale test application called for penetration to a given point in the engine structure. The chief purpose of these tests was development of a charge that would fulfill the function required for a coherent system feasibility study, rather than final design of the best possible charge for the specific application. This latter type of development, referred to as system performance optimization, cannot and should not be undertaken until the actual engine material and design are fairly well established.

The Mark A concept development series included tests utilizing four FSSE targets. Four FSSE models were also expended in support of the Mark C concept. Three FSSE models were used to evaluate the ACDS Mark D and Mark J concepts. One half-length, full-diameter simulated engine target each was used for tests of the Mark D/J and Mark B concepts.

3. Review of Significant Tests

a. Mark A Concept

Utilizing the procedure discussed in Section III. D. 2, the development of the Mark A concept began with a number of linear shaped

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charge cutting effectiveness tests. These tests were conducted against stacks of material simulating the layers of the full-scale target which, in turn, simulated the current NERVA engine design. The aft-entry, delayed dispersion conical shaped charge used on the first full-scale Mark A concept tests was an item developed previously by Aerojet on another ordnance program. The concept's explosive components were combined in Test AC-20 conducted during July 1962. The model consisted of a half-length section of a steel Polaris Stage I motor casing (including end closures) that was fitted with a Titan Stage II nozzle (less skirt extension), 3/4-in.-dia AGSX grade commercial electrode graphite rod representing the reactor core material, rectangular magnesium tooling plate simulating the beryllium outer reflectors, and rectangular HLM grade commercial graphite representing the graphite inner reflectors. A total net explosive weight of 142 lb of explosive-shaped charges was used for this test. The test setup is shown in Figure 3. Three circumferential linear shaped charges were arranged about the pressure vessel to sever the vessel and the magnesium outer reflector assembly. The smaller longitudinal interconnecting charges provided pressure vessel cutting only. The conical shaped charge was placed on the nozzle center line 77 in. below the nozzle throat or just outside the nozzle exit plane. The conical shaped charge was oriented to fire through the nozzle throat along the core axis. The test results (Table 1) indicated an overkill condition since the core was pulverized and evenly dispersed over a much greater area than necessary to satisfy the anticriticality destruct criteria (Figure 4). Further testing of this concept awaited availability of a model more nearly simulating the current NERVA engine design.

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Figure 3
Test AC-20: Test Setup

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Sample Location (ft from Ground Zero)	Sample Weight (lb)	Avg Weight (In 25-in.-dia Area)** (lb)
5	2.50	0.95
10	3.06	1.17
15	4.44	1.69
20	5.00	1.90
25	5.81	2.22
30	5.31	2.02
35	8.25	3.14
40	3.75	1.43
45	4.00	1.52
50	0.75	0.29

*Data were taken from a 1 sq yd sample area.

**Calculated values to compare with subsequent sampling areas compatible with criteria.

Table 1

Test AC-20: Fragment Dispersal*

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Figure 4
Test AC-20: Results

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In March 1963, a FSSE target was prepared for the second Mark A concept test (Test AC-131). The test model consisted of a simulated NERVA engine employing an aluminum pressure vessel (a mass and dimensionally simulated forward head structure), simulated internal engine components including a fully suspended core and a steel conical aft-closure simulant. The results of Test AC-20 had indicated that a lighter and less complex linear shaped charge array could be utilized and yet be compatible with the anticriticality destruct criteria.

The linear shaped charge array for Test AC-131 (Figure 5) consisted on one circumferential and four equally spaced longitudinal charges. The explosive required to penetrate the 1.125-in.-thick aluminum pressure vessel used in Test AC-131 was greater than that required to penetrate the 0.225-in.-thick steel Polaris motor casing; hence, an increase in explosive per unit-charge-length was required. The circumferential charge was located at the engine's outer reflector sector support ring plane. The charge was designed to penetrate the pressure vessel, remove the forward head assembly and sever the reflector sectors from their support ring and relieve the forward core support plate attachment. Three of the longitudinal linear shaped charges were designed to cut through the aluminum pressure vessel. The fourth longitudinal charge, large enough to penetrate the pressure vessel, the simulated outer magnesium reflectors, and the steel inner reflector assembly barrel, was located on the opposite side of the model from the conical shaped charge mounted on the aft closure and aimed to fire into the core. 4 ?

Structural analysis indicated the inadvisability of mounting the conical shaped charge in the nozzle as in AC-20 because of excessive skirt loads. Interface problems would result if the shaped charge

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Figure 5
Test AC-131: Test Setup

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were mounted on the forward dome of the lower booster stage. It appeared that a more desirable mounting location would be close to the nozzle closure attachment plane. The location and orientation was selected to require jet penetration of as little material as possible before entering the core assembly. These considerations were responsible for the location of aft entry conical shaped charges in this and subsequent tests. The conical shaped charge for this test consisted of a 5-in.-dia 120° included angle conical shaped charge. The wide angle liner configuration was chosen in preference to the deep (53° included angle) conical liner used in Test AC-20 because of the lack of apparent lateral jet dispersion demonstrated by complete axial penetration of the core and forward head structure in that test. Component and subscale tests conducted with various liner configurations led to the conclusion that the charge selected for Test AC-131 was a better fragment dispersal charge than that used for Test AC-20. Results of a single 8-in.-dia, 120° conical shaped charge fired against a steel confined concrete target are shown in Figure 6. The shaped charge of deep conical liner configuration develops a well focused jet with limited lateral energy. The shaped charge of shallow conical liner configuration containing a similar amount of explosive, delivers its energy over a larger impact area with a consequential increase in lateral effect. The selected conical shaped charge was mounted on the steel cone simulating the convergent portion of the nozzle with no standoff to the cone surface. The total net explosive weight of this destruct system was 96 lb, of which 16 lb were in the conical shaped charge.

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Figure 6

Results of Crude Simulant Test Using Mark A Concept Conical Shaped Charge

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The linear shaped charge array was simultaneously initiated at the four "T" junctions. Initiation of the conical shaped charge lagged 300 μ sec behind completion of the pressure vessel cutting charge propagation. The results of Test AC-131 (Figure 7 and Table 2) indicated insufficient core dispersal, leaving concentrations of core material approximately 50% in excess of that permitted by the tentative ACDS criterion. The large difference in dispersion between Tests AC-20 and AC-131 is primarily attributable to major differences in target toughness. The pressure vessel material and thickness effects have been noted previously. The increased inertia of the heavier pressure vessel used for Test AC-131 contributed some additional confinement to the core. Another facet of the confinement effect is that the aluminum pressure vessel was not cleanly cut and was partially fractured. Additional confinement was contributed by 12 large cast magnesium sectors bolted to heavy end support rings used for Test AC-131 as opposed to 23 rectangular magnesium bars bolted individually to the pressure vessel as in Test AC-20. The core bundle used in the AC-20 model was loosely stacked in the target as opposed to the core bundle which was rigidly supported in compression from a simulated upper support plate on 163-1/8-in.-dia steel rods and a plywood aft support block inside of the welded steel inner reflector assembly barrel for Test AC-131. These tie rods and end conditions presented a restraint to dispersion that was not defeated by this particular explosive charge combination.

This target difference is illustrated by comparison of Figure 8 "Simulated Engine Test AC-20" and Figure 9. The difference in reflector configuration and the steel tie rods is evident in the model for AC-131.

Figure 7
Test AC-131: Results

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Sample Location with Respect to Ground Zero	Sample Weight (lb)
26' West	19.7
10' North	17.8
14.5' North East	16.1
19.5' North East	14.8
27' North East	13.4

Table 2

Test AC-131 Results: 25-in.-dia Sample Area

Figure 8
Simulated Engine: Test AC-20

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Figure 9
Mod 2e Target: Test AC-131

Test AC-133, conducted in April 1963, was the next test in the Mark A concept series. The linear shaped charges were fabricated of aluminum instead of the commonly used steel material and were increased in size to ensure cutting of the pressure vessel. The conical shaped charge was increased to a diameter of 6 in., with a corresponding increase in explosive weight of 9 lb. This was done to increase the dispersal effect of the conical shaped charge.

The delay between completion of pressure vessel cutting and initiation of the conical shaped charge was increased to 650 μ sec. The time delay was increased to evaluate its effect as well as to ensure complete core confinement relief by the large longitudinal linear shaped cutting charge. The total net explosive weight for this test was 106 lb; 25 lb in the conical shaped charge and the remainder in the linear shaped charges.

The results of the test are depicted in Figure 10. Table 3 describes the maximum core material concentrations.

The core material dispersion failed to meet the tentative anticriticality destruct criteria by a greater margin than previous tests in this series. The fragment pattern suggested too great a delay between the cutting and dispersal charges. Additionally, two quarters of the pressure vessel failed to separate at the heavy lower flange.

The next test in this series was designated Test AC-155 (Figure 11). The target was similar to those used for AC-131 and AC-133 except that the pressure vessel was 0.80-in.-thick 6061-T6 aluminum alloy as compared with the non-heat treated 1.13-in.-thick 6061-F previously used. This thinner material best represents the NERVA engine

Figure 10
Test AC-133: Results

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Sample Location with Respect to Ground Zero	Sample Weight (lb)
11.5' West	45.6
12.5' East South East	22.2
15.0' South East	24.0
18.7' South South East	18.4

Table 3

Test AC-133 Results: 25-in.-dia Sample Area

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Figure 11
Test AC-155: Test Setup

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pressure vessel to date within the limiting conditions specified in Section III. E of this report. Because the large, longitudinal linear shaped charge apparently contributed to an asymmetrical dispersion pattern which was not particularly desirable, it was replaced with a small linear shaped charge to merely sever the pressure vessel. The dispersion energy of the conical shaped charge was increased to effect the remaining core confinement release and fragment dispersion effect of the heavy longitudinal charge.

This dispersal charge took the form of two 10-in.-dia, 120° included angle conical shaped charges located on opposite sides of the aft closure and in line with two of the longitudinal linear shaped charges. Because the results of Test AC-131 and AC-133 indicated the undesirable effect of a long time delay, the delay was decreased back to the 100 μ sec used successfully in Test AC-20.

The explosive array for this test consequently consisted of the circumferential linear shaped charge located at the reflector sector-support ring to sever the pressure vessel, remove the forward head assembly, release the forward core support plate and sever the outer reflector sectors from their support ring; and four 50-in. lengths of linear shaped charge arranged longitudinally and equally spaced on the pressure vessel extending between the circumferential charge and the sturdy lower flange. To ensure severing the lower flange, the longitudinal charges were extended across the flange with a 6 in. piece of linear shaped charge of the same cross-section as the circumferential linear shaped charge. This linear shaped charge configuration was cast with a net weight of 60 lb of Octol explosive. The two 10-in.-dia conical shaped charges, each containing 120 lb of Composition B explosive, were installed in mounting chutes located

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on the aluminum aft closure cone representing the convergent portion of the nozzle. These charges were installed with a "one shaped charge cone diameter" standoff to the aft closure surface.

The total explosive weight represented by this particular test was 300 lb, with no attempt to optimize the charge size. Considerable weight reduction in this concept can be made without appreciable decrease in effectiveness through subsequent development efforts (such as application of wave shaper technology) once the concept feasibility is demonstrated.

The results of this test (Figures 12 and 13) met the tentative anticriticality destruct criteria in that the maximum concentration of core material was found to be 8, 6 lb within a 25-in.-dia area (Table 4). This concentration was found 7 ft from Ground Zero. It was noted that no other area of the dispersion pattern even approached this high a concentration indicating perhaps a random occurrence. Inspection of the engine parts after the test indicated that all of the explosive components functioned satisfactorily. The pressure vessel was cleanly cut and the lower flange was severed at all four points. The magnesium reflector simulant was separated from its support ring and well dispersed about Ground Zero. By satisfying the tentative anticriticality dispersion criterion, this test demonstrated the feasibility of the Mark A concept against a full-scale semi-accurate NERVA engine model. Based on this performance demonstration, the detail design of the components was begun in preparation for the Milestone 25 report.

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Figure 12
Test AC-155: Test Results (View A)

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Figure 13
Test AC-155: Test Results (View B)

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Sample Location with Reference to Ground Zero	Sample Weight (lb)
7' South West	8.61
280' West	0.09
260' West	0.09
240' West	0.14
220' West	0.32
200' West	0.20
180' West	0.14
160' West	0.50
140' West	0.46
120' West	0.29
100' West	0.17
80' West	0.40
60' West	0.33
40' West	0.32
20' West	0.56
Ground Zero	0.42
20' East	0.72
40' East	0.59
60' East	0.34
80' East	0.39
100' East	0.50
120' East	0.27
140' East	0.33
160' East	0.71
180' East	0.72
200' East	0.47

Table 4

Test AC-155 Results: 25-in.-dia Sample Area

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b. Mark C Concept

The Mark C concept evaluation began with an extensive series of shaped charge tests against full-scale, unconfined and confined concrete targets and progressed to FSSE targets. The procedure of evaluating shaped charge performance characteristics against inexpensive simulants was selected because the large number of full-scale tests required would have made the program excessively expensive if more complex targets had been used.

The concrete simulant was specially mixed to approximate the bulk density and strength of the graphite reactor core material. Samples of the cured concrete were tested and found to have a bulk density slightly in excess of the core material, and in addition were stronger, thereby providing a conservative margin in these preliminary investigations. The important technical considerations omitted because of cost were: (1) simulation of the strong anisotropic characteristics of the NERVA engine core design, including the coolant-hole pattern and fuel element interfaces; (2) simulation of the confinement characteristics exhibited by the beryllium outer reflector structure; and (3) simulation of the heat-treated pressure vessel failure characteristics.

After considerable investigations using the confined concrete targets, an 8-in.-dia, 120° aluminum-liner conical shaped charge loaded with approximately 57 lb of Composition B explosive demonstrated promising performance. This conical shaped charge was not weight

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optimized. This single charge was utilized in Test AC-124 against a full-scale, confined (Polaris motor casing) concrete target. A single charge configuration was emphasized because of its simplicity with inherent advantages of reliability and ease of ejection. The post-test debris indicated that adequate fragmentation and dispersion was achieved (Figure 6).

Following this, another test (Test AC-128) was conducted on a more accurate FSSE utilizing a 48-in.-dia x 1/4-in.-thick wall, mild-steel chamber simulating the aluminum NERVA engine pressure vessel. The steel casing contained simulated outer and inner reflectors of curved magnesium sections and graphite slabs, respectively, surrounding a core comprised of 3/4-in.-dia AGSX grade graphite-rod material. The single explosive charge (same as that used in Test AC-124) failed to rupture the steel casing, and consequently left the majority of the target intact. Some minor distortion was noted on the inner reflector barrel which indicates that some lateral energy from the shaped charge was involved, but not to the degree necessary to relieve the core confinement.

Further efforts to demonstrate the feasibility of the Mark C concept consisted of evaluating the relative performance of six shaped charges positioned around the aft closure. This was done in an attempt to alter the lateral jet energy distribution within the core to provide greater bursting effects near the inner boundaries of the reflectors and pressure vessel. This array was tested first against a number of confined concrete targets, and then against three more accurate FSSE targets, (Tests AC-127, AC-130, and AC-161). The target used in Test AC-127 (Figure 14) consisted of a 6061-F aluminum casing, a mass-simulated forward head structure, simulated outer and inner reflector materials, and a simulated

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Figure 14
Test AC-127: Test Setup

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full-scale core fully suspended from an aluminum, simulated forward support plate. It was used with 211 steel 3/16-in.-dia tie rods passing through individual 3/4-in.-dia graphite tubes to simulate as accurately as possible the current B-4 module design. The target used in Test AC-130 (Figure 15) included a 48-in.-dia x 1/4-in.-thick mild-steel chamber simulating the aluminum NERVA engine pressure vessel containing simulated outer and inner reflector materials, a steel simulated aft closure, and 3/4-in.-dia AGSX grade graphite-rod core material. The shaped charges used in both tests were essentially the same, differing only in that optimum explosive waveshapers were used in Test AC-127 and an extended explosive column length (increased explosive weight) was used in Test AC-130. Test AC-130 was run to confirm the results demonstrated by Test AC-127 in that the wave-shaped charges used on that test contained known casting flaws. It was felt that the effect of these flaws should be evaluated against the complex target. The total net explosive weights were 94 lb and 218 lb, respectively. The results of these tests (Figures 16 and 17) proved the inadequacy of a combination of these particular conical shaped charges.

A heat-treated 0.80-in.-thick wall aluminum pressure vessel with a simulated NERVA engine internal design was the target for Test AC-161 conducted 4 June 1963. The explosive shaped charges consisted of four 8-5/8-in.-OD x 10-1/2-in.-long 90° aluminum conical shaped charges loaded with Octol explosive. This charge had shown promise when fired against full-scale, confined concrete targets (Tests MF-109 and MF-113). These charges were arranged around the simulated nozzle with 3-, 6-, 9-, and 12-ft standoffs. The total net explosive weight was 134 lb. When initiated simultaneously, impact sequence was attained through the various standoffs. Empirical evidence suggested that better

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Figure 15
Test AC-130: Test Setup

Figure 16
Test AC-127: Results

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Figure 17
Test AC-130: Results

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inter-jet reinforcement of multiple shaped charges intersecting within the core could be obtained by non-simultaneous jet penetration. Previous multiple charge Mark C tests were conducted to obtain simultaneous dynamic jet intersection within the core. Non-simultaneous charge effects can be accomplished by initiation delay between charges, a variation in detonation velocity or standoff distance between the charge and the target, by using a variety of standoffs as well as dispersion results of the staggered blast effects. This combination, however, failed to rupture the pressure vessel, and, although the core material was adequately fragmented the dispersion was not sufficient.

c. Mark D and Mark J Concepts

The Mark D and Mark J concepts differ only in the manner of delivery of the internal burster charge. The explosive feasibility phase has been conducted to determine minimum (single) projectile requirements. An increase in the size or number of projectiles used, as might be indicated by the results of the PODS development program (Sub-Subtask 1.6.5), and will consider the need for greater dispersion or defeat of the in-place interstage structure. Once the high-explosive-filled projectiles are positioned within the core, the explosive mechanism required to achieve the tentative anticriticality destruct criteria are essentially the same in either case. Because of this, parametric test data gained from the detonation of static burster charges, statistically emplaced within simulated engine targets, were utilized in the investigation of the Mark D and Mark J concepts. From the quantitative results obtained in the PODS parametric explosive evaluation program it is certain that the tentative anticriticality destruct criteria can be achieved using the smallest projectile presently under

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consideration, i. e. , 105 mm (30 lb net explosive weight of TNT, Composition B, or Octol). Essentially, the primary effort for the anticriticality portion would comprise establishment of: (1) ideal configuration and weight combination for the ejection-type system, and (2) means to effect incorporation in the concurrently developed PODS for the bifunctional system.

Several internal burster configurations were compared for gross effects using full-scale confined concrete targets. A 6-in.-dia glass-encased (round bottom flask) spherical explosive charge, a multi-direction linear shaped charge firing radially outward, and cylindrical charges of various lengths and diameters, with and without charge-confinement casings, were tested in various positions within the simulated cores. Based on the cumulative results, a 4-in.-dia, cylindrical, 0.18-in.-thick, steel-encased charge 32 in. long containing 23 lb of Composition B explosive was selected as the most promising charge to use in a simulated engine target. The test of this charge (Test AC-129: Figure 18) was conducted using a target consisting of a 48-in.-dia x 1/4-in.-thick ductile-steel wall pressure vessel containing simulated NERVA engine components. Evaluation of the post-test fragment dispersion (Figure 19) indicated that the tentative anticriticality destruct criteria was achieved (Table 5).

Subsequently, the charge length was reduced with a compensatory increase in charge diameter to accommodate a similar amount of Composition B explosive for the next internal burster ACDS concept test. Data generated in the concurrent mechanical feasibility study suggested limiting the explosive-charge column length to 20 in. for aft-closure entry ejectable Mark D/J concept projectiles so that the launching mechanism would not extend beyond the nozzle skirt plane. Such a charge (Test AC-132)

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Figure 18
Test AC-129: Test Setup

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Figure 19
Test AC-129: Results

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Sample Location With Respect to Ground Zero	Sample Weight (lb)
8' South	4.75
13' East South East	7.45
35' East South East	7.28*
38' East South East	7.4*

*Samples were weighed in a wet condition.

Table 5

Test AC-129: 25-in. -dia Sample Area

was tested against a simulated NERVA engine with an aluminum pressure vessel, a mass-simulated forward-head structure, and simulated internal engine components including a fully suspended core using 163 steel 1/8-in.-dia tie rods, and a steel conical aft-closure simulant. The test resulted in a failure to disperse the core material sufficiently to meet the criteria (Figure 20). The solid 3/4-in.-dia AGSX grade graphite rods simulating the core elements were well fragmented, but the material concentration near Ground Zero exceeded the maximum allowable quantity by 150% (Table 6). The decrease in performance exhibited between Tests AC-129 and AC-132 is believed to have been caused primarily by the change to a more compact charge configuration. The results of Test AC-129 were repeated in Test AC-154 (Figure 21) using a similar charge configuration, 4-in.-dia, 32-in.-long, with Octol rather than Composition B as the explosive. The target model incorporated a heat-treated aluminum pressure vessel and the same simulated NERVA engine internal structure as previously employed. The shadow shield was mass-simulated with a welded steel disc assembly placed on top of the engine assembly. The nozzle restriction was simulated with a steel cone having a throat diameter relief in the center. The maximum core material concentration within any 25 in. diameter surface area was measured after the test was 7.5 lb, which satisfies the tentative anticriticality destruct criteria (Table 7).

d. Conclusions

The test series outlined in this section established the feasibility of an explosive ACDS employed against semi-accurate FSSE models. The Mark A concept or the internally planted high-explosive projectile (Mark D or Mark J concept) will achieve the tentative anticriticality destruct criteria.

Figure 20
Test AC-132: Results

Sample Location With Respect to Ground Zero	Sample Weight (lb)
4' South	31.7
3' East	32.8
9' East	23.0
13' East	19.0
15' East	18.2

Table 6

Test AC-132: 25-in.-dia Sample Area

Figure 21
Test A-154: Results

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Sample Location With Respect to Ground Zero	Sample Weight (lb)
3' Northwest	7.47
12.5' West South West	6.23
38.7' West South West	4.29

Table 7

Test AC-154: 25-in.-dia Sample Area

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It is recommended that the Mark A concept should be developed as the primary ejectable ACDS. The Mark D or Mark J system, as determined by the post-operation destruct phase of the program should be developed as the bifunctional or backup ACDS rather than as a secondary ejectable ACDS in the small, single projectile aft entry form. Prior to further empirical development, applicable explosive ACDS performance should be verified on accurate NERVA FSSE target models incorporating B-4 elements or accurate simulants, and beryllium reflector material.

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E. NERVA ENGINE SIMULATION STUDY PROGRESS

The performance of a given explosive destruct system, depends on the target (NERVA engine) design; consequently, the materials and construction of the simulated NERVA engines must be considered carefully when evaluating ACDS concept test results. The effect of engine structural materials on final tests of two variations of the Mark A concept (Tests AC-131, AC-133, and AC-155) and of the small, ejectable Mark D/J concepts (Tests AC-129, AC-132, and AC-154) are qualitatively discussed in Section III, D. Mark B concept performance (Test AC-86), although highly effective in destroying the structural integrity of the engine, did not produce sufficient evidence of dispersion capability or weight efficiency to justify further study. Mark C concept explosive performance has been inadequate to date (Tests AC-127, AC-128, AC-130, and AC-161), and the use of a more accurately simulated engine with this concept would not improve the results. Therefore, the Mark C system is not considered here.

1. Engine Simulation - Mark A Concept

A target model configuration, typical of those used in tests to date, is shown in Figure 9.

One configuration (Mod 2) of the Mark A ACDS concept, demonstrated by Tests AC-131 and AC-133, utilized linear shaped charges to relieve all but inertial confinement of the core and the slight confinement at the aft end of the simulated pressure vessel where the flange was not cut. As indicated in Table 8, the load-transmission properties of the core are not a major factor in this configuration, because large core confinement rupture loads are not required as a functional effect of the conical shaped charges during core dispersal. Comparing the simulated with the actual NERVA engine design, the pressure vessel material has a minor effect on linear shaped charge size. The overall effect of the substitute reflector segments compared with actual or even modified reflector design would be a change in size of the linear shaped charges as indicated in Table 8. Minimal differences are expected in the dispersion charges between the simulated engines and the NERVA engines.

Another configuration of the Mark A ACDS used in Test AC-155 required severance of the pressure vessel in conjunction with large delayed conical shaped charges fired from the aft closure to relieve the inner and outer reflector assembly confinement and adequately disperse the core. Because the pressure vessel used in this test was of the same material but slightly thicker than the actual pressure vessel, a slight decrease in linear

ACDS and Components	NERVA Reactor Component					
	Pressure Casing	Beryllium Reflector	Support Cylinder	Graphite Reflector	Thermal Insulator	Core Elements
Mark A Concept (Tests AC-131 and AC-133)						
Linear Shaped Charge for Casing Cutting	Could be slightly decreased for actual reactor	NA	NA	NA	NA	NA
Linear Shaped Charge for Casing and Reflec- tor Cutting	Could be slightly decreased because of pressure casing, but control rod in ac- tual reflector would probably require a compensating increase		NA	NA	NA	NA
Linear Shaped Charge for Casing, Reflector and Support Cylinder Cutting	Could be slightly decreased because of pressure casing, but control rod in actual reflector would probably require a compensating increase		Close simulation, minor changes in charge size re- quired	Very minor differ- ence in back of support cylinder being cut	NA	NA
Conical Shaped Charge for Core Dispersion	NA	NA	NA	NA	NA	Degree of non- simulation would require minor in- crease in charge size
Mark A Concept (Test AC-155)						
Linear Shaped Charge for Casing Cutting	Could be slightly decreased for ac- tual reactor	NA	NA	NA	NA	NA
Conical Shaped Charge for Support Cylinder Rupture and Core Dis- persion	Inertial (mass) effects could cause slight charge-size increase	minor effect	minor effect	minor effect	minor effect	Large effect, prob- ably the actual re- actor will require a large charge
Mark D and Mark J Con- cepts						
Projectile for Casing Fracture and Core Dispersal	Large effect, actual reactor would re- quire smaller pro- jectile if all other parameters were constant	Reasonable strength and density simula- tion, minor effect	minor effect	minor effect	minor effect	Large effect, the actual reactor would require a larger projectile if all other param- eters were constant

Table 8 Effect of Inaccuracies in Material Simulation on ACDS Performance
and on Component Size Requirements.

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shaped charge size and weight would be possible in an ACDS used against the NERVA engine. The load transmission properties of the core, however, become of great importance to the success of this configuration because the inner reflector assembly barrel is not cut by the linear shaped charges. If this thin (0.60-in.) steel cylinder is not ruptured by the conical shaped charges, core dispersal becomes minimal. The lower load transmission properties of the B-4 elements (compared to 3/4-in.-dia solid round graphite rods) are more critical for this system than for the Mark D/J concept because the conical shaped dispersion charges do not transmit radial loads of sufficient intensity or duration to compensate for the large difference in load transmission capabilities which probably exist between the simulated and the actual core elements. For this reason, two large conical shaped charges having large impact area capability were used in Test AC-155 with intersecting jets to increase the lateral energy coupling for better fragment dispersal.

2. Engine Simulation - Mark D/J Concept

A target model configuration typical of those used in tests to date is shown in Figure 22. The simulated pressure vessel and core material are of prime importance in evaluating Mark D/J concept performance against the tentative ACDS dispersion criterion. This is because pressure vessel rupture is caused by internal pressure (radial movement of core material and of detonation products). As the size and number of Mark D/J explosive projectiles increase above this minimal level toward that required to achieve the present PODS fragmentation criterion, more prominent damage mechanisms are evident - that of interchange reinforcement of dynamic effects and high velocity explosive jetting. Since these complex effects have not been

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Figure 22
Mark D/J ACDS Target

observed in the studies supporting the evaluation of the small Mark D/J concept to meet the ACDS criteria, the discussion here concerns only the simple internal pressure effects.

A conservative approach must be maintained when using data for empirical studies of complex systems consisting of materials and simulants having wide variations in physical properties and tested against targets based on a mechanical design that is in a state of constant flux. Accordingly, a simple relationship has been derived that has been useful in predicting, and thereby maintaining, a controlled degree of conservatism from test to test. This relationship is based on the premise that the NERVA engine should not be more difficult to defeat than the test target. The two major effects which control this relationship for the small Mark D/J ACDS concept are that of pressure vessel fracture energy and core load transmission. These two factors must be made compatible by either design adjustments in the pressure vessel to accommodate available core material or, alternately, selection of a suitable core simulant to match the desired pressure vessel characteristics.

The pressure vessel has a low enough ratio of wall-thickness-to-diameter that it can be considered to be a thin-walled cylinder that fails due to tensile or hoop stress. The cylinder expands under internal pressure until a crack forms. Propagation of this crack is not highly predictable, but, once it starts, the entire structure will generally fail. To compare the simulated and actual pressure vessels, the energy required to rupture the pressure vessel materials in simple tension will be compared. Generally, the energy can be expressed as

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$$W = \int_{X_{\text{initial}}}^{X_{\text{final}}} p(x) dx \quad (1)$$

where:

$p(x)$ = force varying with x

x = displacement in the direction of the force.

For a constant cross-sectional area and strain independent of x , the energy becomes:

$$W = A l \int_{\sigma}^{\epsilon_{\text{ultimate}}} \sigma_x d\epsilon \quad (2)$$

where:

σ_x = tensile stress

ϵ = tensile strain

A = cross-sectional area of material being loaded

l = length of material over which strain occurs.

Thinning of the material under stress requires the use of true-stress-true-strain data, a cross sectional area varying with x , and strain varying with x . Obtaining the data to accurately calculate the energy to rupture the pressure vessel would be a sizable experimental project; therefore, an approximate comparison will be made for the following various materials.

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- a. NERVA pressure vessel - 0,670-in.-thick 6061-T6 aluminum alloy
- b. Test AC-132 - 1,13-in.-thick 6061-0 aluminum alloy
- c. Test AC-154 - 1,13-in.-thick 6061-T6 aluminum alloy.

Future modifications to the simulated pressure vessel design provide 0,80-in.-thick aluminum alloy in both the "0" and the "T-6" condition. These vessels are fabricated per the ASME unfired pressure vessel codes and will be assembled with closely simulated reflectors and other internal structural components. The cores will consist of government furnished NERVA B-4 geometric simulant elements and/or depleted uranium loaded B-4 elements if these elements are available to the program.

The fracture energy of a material is obtained by integrating the area under the stress-strain curve. The approximations used in the fracture energy (toughness) comparisons between the various pressure vessel materials are:

- a. $\int_{\sigma}^{\epsilon_{ultimate}} \sigma d\epsilon$ is the area under the conventional stress-strain curve.
- b. Strain rate* and dynamic effects are not considered.

* Plasticity, Proceedings of the Second Symposium on Naval Structural Mechanics, Edited by E. H. Lee and P. S. Symonds, Pergamon Press, 1960. "Problems remain in those areas where it is uncertain how to apply the dynamic characteristics of the plate material. This is demonstrated by the following investigations. Equally thick panels of a variety

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- c. The effects of A and ϵ varying with x are similar enough so that if a ratio of failure energies for the materials is taken, the error becomes small. The axial length of the pressure vessel over which the fracture starts is considered equal in all cases.

Using 6061-T6 aluminum alloy data from Military Handbook MIL-HDBK-5, March 1959, and 6061-0 aluminum alloy data from test bars cut from one end of a fabricated pressure vessel, the ratio of the failure energies (toughness) of 6061-T6 aluminum alloy to 6061-0 aluminum alloy is 0.78. Taking thickness variations into account, the pressure vessel fracture energy ratios are:

a. 6061-0 Aluminum Alloy

$$(1) \frac{\text{NERVA Pressure Vessel}}{\text{Test AC-132}} = 0.78 \times \frac{0.67}{1.13} = 0.46$$
$$(2) \frac{\text{NERVA Pressure Vessel}}{\text{Future Tests}} = 0.78 \times \frac{0.67}{0.80} = 0.65$$

b. 6061-T6 Aluminum Alloy

$$(1) \frac{\text{NERVA Pressure Vessel}}{\text{Test AC-154}} = 1.0 \times \frac{0.67}{1.13} = 0.59$$
$$(2) \frac{\text{NERVA Pressure Vessel}}{\text{Future Tests}} = 1.0 \times \frac{0.67}{0.80} = 0.83$$

* (Footnote, continued)

of different steels used in shipbuilding and having different yield strengths and stress-strain curves were subjected to identical simple dynamic loads, and the final strains and damage contours were determined experimentally. From these measurements the energy absorbed in plastic deformation was calculated for each plate based on its experimentally determined static stress-strain curve. The thus-determined plastic work for the different plates

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These values indicate that with the small Mark D/J concept the actual NERVA pressure vessel is much easier to rupture than those used in the simulated engines tested to date. However, the new 0.80-in.-thickness does not provide as much conservatism, when using solid rod core material, as does the thicker material used in a number of recent tests (AC-132 and AC-154). The 0.67-in. design thickness used for the actual engine pressure vessel is measured between the circumferential stiffening ribs (Aerojet Drawing 283094) where the crack is most likely to start under internal pressure. The two 0.78-in.-thick stiffener areas would not significantly retard crack propagation. Should the actual pressure vessel be constructed without stiffener zones, the probability and location of crack initiation would be as difficult to predict as those for the simulated engines.

* (Footnote, continued)

agreed for all materials, which was most surprising since strain rates of 50-in./in./sec were observed during the deformation process.¹⁴ Since the different steels used are known to exhibit different strain-rate effects the results were interpreted to mean that such effects were not significant in this case of large plastic deformation. This example demonstrates the difficulty which the naval architect faces in making use of strain-rate considerations in energy absorption calculations for structures undergoing large plastic deformations. It also demonstrates the need for research efforts to eliminate the existing contradictions."

A. H. Keil, Problems of Plasticity of Naval Structures: Explosive and Impact Loading, p. 33.

- (14) Lisanby, J. W., Rasmussen, J. E., and Schauer, H. M., "Comparison of Dynamic Yield Effects of Steels" Underwater Explosions Research Division Report 10-57, June 1957.

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The other major factor affecting the ACDS Mark D/J concept performance is the capability of the core to transmit radial loads outward to the pressure vessel wall. An experiment was conducted to obtain a comparison of load transmission properties of the graphite electrode stock with those of extruded graphite material machined to simulate the geometry of the actual core elements. Mild-steel cylinders, 6-in.-ID x 0.25-in.-thick wall x 6-in.-long, were filled with core elements and a 5/8-in.-dia Composition B explosive charge was detonated in the center of each cylinder. The damage contour of the deformed cylinders was measured and the energy of deformation was obtained by a numerical integration of the conventional stress-strain curve along the length of the cylinder. In this case, accurate measurements were obtained because the strains were not large enough to cause appreciable thinning of the cylinder wall. As in the case of the pressure vessel calculations, the strain-rate effects were neglected. The types of core elements compared were the 3/4-in.-dia, solid, round AGSX graphite rods with a B-1 hexagonal configuration machined from HLM graphite (simulated B-4 elements were not available). The ratio of deformation or load transmission energies was:

$$\frac{3/4\text{-in. Round Rod}}{3/4\text{-in. Hex B-1}} = 1.33$$

indicating the greater load transmission capabilities of the present core element simulant compared to a geometry more simulative of the actual case. The load transmission ratio would be greater than 1.33 for 3/4-in.-dia round rods compared to B-4 elements because the B-4 element is more fragile, and has more than twice the void volume of the hexagonal B-1 element due to coolant hole differences.

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The relationship to be used is:

$$\frac{\text{NERVA engine}}{\text{Simulated engine}} = \left(\frac{\text{Pressure Vessel}}{\text{Fracture Energy Ratio}} \right) \times \left(\frac{\text{Core Load}}{\text{Transmission Ratio}} \right) \leq 1$$

Using the energy transmission ratio of 1.33 the relative energy required for a Mark D/J concept to rupture the actual NERVA pressure vessel (thereby permitting core dispersal) compared to that required in a simulated engine are as shown below from the previously calculated factors:

a. 6061-0 Aluminum Alloy

$$(1) \quad \frac{\text{NERVA engine}}{\text{Test AC-132 (1.13-in.)}} = 0.46 \times 1.33 = 0.61$$

$$(2) \quad \frac{\text{NERVA engine}}{\text{Future Tests (0.80-in.)}} = 0.65 \times 1.33 = 0.86$$

b. 6061-T6 Aluminum Alloy

$$(1) \quad \frac{\text{NERVA engine}}{\text{Test AC-154 (1.13-in.)}} = 0.59 \times 1.33 = 0.79$$

$$(2) \quad \frac{\text{NERVA engine}}{\text{Future Tests (0.80-in.)}} = 0.83 \times 1.33 = 1.10$$

The first three of these values indicate that the NERVA engine core will be more readily dispersed than the simulated engines which provides a calculable degree of conservatism in the testing effort. The last value indicates an optimistic effect which is not desirable at this time. However, if the load-transmission ratio increased only slightly above the 1.33 magnitude (entirely possible, when comparing 3/4-in.-dia round graphite element effects with those of the B-4 geometry), all of the resultant values would exceed 1, indicating that testing conservatism no longer exists. The value of 1.33 for load transmission obtained for the hexagonal B-1 elements serves mainly as an indicator at this time, and a comparative test using extruded elements of

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B-4 geometry will be conducted using Government furnished NERVA elements when available. Attempts to use fracture data obtained from B-1 and B-4 elements machined from extruded HLM (commercial) graphite to simulate full extrusions were not successful due to physical property differences brought about by the respective fabrication processes. Considerable differences in dynamic response properties are thought to exist between the extruded B-4 geometric simulant, the depleted fuel-loaded old-style B-4 elements, and the depleted fuel-loaded new-style B-4 elements. Dynamic response property differences between depleted fuel-loaded B-4 elements, enriched fuel-loaded B-4 elements, and B-4 elements with high fission product inventories of both the old and new fuel types are not known at this time.

3. Conclusions

This discussion has considered only major inconsistencies between the simulated and the actual engines. The indication is that the success of the various systems on an actual NERVA engine can be summarized as follows:

a. Mark A Concept of Test AC-155 Configuration

Reasonable doubt now exists that this configuration can guarantee achievement of the required anticriticality dispersion criterion when using the actual engine core elements due to the large difference in load-transmission properties of the actual and the simulated core elements. Any reduction in the size of the delayed dispersion charge is not recommended until tests are performed with B-4 elements; rather, the size of these charges may have to be increased slightly to obtain a margin of adequate performance.

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Alternatively, the required size of the dispersion charges could be reduced substantially if the inner reflector assembly barrel is severed as in Tests AC-131 and AC-133 instead of sole dependence on internal rupture loads produced by the large dispersion charges.

b. Mark A Concept of Tests AC-131 and AC-133
Configuration

These systems should perform similarly on the NERVA engine as they have on simulated engines. Reduced timing delays between the linear shaped charges and the dispersion charge should result in better dispersion performance based on Test AC-155 results. Achievement of the anticriticality dispersion criterion is deemed feasible since the mechanism is understood despite the fact that it has not been demonstrated adequately by test.

c. Mark D/J Concept of Tests AC-129, AC-132,
and AC-154 Configuration

The load transmission properties of the actual and simulated cores definitely affect this system, but no drastic increase in the size of the projectile of Test AC-154 can be foreseen because dispersion performance exceeded the minimal requirements. This conclusion can be given a more quantitative basis only after a load-transmission ratio is obtained for B-4 elements. It is clearly evident that utilization of a single full-core-length projectile of 105 mm, 133mm, or 155 mm (possible in the

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large bifunctional system) will provide an over-kill condition with 3/4-in.-dia round graphite rod simulant and perhaps produce a similar, if somewhat pronounced, effect using the B-4 elements. Here again, a proper dynamic engine simulation is based on compatibility of: (1) the pressure vessel fracture-energy ratio, and (2) the core-load transmission ratio.

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F. MECHANICAL FEASIBILITY STUDY PROGRESS

The purpose of the Mechanical Feasibility study being conducted on the various ejectable ACDS and non-ejectable (bifunctional) ACDS/PODS is to explore methods and devices for mounting, ejection or translation, and control and firing for these systems. From this investigation, the system offering the best feasibility as an integratable ejectable ACDS will be selected and designed for incorporation with the NERVA engine. Also a parametric study is being conducted to formulate the design of a bifunctional system to be integrated with the NERVA engine complex. The resultant designs and analyses will be submitted in the Milestone 25 report.*

1. Destruct System Design Criteria

In addition to fulfilling the basic fragmentation requirements, the ACDS must exhibit the following inherent characteristics:

- a. Minimum system weight
- b. Rapid response
- c. High reliability
- d. Capability to operate in the established environments
- e. Integratable into the engine complex
- f. Optimum mounting and ejection features
- g. Safety considerations.

* Milestone 25 Report - REON Report RN-S-0022

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Several explosive ACDS concepts have been evolved that employ various types of linear shaped charges, conical shaped charges, and projectile (internal) charges, either separately or in combination (Figures 2a and 2b).

The explosive requirements for desired fragmentation will be determined from empirical data derived from the concurrent explosive performance study. Results of tests conducted to date indicate the Mark A and the aft-entry Mark D concepts offer the most promise as ejectable ACDS. Detailed arrangements and approximate size of either the explosive array or the launch mechanism, or both, for these systems are shown in Figures 23 and 24. Typical configurations of the basic charges employed are shown in Figures 25, 26, and 27. Figure 27 describes a portion of a projectile weight-trade-off study in which two types of metals were selected for the casing walls.

In addition to demonstrating explosive feasibility, the Mark D and Mark J concepts are also the most favorable for incorporating an ACDS and a PODS into a single bifunctional system. In this application, the launch tubes and projectiles would be located forward of the shielded area, thereby eliminating the need for their removal upon startup of the NERVA engine. This results in a significant weight reduction by eliminating the ejection fixtures required for an ejectable ACDS.

Mechanical feasibility studies on the ejectable ACDS have been concentrated on the Mark A and the aft-entry Mark D/J systems, with the studies on bifunctional systems directed toward the forward-mounted Mark D and Mark J systems. Areas under investigation include:

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Figure 23
ACDS Mark A Concept

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Figure 24
ACDS Mark D Concept

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Figure 25
Typical Mark A ACDS Conical Shaped Charge

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Designation	*Inside Liner Width (in)	**Liner Height (in)	Liner Shape Angle α (°)	Liner Material Thickness (in)	Liner Material	Explosive	Explosive Weight (lb/ft)	Liner Weight (Modified) (lb/ft)	Total Weight (lb/ft)
L-23	1.75	2.50	60	0.060	C-1010 CRS	Composition B	2.270	0.701	2.971
L-31-5	2.50	6.00	60	0.060	C-1010 CRS	Composition B	9.880	1.008	10.888
L-40-3	0.50	1.00	60	0.018	C-1010 CRS	Octol	0.308	0.060	0.368
L-41	1.75	2.50	60	0.063	6061-C AL	Octol	2.380	0.254	2.634
L-42	0.75	1.50	60	0.032	6061-0 AL	Octol	0.708	0.055	0.763
L-43	2.50	6.00	60	0.063	6061-0 AL	Octol	9.380	0.365	9.745

Figure 26
Typical Mark A ACDS Concept Linear and Curvilinear Shaped Charges

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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.)	34.34	44.03	52.03	0.250 STL	23.0	77.21	85.35
133 (5.250 in.)	32.00	43.61	51.61	0.750 AL	23.0	88.12	98.74

Figure 27
Mark D Concept Projectile Configuration

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- a. support structure
- b. ACDS ejection mechanism
- c. actuation and launch mechanisms
- d. basic projectile and shaped charge configuration
- e. location and space limitations
- f. system weights
- g. fire control, fuzing, and initiation
- h. response time
- i. reliability
- j. post-ejection dynamics.

Inasmuch as the explosive application on the Mark B and Mark C concepts (considered as ACDS), and on the Mark I and Mark M concepts (considered as bifunctional ACDS/PODS) have proved inadequate or have produced marginal or unreliable fragmentation results to date, these concepts have not been actively pursued beyond the stage of preliminary design and testing.

To develop configurations of the lightest possible weight, systems are being designed on a "minimum redundancy" basis. Such a system will utilize the minimum number of charges and critical components required to produce the desired results. Added redundancy could be achieved by duplicating the explosive array; however, this would make the destruct system too heavy. It is anticipated that the redundancy in the initiation system will be adequate to meet the reliability requirements.

The evaluation and analysis of the candidate destruct systems are based on the environmental conditions specified in Table 9. Additional discussion of the most promising destruct concepts follows.

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Operating Conditions	ACDS (Booster Operation)	Bifunctional Systems (Booster and NERVA Engine Operation)
SUSTAINED LOADING		
Linear acceleration	+8.0 g to 1.2 g parallel to thrust axis ±1.0 g normal to thrust axis	+8.0 g to 1.2 g parallel to thrust axis ±1.0 g normal to thrust axis
Spin acceleration and velocity	Negligible	Negligible
Angular acceleration and velocity in pitch and yaw modes	1 rad/sec ² and 10 degrees/sec	1 rad/sec ² and 25 degrees/sec
DYNAMIC LOADING*		
Vibration (in three mutually perpendicular axes)**	2 g - 0 to peak, 5 to 45 cps 0.019 double amplitude - 45 to 85 cps	2 g - 0 to peak; 5 to 45 cps 0.019 double amplitude - 45 to 85 cps
Random vibration	Flat spectra density of 0.5 g ² /cps over a band of 5 to 2000 cps	Flat spectra density of 0.5 g ² /cps over a band of 5 to 2000 cps
Shock (in three mutually perpendicular axes)	30 g - 1/2 sine wave	30 g - 1/2 sine wave
a. Rise time if primary frequency is ≤ 350 cps	$\left(\frac{700}{\text{primary frequency}} - 1 \right) \text{ msec}$	$\left(\frac{700}{\text{primary frequency}} - 1 \right) \text{ msec}$
b. Rise time if primary frequency is ≥ 350 cps	1 msec	1 msec
AMBIENT CONDITIONS		
Pressure	~ 30 in Hg to 10 ⁻⁸ mm Hg	~ 30 in Hg to 10 ⁻¹² mm Hg
Temperature	-130° to +103°F	-234° to +250°F
Humidity	0 to 100%	0 to 100%
<p>* Component requirements in the order shown</p> <p>** Components to withstand vibration at major resonances for not less than six minutes</p>		

Table 9
Destruct System Design Criteria
Non-Nuclear Environment

2. Destruct Modes

a. Mark A ACDS - Ejectable

The Mark A system, as demonstrated by Test AC-155, is made up of an array of linear shaped charges located around the pressure vessel with two conical shaped charges located either on or near the nozzle cone (Figure 28). The linear shaped charges are arranged with a curvilinear ring of charges located on a level with the top of the core at the intersection of the outer reflector segments and the top support collar, and four core-length (or slightly longer) longitudinal linear shaped charges equally spaced around the periphery of the pressure vessel. The conical shaped charges located at the nozzle cone are positioned so that their combined jet action will be concentrated in the core. This is done so that maximum reenforcement and dispersion of translated energy (and attendant fragmentation) can be derived from jet interaction of the double conical shaped charge arrangement.

Since the explosive feasibility tests have demonstrated that the Mark A system of this configuration has met the tentative fragmentation and dispersion requirements specified, special emphasis has been placed on the mechanical feasibility evaluation and analysis of this system. The alternate Mark A configuration, as represented by Tests AC-131 and AC-133, did not demonstrate adequate performance but, because of its direct method of core confinement release, further feasibility considerations will be made.

b. Mark D ACDS - Ejectable

The Mark D ACDS concept consists of one high-explosive projectile located in a launch tube that is mounted alongside the rear nozzle cone and skirt as previously shown in Figure 24. The orientation

Figure 28 Mark A Concept

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of the launch tube is such that the projectile will penetrate the core diagonally offset from the center. The projectile assembly consists of the following major components: (1) cartridge case containing the propellant charge; (2) body containing the high explosive; and (3) armor-piercing head ogive with an impact/delay-type fuze. In addition, the projectile assembly is equipped with an igniter at the end of the cartridge case, a gas check at the projectile base, which prevents leakage of propelling gases past the projectile, and shock discs at each end of the projectile body for cushioning and attenuating deleterious shock propagation to the high explosives during projectile acceleration, impact, and penetration.

The launch-tube assembly will be either of closed breech or of recoilless geometry, depending upon its material, weight, and space limitations.

Upon initiation of the propellant charge, the projectile will accelerate and impact the convergent portion of the engine nozzle, triggering the impact-type fuze mounted in the nose of the projectile. The nominal nose-fuze delay will be such that initiation of the explosive charge will occur when the projectile has reached the desired offset position near the center of the core.

Evaluation of explosive feasibility experiments to date on the Mark D concept indicates that a single internal-burster projectile containing 23 to 25 lb of Composition B explosive with an approximate column length of 32 in. will provide the required fragmentation effect. Special emphasis has, therefore, been directed toward the preliminary study of the projectile and launch-tube assembly applicable to the concept. Two basic

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projectile diameters (calibers) are anticipated for the ACDS or bifunctional Mark D system: 105mm (4.125 in.), and 133mm (5.250 in.). Investigations have been conducted to develop an optimum type of charge tube and armor-piercing ogive for the projectile (Figure 27).

The design of the launch-tube assembly is dependent upon the projectile weight and length as a function of velocity for proper core penetration. Also, the projectile travel time (acceleration time) is a prime factor; the shorter this time, the higher the breech-section pressures. Since rapid-response time is of utmost importance in the ACDS, a projectile acceleration time in the order of 5 to 8 msec has been set as a reasonable criterion. Although the exact projectile velocity for desired penetration and implantation in the core has not been established, a velocity range requirement of 500 to 800 fps has been tentatively established for the small aft-entry Mark D system upon which to base the analysis.

Preliminary evaluation of the Mark D ACDS indicates that this system exhibits several advantageous features and a considerable amount of investigation and analysis has therefore been conducted on this system.

c. Mark D and Mark J - Bifunctional Systems

Because of the similarity in function of the Mark D and Mark J bifunctional systems, they will both be discussed in this subsection. The Mark D or Mark J bifunctional system consists of from 4 to 6 launch tubes of either closed breech or recoilless configuration located forward of the shielded area. The orientation of the launch tubes is such that the projectiles will penetrate the forward shield and travel into the core

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in a circular array with a radius of approximately 0.5 to 0.7 of the core radius. The projectiles on the Mark D or Mark J bifunctional systems will be of similar configuration, but will be larger than the projectiles on the ejectable Mark D or Mark J ACDS. Only one of these projectiles will be required for the ACDS function. The CFS would be modified to provide an override to accomplish this function. The devices should all be of similar size and performance capability to ensure proper spatial distribution of energy to satisfy the stringent postoperation destruct criteria.

However, in the event that gross over-kill is objectionable, the ACDS operation may be accomplished by one of the launch tubes and projectiles being of smaller caliber or of shorter length, or both, than those remaining so that an explosive load applicable to the anticriticality requirements could be used. Since the ACDS projectile might have a smaller charge, the explosive quantity in the other 3 or 5 remaining projectiles would be increased to compatible limits for PODS function. This might entail radical performance effects brought about by the unequal spatial distribution of these projectiles.

Inasmuch as the ACDS portion of the bifunctional system will require the added penetration capability and may require the method of simultaneous initiation in reference to the multiple projection array for PODS function, it is preferred to employ multiple projectiles of identical geometry and capability, rigidly emplaced in the forward end of the NERVA engine compartment.

Preliminary evaluation of translated or liquid-explosive transfer systems of the Mark D or Mark J configuration indicate several disadvantages. Basically, reliability and response-times

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are affected. Preliminary analysis of a translated system with the single ACDS launch-tube and projectile assembly, initially located at the nozzle cone, indicated that this system was not justified.

3. Experimental Work

Experimental accomplishments applicable to the ACDS and to the bifunctional system development were demonstrated by:

- a. Promising performance of T8 mortar propellant, using a Pyrocore igniter implemented by an SI-119 flash charge and a confining screen membrane (Tests MF-93 through MF-105).
- b. Formations of the jet conducive to shaped charge initiation application of the implanted projectile explosive charge.
- c. Penetration through a simulated forward-head structure by a conical shaped charge to permit unobstructed insertion of the Mark J bifunctional system projectile (Tests MF-10 and MR-12, MF-83 through MF-89, MF-106, MF-107, and MF-112).
- d. Competitive performance of a lead-lined conical shaped charge for the same application (Test MF-112) as in c above.
- e. Optimization of linear shaped charge development with waveshapers (Tests MF-116 through MF-133).
- f. Investigations of explosive bolt and MDF methods of implementing ejection.

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Although the limited experimental effort on the methods of effecting ejection has not considered the latest proposed destruct system installation, sufficient preliminary information is available to predict adequate performance for the concept previously shown in Figure 23. Based upon the results of experiments performed to date, it can be postulated that a significant reduction in the linear shaped charge weight can be realized by employing the waveshaper and optimized standoffs without sacrificing penetration performance.

4. System Weight Analysis

A preliminary analysis to determine an order of magnitude of subsystem and system weights for the various candidate destruct systems was initiated. This analysis is summarized in Table 10. To offer a better evaluation of the relative total-system weights applicable to the bifunctional systems, the Total System Weight column in Table 10 has been divided into two parts which show the applicable weight of: emplaced systems, and translated systems.

The ejectable ACDS are all considered emplaced in contrast to the bifunctional systems on which some of the modes of arrangements in Table 10 could be utilized.

In an emplaced bifunctional system the explosive arrays would be placed above the shadow shield as close to the core as possible in a ready-to-fire position with no translation required before operation. This results in a system with a relatively short response time and good reliability. However, the parasitic weights imposed by heavy shielding and cryogenic cooling, if required, for PODS operation could add considerably to the overall system weight.

System	Application	Explosive Application To Date	Explosive (Solid) Weight Less Liner Weight (lb)	Liner and/or Projectile Weight ¹ (lb)	Actuation, Launch and/or Translation-Mechanism Weight (lb)		Initiation Weight ¹ (lb)	CFS Weight ¹ (lb)	Ejection Mechanism and/or Support Structure Weight ¹ (lb)	Shielding Weight ¹ (lb)	Cryogenic Cooling System Weight ¹ (lb)	Total-System Weight ¹ (lb)	
					Propellant ¹	Mechanism ¹						Emplaced	Translated
Mark A	ACDS Ejectable	Promising - Additional Experiments Planned	128.4 ² Ref Test AC-155	15 - 35	None	None	3.0 - 6.0	31 - 120	75 - 150	None	None	252 - 439	NA
Mark D	ACDS Ejectable	Promising - Requires Further Development	23.0 Ref Test AC-129	50 - 80	0.5 - 15.0	100 - 250	0.1 - 3.0	31 - 90	75 - 125	None	None	280 - 586	NA
Mark J	ACDS Ejectable	Promising - Requires Further Development	48 - 65	60 - 100 ³	0.5 - 12.0	100 - 200	0.1 - 3.0	50 - 110	75 - 125	None	None	334 - 615	NA
Mark D (Bitunctional)	ACDS Nonejectable	Promising - Requires Further Development	23 - 80 ¹	50 - 110	1 - 24	100 - 300	0.5 - 3.0	31 - 62	20 - 50	NA	NA	226 - 629	NA
	PODS	Promising - Requires Further Development	198 - 480 ¹ 198 - 480 ¹	141 - 650 141 - 650	6 - 144 6 - 144	600 - 1800 750 - 1950	3 - 60 3 - 60	35 - 370 70 - 405	120 - 260 180 - 310	310 - 720 310 - 720	30 - 200 30 - 200	1443 - 4684 NA	NA 1688 - 4919
Mark J (Bifunctional)	ACDS Nonejectable	Promising - Requires Further Development	48 - 100	60 - 130 ³	0.5 - 18.0	100 - 250	0.5 - 3.0	31 - 80	17 - 38	NA	NA	257 - 619	NA
	PODS	Promising - Requires Further Development	300 - 601 300 - 601	182 - 389 ³ 182 - 389 ³	3 - 120 3 - 120	210 - 1500 450 - 1650	3 - 60 3 - 60	50 - 480 85 - 515	100 - 230 160 - 290	310 - 720 310 - 720	30 - 60 30 - 60	1188 - 4160 NA	NA 1523 - 4405

¹Estimated
²Weight based on overkill results of Test AC-155 and probable explosive component optimization
³Includes shaped charges

NA = Not Applicable

Table 10
ACDS and Bifunctional Destruct
System Evaluation

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In a liquid-explosive transfer system, the liquid explosive would be stored in a container located above the shadow shield with a pumping or an expulsion system, or both, for transferring the explosives to properly shaped and thermally controlled containers surrounding the pressure vessel. The shielding and thermal requirements for such a system would be nominal, but the system complexity would be great, primarily because of the environmental control problems.

The preliminary weight analyses of the various candidate destruct systems were based on:

- a. Explosive weights per latest applicable explosive feasibility tests.
- b. Hardware weights per preliminary designs and estimates.
- c. Redundancy in the initiation system only.
- d. Single Mark D and Mark J ACDS projectiles of 105mm and 133mm dia.
- e. Mark D and Mark J launch tubes of either closed breech or recoilless geometry.
- f. Muzzle velocity: 500-800 fps for Mark D ACDS concept; 400-500 fps for Mark J ACDS concept; 900-1300 fps for Mark D bifunctional system concept; 400-600 fps for Mark J bifunctional system concept.

An analysis of the parametric evaluation of the closed breechgun concept is discussed in Section III, F. 5.

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5. Preliminary Parametric Evaluation - Closed Breech Gun

A preliminary design of a closed breech gun was made to approximate the Mark D ACDS system weights for analysis purposes. Inasmuch as the basic explosive charges have not been finalized, this analysis was limited to a parametric study and trade-off evaluation to establish a range of system weights. A ready solution existed in internal ballistic calculations by using the Heydenreich method, in that empirical coefficients have been established to allow calculations of pressure, time, and velocity vs travel of the projectile without the use of the more cumbersome exact equations.

The most significant factor in determining the characteristics of the pressure curve is η , which is the ratio of mean pressure to maximum pressure. Muzzle velocity then may be expressed by the following equation:

$$V_o = \frac{2SB(\eta)}{t_a} \quad (3)$$

where:

S = distance of acceleration in feet

$B(\eta)$ = empirical coefficient as a function of η

t_a = acceleration time in seconds

The propellant weight can be calculated by:

$$G_f = \frac{G_p}{\frac{30.2}{\left(\frac{V_o}{1000}\right)^2} - 0.5} \quad (4)$$

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where:

G_p = projectile weight in lb.

Maximum chamber pressure is given by:

$$P_{\max} = \frac{V_o^2 (2G_p + G_f)}{g S \pi D^2 \eta} \quad (5)$$

where:

g = acceleration of gravity (ft/sec²)

D = diameter of the projectile in inches.

The projectile position at peak pressure ($P_{\max}$) can be expressed as:

$$\lambda = S \Sigma (\eta) \quad (6)$$

where:

$\Sigma (\eta)$ = empirical correction factor as a function of η .

Instantaneous velocity in multiples of λ can be obtained by:

$$V_i = V_o \Phi (\eta) \Omega (\lambda_i) \quad (7)$$

where:

$\Phi (\eta_i)$ = empirical coefficient as a function of η

$\Omega (\lambda_i)$ = empirical coefficient as a function of λ_i .

Instantaneous pressure in multiples of λ can be expressed by:

$$P_i = P_{\max} \psi (\lambda_i) \quad (8)$$

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where:

$\psi(\lambda_i)$ = empirical coefficient as a function of λ_i .

Determination of breech and barrel wall thickness can be made by Lamé's formula for the appropriate allowable stress by:

$$t_i = R - r = r \left[\sqrt{\frac{S_a + P_i}{S_a - P_i}} \right] - 1 \quad (9)$$

where:

R = outside radius in inches

r = inside radius in inches

S_a = allowable stress in lb/in.²

P_i = instantaneous pressure along the gun bore.

Determination of barrel weight can then be readily obtained from the ballistic curves and drawings derived.

A summary of the analysis of a typical Mark D ACDS is graphically shown in Figure 29 which depicts a family of curves and describes the effects of parametric trade-off. The time required from projectile initiation to exit from the muzzle (system response time) and maximum pressure are plotted as a function of η for the range of projectile diameters, weights, velocities, and acceleration distances anticipated. A typical pressure-vs-projectile travel curve is given in Figure 30 for a 4.9 msec response-time system. A plot of equivalent allowable stress pressure for determination of wall thicknesses is also shown in Figure 30. The discontinuity and rise in this curve is due to joint contributions of the segmented barrel design.

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Figure 29
Comparison of Effects of
Parametric Trade-off

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Figure 30
Pressure vs Projectile Travel

A plot of destruct package weight vs response time (Figure 31) indicates that the system of minimum weight for the given set of conditions occurs at approximately 3 msec response time. The increase in weight for the rapid response/rapid decay system is partially due to determination of structural integrity of the terminal end of the barrel by dynamic flight loads rather than to 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 titanium in the muzzle end of the gun. In addition, the segmented gun design readily lends itself to material substitutions.

The effects of response times upon a pressure profile are given in Figure 32. Due to the relatively slow pressure buildup and decay, thicker sections are required on the muzzle end of the barrel for slow-response systems, and these may entail a heavier barrel.

The performance predicted by the graphs assumes a rigidly mounted device with minimal recoil. Allowance must be made in performance depending upon the span and rigidity of restraining structural members. Further modifications may be required because actual propellant, initiation train, and projectile geometry are contingent upon empirical substantiation and development. Due to system integration limitations, further parametric trade-offs may also be required prior to design formulation of the ultimate integrated system. This analysis will be continually reviewed and upgraded, as additional information is available, to ensure an adequate analysis and optimized destruct system.

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Figure 31
Destruct Package Weight vs Response Time

Figure 32
Effects of Response Times
Upon Pressure Profile

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6. System Response Analysis

The purpose of this analysis is to evaluate the response times that can be anticipated for the various destruct system concepts. Design of a preliminary CFS, initiation devices, and an explosive train was accomplished as a basis for this evaluation. Figures 33, 34, and 35 show the CFS diagrams for the most promising ejectable ACDS (Mark A and Mark D) and for the Mark D bifunctional system. Table 11 lists the anticipated weights of the CFS for the ACDS and the bifunctional systems. The majority of the components used in the CFS are of existing design with proved functional reliability. Detailed discussion of these devices is presented in Section III. G. 2. To provide high reliability, the systems have been made redundant by providing parallel loops in the electrical and explosive circuitry both for the destruct and for the jettison phase of the CFS. The basic firing system response times from closure of destruct-relay contacts to main-charge initiation, including projectile travel and system jitter (as applicable), are listed in Table 12.

For the ACDS, the Mark A concept, in comparison with the Mark D concept, exhibits very good response time, since this system is mounted in the "as fired" position and does not require any delay (i. e., projectile travel) time before main-charge initiation. The only delay encountered is in the CFS and in the basic initiation jitter inherent to the explosive array. In contrast, the Mark D system exhibits a longer overall system response time because of the time required for the acceleration and insertion of the projectile into the reactor core.

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Figure 33
Mark A ACDS CFS Diagram

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Figure 34
Mark D ACDS and Bifunctional Destruct System CFS Diagram

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Figure 35
Mark D Bifunctional CFS Diagram

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Description	Unit Weight (lb)	ACDS				Bifunctional			
		Mark A		Mark D		Mark D		Mark J	
		Quantity	Component Weight (lb)	Quantity	Component Weight (lb)	Quantity	Component Weight (lb)	Quantity	Component Weight (lb)
Firing-Pulse Generator (AGX-4403-40-1)	0.10	4	0.40	4	0.40	1	0.10	2	0.20
Firing Unit (AGX-4403)	0.63	4	2.50	4	2.50	1	0.63	2	1.26
Connectors (AGX-4403)	0.10	4	0.40	4	0.40	1	0.10	2	0.20
Safe/Arm Unit	0.50	4	2.00	4	2.00	1	0.50	2	1.00
HV TRIAX Cable	0.063 lb/ft	10 ft	0.63	10 ft	2.63	2 ft	0.13	6 ft	0.38
Detonator (AGX-2008) Incl. Connector	0.47	4	1.90	4	1.90	1	0.47	2	0.94
Delay Timer	0.50	--	--	--	--	--	--	2	1.00
MDF Leads	0.015 lb/ft	30 ft	--	--	--	--	--	1 ft	0.02
System Weight Totals			8.28		7.83		2.06		5.00

Table 11
CFS Weight for the ACDS and Bifunctional Systems

Destruct Function	Time (μsec)			
	ACDS		Bifunctional	
	Mark A	Mark D	Mark D	Mark J
Response - Firing-Pulse Generator (AGX-4403-40-1)	2.0 (± 1.0)	2.0 (± 1.0)	2.0 (± 1.0)	2.0 (± 1.0)
Response - Firing Unit (AGX-4403)	3.0 (± 1.0)	3.0 (± 1.0)	3.0 (± 1.0)	3.0 (± 1.0)
High voltage TRIAX Cable (10 ft ACDS; 3 ft Bifunctional system)	*	*	*	*
Response - EBW Detonator (AGX-2008)	2.0 (± 1.0)	2.0 (± 1.0)	2.0 (± 1.0)	2.0 (± 1.0)
Propagation - MDF Leads	250.0 (± 20.0)	*	*	50.0 (± 4.0)
Built-in delay - first and last explosive charge	300.0 (± 8.0)	NA	NA	NA
Acceleration - Projectile	NA	7,000.0 $\left(\begin{smallmatrix} + 3000.0 \\ - 2000.0 \end{smallmatrix}\right)$	8,000.0 $\left(\begin{smallmatrix} + 4000.0 \\ - 3000.0 \end{smallmatrix}\right)$	8,000.0 $\left(\begin{smallmatrix} + 4000.0 \\ - 3000.0 \end{smallmatrix}\right)$
Penetration - Projectile	NA	14,800.0 $\left(\begin{smallmatrix} + 1000.0 \\ - 2000.0 \end{smallmatrix}\right)$	16,000.0 $\left(\begin{smallmatrix} + 2000.0 \\ - 3000.0 \end{smallmatrix}\right)$	16,800.0 $\left(\begin{smallmatrix} + 2000.0 \\ - 3000.0 \end{smallmatrix}\right)$
Initiation jitter - Explosive charges	40.0 (± 8.0)	30.0 (± 3.0)	30.0 (± 3.0)	500.0 (± 50)
TOTAL RESPONSE (Command signal to initiation of main destruct charge)	597.0 (± 39.0)	21,837.0 $\left(\begin{smallmatrix} + 4006.0 \\ - 4006.0 \end{smallmatrix}\right)$	24,037.0 $\left(\begin{smallmatrix} + 6006.0 \\ - 6006.0 \end{smallmatrix}\right)$	25,357.0 $\left(\begin{smallmatrix} + 6057.0 \\ - 6057.0 \end{smallmatrix}\right)$
* Negligible				

Table 12
ACDS and Bifunctional Destruct
System Response Times

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Although the response times listed may appear to be excessive from an ordnance point of view, the delays described are relatively insignificant in comparison with the overall time lapse for either a ground controlled or an in-flight sensor controlled countermeasure.

Concepts requiring multiple points of initiation will inherently exhibit random jitter that will increase the total-system response time. Since the primary factors affecting response time for the Mark D system are acceleration and penetration times of the projectile, an effort will be made to control pertinent parameters (i. e., muzzle velocity, delay train, etc.) wherever practicable in order to reduce the response time to a minimum.

7. System Reliability (Non-nuclear environment)

The ACDS and the bifunctional ACDS/PODS can each be defined as an assembly of components that include pyrotechnic and explosive devices for effecting NERVA engine destruct on command when the release of chemical energy is electrically stimulated. The selfpowered system accepts commands, routes discrete signals, and performs the intended function.

Explosive devices present a peculiar type of reliability problem; i. e., to demonstrate that such devices will perform in accordance with specified reliabilities, the units must be destroyed. Therefore, a reliability of explosive components is estimated, based on a statistical sampling of units manufactured under rigorously controlled processes. To forecast reliability based on a statistical sample, complete assurance is required that the sample is representative of the homogeneous group from which it is taken. To ensure homogeneity of a particular group, every conceivable variable in the manufacturing and processing of the group must

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be controlled. These variables include those associated with the metal components, the explosive materials, manufacturing processes, and the human element.

Reliability is not an all inclusive statement. A specific reliability must be related to function. Reliability of a no-fire function, for instance, must be established at that maximum environmental stress which most affects the no-fire function of the device in question. Because the no-fire function of an explosive device is essentially determined by the amount of heat (or input energy) it can withstand without initiation of the explosives, it follows that a maximum environmental stress can be expected at the highest temperature environment specified. Therefore, all reliability testing for no-fire should be conducted at the maximum temperature extreme.

The precise statistical techniques and designs of experiments to implement such a program are beyond the scope of discussion herein; however, it should be pointed out that the order-of-magnitude of components required for basic design concepts can be approximated.

In establishing reliability figures for the ACDS and bi-functional systems the reliability figure-of-merit (RFM) approximation method is used to predict performance based on the present state-of-the-art of similar devices. A summary of the analysis based upon this method is given in Tables 13 and 14. It should be noted that the subsystem values derived consider neither the circuitry prior to the trigger-pulse input to the firing-pulse generator (FPG) nor the effects associated with penetration or destruction of the reactor core. As information regarding detailed

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Component Function	Mark A		Mark D	
	Single System	Redundant System	Single System	Redundant System
1. Firing-Pulse Generator (FPG)	.9998	.99999996	.9998	.99999996
2. FPG Through EBW Firing Unit	.9996	.99999984	.9996	.99999984
3. FPG Through Safe/Arm Device	.9993	.99999951	.9993	.99999951
4. FPG Through EBW Detonator	.9991	.9999992	.9991	.9999992
5. FPG Through Detonator/MDF Interface	.9971	.9999916	.9971	.9999916
6. FPG Through MDF Leads	.9969	.9999904	.9969	.9999904
7. FPG Through MDF/Booster Interface	.9968	.99999	NA	NA
8. FPG Through Booster/Shaped Charge Interface	.99675	.99999	NA	NA
9. FPG Through Shaped Charge	.99674	.99999	NA	NA
10. FPG Through Propellant Igniter (Mark D Concept)	NA	NA	.9966	.999989
11. FPG Through Propellant Charge (Mark D Concept)	NA	NA	.99658	.999988
Total Subsystem Reliability	.99674	.99999	.99658	.999988

Table 13

Calculated RFM for ACDS Based on a 95% Confidence Level
Non-Nuclear Environment

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Component Function	Mark D		Mark J	
	Single System	Redundant System	Single System	Redundant System
1. Shaped Charge Delay Timer (Mark J)	NA	NA	.9990	.999999
2. Firing-Pulse Generator (FPG)	.9998	.99999996	.9998	.99999996
3. FPG Through EBW Firing Unit	.9996	.99999984	.9996	.99999984
4. FPG Through Safe/Arm Device	.9993	.99999951	.9993	.99999951
5. FPG Through EBW Detonator	.9991	.9999992	.9991	.9999992
6. FPG Through Detonator/MDF Interface	.9971	.9999916	.9971	.9999916
7. FPG Through MDF Leads	.9969	.9999904	.9969	.9999904
8. FPG Through Propellant Igniter	.9966	.999989	.9966	.999989
9. FPG Through Propellant Charge	.99658	.999988	.99658	.999988
10. FPG Through MDF/Initiator Shaped Charge Interface	.9968	.99999	.9968	.99999
11. FPG Through Initiator Shaped Charge/Booster Interface	.99675	.99999	.99675	.99999
12. FPG Through Initiator Shaped Charge	.99674	.99999	.99674	.99999
13. Delay Timer Through Forward Shaped Charge (Mark J)	NA	NA	.99574	.999982
Total Subsystem Reliability	.99333	.999966	.9926	.999941

Table 14
Calculated RFM for Bifunctional System
Based on a 95% Confidence Level
Non-Nuclear Environment

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interface design and empirical substantiation of the reliability of destruct modes become available, the analysis will be expanded to embrace total-system reliability.

Most missile destruct systems are designed to perform one distinct function; i. e., to preclude or to terminate the thrust of a rocket engine. However, the criteria for the NERVA engine ACDS dictate that it shall be capable of performing a wider range of functions than has been required of any other known destruct or safety system. Reliability therefore becomes extremely critical, especially in areas where a single malfunction might result in the failure of the system to perform its intended function.

As previously mentioned, the most common method of providing high reliability in ordnance systems is to make the system redundant by providing parallel loops in the electrical and explosive circuitry and by duplicating every component. This is usually relatively uncomplicated; however, because of the fragmentation and dispersion requirements for NERVA engine destruct, for an ejectable ACDS, it may be necessary to use destruct-mechanism components of such magnitude of weight to prohibit complete redundancy. Redundancy for a bifunctional ACDS/PODS may be easier to attain, in that a portion of the PODS could be used as backup to effect anticriticality destruct if required.

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All of the elements in the ACDS and in the bifunctional systems are of basic types that have histories from which their attainable reliabilities are known. These are used both for the RFM analysis and for evaluating the space and weight of alternatives. Once system design is established, statistical analysis dictates the planning of developmental tests and of reliability and quality assurance tests so that true reliability is established at acceptable levels.

The Mark D and Mark J ACDS and bifunctional systems are nearly identical in arrangement and in basic function to the Mark D and Mark J PODS. The exceptions are that the ejectable ACDS is mounted on the aft end of the engine alongside the nozzle skirt and is fired forward into the reactor core, while the bifunctional system is mounted on the forward end of the engine and is fired rearward into the reactor core, and that the PODS functional components are considerably larger than those of the ejectable ACDS. If an ejectable ACDS is used it will probably be ejected subsequent to S-N stage separation. Inasmuch as this concept will not be subjected to the extreme thermal and radiation environment existing during or after nuclear-stage operation, there will be a greater probability of achieving the RFM values currently assigned to the existing components yet to be derived.

To establish the RFM for each component in the system, they have been separated and are presented herein in sequence, starting with the FPG. It should be noted that the FPG, the exploding bridgewire (EBW) firing unit, the safe/arm device, the cables and connectors, the EBW detonator, and the MDF leads are the same on all destruct concepts. The specifications given are per non-nuclear environments only.

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a. Firing - Pulse Generator

The EBW FPG, Model AGX-4403-40-1, is used to provide a reliable and uniformly acceptable trigger pulse for the EBW firing unit, Model AGX-4403. The FPG accepts any 28 vdc switch closure of more than 10 μ sec duration (regardless of contact "bounce" or transients) and delivers an output trigger pulse of 27 (± 4) vdc with a 2 μ sec rise time.

The FPG specifications (non-nuclear environment) are:

Length:	0.94 in.
Width:	0.75 in.
Height:	1.00 in.
Volume:	<1.00 in. ³
Weight:	<1.50 oz
Input Impedance:	1000 ohms
Shock:	100 g for 11 msec
Vibration:	0.3-in. double amplitude (DA) for 2 to 20 cps - 30 g from 20 to 2000 cps
Operating Temp:	-55° to + 85°C

Solid-state circuit potted and hermetically sealed in a metal crystal can.

This FPG unit has been extensively used by Aerojet and subjected to severe, repeated testing with no deleterious effects on performance. Based on these performance data, the FPG is tentatively assigned an RFM of .9998.

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b. EBW Firing Unit

The EBW firing unit, AGX-4403, is a single-function, miniature unit designed to provide an acceptable, small, and lightweight, high-energy power supply and firing control device for use with EBW initiators. This unit has discriminating trigger-signal-acceptance networks and can be modified to meet specific requirements. The design characteristics and package configuration of the unit have been established to provide highly reliable performance, high resistance to rigorous environments, small size, lightweight, and versatility of installation. The high-voltage converter, into which the nominal 28 vdc power is fed to charge the high-energy storage capacitor, is a special transistorized push-pull inverter that produces an extremely precise square-wave output. The output of this inverter is fed through a stepup transformer to a voltage-doubler-type rectifier circuit. The output of this rectifier circuit is fed to the high-energy storage capacitor (1 μ f). When input power is removed, safing of the unit is accomplished through redundant bleeder circuits that discharge the capacitor in 30 sec. A tap in the bleeder circuit permits monitoring the capacitor energy level. A maximum of 15 vdc level at the bleeder output indicates a 2000 vdc charge level on the storage capacitor. By using the voltage-doubler circuit and the unique inverter design, and by careful selection of components, component derating in excess of several hundred percent is accomplished.

Triggering of the high-energy storage capacitor is accomplished by applying a properly shaped 28 vdc input signal to the trigger-acceptance network. The network discriminates between acceptable and unacceptable triggering signals on the basis of the signal voltage level, rise

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time, and duration. An acceptable trigger signal is fed to an internal pulse-generator circuit that, when energized, applies a 5000 vdc pulse to the energy gate.

The energy gate is a special gap-switch device that, when energized with the 5000-v ionizing input, permits the discharge of energy stored in the capacitor through a properly designed transmission line to the safe/arm device.

The EBW specifications (non-nuclear environment) are:

Input voltage:	27 (± 3) vdc
Surge current:	120 ma
Idling current:	80 ma
Arming time:	4 sec
Safing time:	30 sec
Trigger signal:	27 (± 3) vdc
Response time:	3 μ sec
Output energy:	2 joules
Operating temp:	-55° to +100°C
Storage temp:	-55° to +125°C
Altitude:	∞
Vibration:	0.3-in. DA for 2 to 20 cps 30 g from 20 to 2000 cps
Shock:	100 g for 11 msec
Acceleration:	15,000 g for 11 msec
Weight:	10 oz

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Figure 36 shows a block diagram of the internal elements of the circuit. This unit has been subjected to extensive testing by Aerojet, and has been fabricated and delivered as prime hardware. The reliability of the firing unit is .9998 at a 95% confidence level, calculated by failure-rate summation for the described design conditions.

c. Safe/Arm Device

The safe/arm devices commonly used in destruct systems are required by Range Safety procedures. They are electromechanical explosive devices that are armed either manually (at launch) or on command. The electrical, mechanical, and explosive components are located inside one housing, thereby eliminating the requirement for external components. Because the EBW concept is being incorporated in this system, an external safe/arm device is required. Its function is to prevent stray current from reaching the EBW detonator through the interconnecting cable during assembly prior to launch and also to pass current from the EBW firing unit to the detonator on command to fire. This is accomplished through the use of a 28 vdc energized relay that is capable of withstanding the high voltage output of the EBW firing unit. The device incorporates a spring-loaded slider lock pin that moves into position at arm, and holds the relay contacts closed. The slider is also relay operated. On command to safe, a 28 vdc current is applied to the slider relay, allowing the arming contacts to open, and thus breaking continuity between the EBW firing unit and the EBW detonator. The safe/arm device is assigned .9997 as an RFM,

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Figure 36
Firing Unit Elements

d. EBW Detonator

The EBW detonator, AGX-2008, embodies a spark gap in series with an EBW. The spark gap acts as a circuit interrupter both to protect the assembly and to provide additional safety against no-fire energy levels, both ac and dc. By varying the gap dimension within specific tolerance ranges, the assembly can be tailored to any specific all-fire voltage level while retaining adequate no-fire safety. The bridgewire supplies the necessary energy for reliable initiation of the explosive base charge without the use of primary explosives. The standard AGX-2008 detonator is at least an order-of-magnitude less sensitive to electrical energy than conventional hot-wire initiators. This detonator will not fire and is not rendered inoperative by application of 0 to 50 vdc from a source of 0.1 to 1.0 ohms impedance. The detonator operates as follows: the initiator bridgewire reacts to the 2 joule output of the firing unit by converting it to shockwaves, incandescent particles, and radiant energy of sufficient magnitude to initiate the high-explosive base charge.

The EBW specifications (non-nuclear environment) are:

All-fire:	2000 vdc at 1 μ f
No-fire:	500 vdc at 1 μ f
	500 vdc, 30-amp source
Function time:	1 to 2 μ sec
Electrostatic safety:	10,000 v
RF safety:	100 mw/cm ² /sec
Bridgewire system:	Single bridge
Dimensions:	0.250 in. in dia x 0.530 in. long (Nominal)

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Weight:	2.0 gm
Temperature range:	-80°F to +386°F
Vibration:	8 g 20 to 100 cps 0.015-in. DA at 100 to 300 cps 7 g 300 to 2000 cps
Shock:	100 g for 100 msec (triangular wave) 100 g for 8 msec (sine wave) 100 g for 6 msec (square wave)

This detonator has undergone extensive development and testing at Aerojet. An RFM of .9998 has been assigned to it.

e. Detonator/MDF Interface and MDF Leads

The RFM of the detonator/MDF interface is greater than .9980 at a 95% confidence level based upon Aerojet experience with relatively complex detonators and explosive connectors. Use by Aerojet of many thousands of feet of MDF with no failures indicates a reliability of .9998 at a 95% confidence level.

f. Propellant Igniter

In the igniter design, the end of the MDF extends directly into the igniter flash mixture, thereby eliminating an interface. The flash mixture is of a composition that is easy to initiate by the flash of the MDF. This mixture has been used extensively by Aerojet as the ignition mix for both propellants and flares. This igniter has been assigned an RFM of .9999.

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g. Propellant

Because of the state-of-the-art of military propellant compositions, the reliability of these propellants is considered high. Assuming reliable function of all components upon which propellant ignition is dependent, an RFM of .99998 is assigned the propellant.

h. Other Considerations

The RMS numbers stated for the preceding components are considered reasonable assignments for preliminary design, recognizing that the system RFM may be adjusted and made compatible with spacecraft requirements as design details are more clearly defined. In some cases, it may be necessary to increase redundancy; in others, it may be possible to improve reliability by deleting some elements.

8. System Ejection Studies

The following three basic staging and sequencing modes have been evaluated in an attempt to select the best ejection concepts for the various ACDS.

a. Ejection with Interstage Structure in Place

This criterion results in relatively difficult physical arrangements since the destruct components must be ejected through and beyond the interstage structure. To accomplish this, the ejected components must be guided in specific directions, by means of rails, cables, or equivalent, out through openings in the interstage structure. These openings would be provided by panels or doors removed by linear cutting charges, explosive bolts or equivalent means for severing support members. It is evident that this particular ejection

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and sequencing mode presents many problem areas which will result in greater system weights, poor redundancy, and decreased reliability. It is not likely that this staging sequence will be employed.

b. Ejection Immediately Prior to, or Simultaneously
With, Stage Separation

In this arrangement the destruct system components could be clamped around the NERVA engine and the destruct package could be supported by cables attached to the interstage structure. This would eliminate the need for bosses or mounting lugs, attached to the engine proper, that could produce hot spots during engine operation. Spring-loaded cables or equivalent mechanisms attached to the interstage structure would serve to pull the destruct system components away from the engine prior to or during stage separation. Ejection at nuclear-stage separation could also be accomplished by mounting the destruct systems on top of the Stage II booster and independent of the NERVA engine. Attachment of the system or systems (bifunctional) components to either the interstage structure or to the Stage II booster would be objectionable in the event of premature stage separation or of misalignment due to local structural failure.

c. Ejection After Nuclear-Stage Separation

This sequencing arrangement appears the most feasible because it allows practically unrestricted ejection directions or paths for the destruct components. However, the ejection energy requirements are greater in that a relatively high imparted velocity is required to effectively separate the package from the payload at a safe distance

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prior to destruction. Delayed initiation would then be used to destroy the explosive charges after separation and prior to impact with the earth's surface. The orientation and method of destruct of the charges after ejection is important in order to prevent accidental damage to the nuclear stage. For example, the jet blast of an initiated conical shaped charge could, if properly oriented, cause serious damage to the nuclear stage at distances of several thousand feet. It will, therefore, be necessary either to arrange the post-ejected destruct devices so that initiation does not occur prematurely, or to make arrangements to orient the charges and point of initiation in a desired position prior to destruct.

Various types of ejection concepts that would be applicable to this ejection mode have been proposed for the ACDS. Figures 37 and 38 depict concepts applicable to the Mark A system; and Figures 39 and 40 show concepts applicable to the Mark D system. These concepts, as well as others, are being analyzed and evaluated further in order to select the most suitable arrangements.

Investigation and design formulation are proceeding both to obtain ejection methods that will exert the smallest dynamic force or reaction on the engine pressure vessel during system ejection and to limit the ejected mass to as few packages as possible. Special emphasis is being placed on limiting the amount of residual mounting hardware permanently attached to the engine to a minimum in order to eliminate possible localized areas of high temperature on the activated engine.

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Figure 37
Mark A ACDS Ejection; Concept 1

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Figure 38
Mark A ACDS Ejection; Concept 2

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Figure 39
ACDS Mounting and Ejection Concept

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Figure 40
Ejectable Mark D ACDS

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Some basic ejection modes under investigation are:

- (1) MDF located in grooves on mounting flanges with necked-down bolts holding the destruct components. Initiation of the MDF severs the bolts, effecting sympathetic separation and ejection.
- (2) Ejection spring, or springs, held under compression by explosive bolts or a combination of necked-down bolts with MDF in grooves on bolt-down lugs. Initiation of the explosive bolts or of the MDF allows the springs to eject the separated destruct components.
- (3) Heavy leaf springs attached to components and held under tension by cable harnesses with explosive bolts or explosive turnbuckle connections. Initiation of either the bolts or the turnbuckles allows the leaf spring to eject the destruct components.
- (4) Rocket motors attached to the destruct package. Initiation would effect withdrawal of pins, causing separation of the destruct components. The rocket motor would pull the components away from the engine.
- (5) Compressed-gas cylinders or other devices effecting separation and ejection.

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- (6) Fusable linkage which would break due to spring loading when walls of pressure vessels are heated by engine operation. Loaded springs or triggering of explosive charges would then provide the necessary ejection force.

9. Emplacement and Integration

A typical installation of the ACDS Mark A concept is shown in Figure 29. This concept is based on the use of compression springs to effect ejection. The system has been divided into four sections to allow the sections of the upper curvilinear shaped charges to clear the external plumbing and to effect a balanced ejection principle with the individual sections pivoting around their upper end. Two sections consist of longitudinal linear shaped charge, a 1/4 section of curvilinear shaped charge, and a conical shaped charge, all interconnected into a structural unit. The other two sections of 1/4 sections of curvilinear shaped charge and the longitudinal linear shaped charge with an extension on the lower end for the lower clamping band. The upper end of each module is lodged in a socket, or pivot housing, welded to the upper pressure vessel flange. A thrust stop attached to the longitudinal member at the lower pressure vessel flange is provided for reacting the forward and aft linear acceleration loads. The four sections are held against the engine pressure vessel by an upper and a lower spring-steel clamping band.

The upper band is located on top of the upper ring of curvilinear shaped charges and the lower band is located at the end of the conical shaped charges. With the system installed, the compression springs located in housings adjacent to the linear shaped charge just above

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the lower engine flange are compressed, storing the energy required for ejection. Each clamping band has one separation point made up of two explosive devices for redundancy purposes. At the moment these separation points are broken, the ejection springs will force each destruct section in a radial direction away from the engine with each section pivoting around its upper end. Each clamping band will be attached to the destruct section opposite the band separation point to effect removal of the band from the engine. The bands will flex open and slip under the external plumbing as they are carried away by the ejected section.

The elimination of the upper clamping band would result in an optimum mounting and ejection arrangement by eliminating problems that might be encountered during ejection of the upper band. However, preliminary stress and vibration analyses indicate that the long unsupported longitudinal members cannot be sized, within reason, to sustain the loads induced by their own weight plus the concentrated loading from the curvilinear shaped charges under the specified load conditions. Therefore, the upper clamping band would need to be retained.

To overcome some of the vibration problems, it is tentatively proposed that the longitudinal member be prestressed; i. e., the member is designed with a slight bow so that it will be pressed against the engine pressure vessel in the installed condition. This condition will, in effect, result in a continually supported member with the frictional forces developed serving to repress tangential loads. The prestressed condition will also repress some of the loads normal to the pressure vessel. As can be seen in Figure 29, the emplacement of a Mark A system of this presently contemplated configuration requires

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a minimum of engine modification. The only major modification required is the addition of the four socket lugs on the upper engine flange. However, one interference problem exists in that the instrumentation bosses and fittings located on the engine pressure vessel (Aerojet Drawing 283094) are directly in line with the longitudinal linear shaped charges and support members. It is therefore recommended that these bosses and fittings be relocated.

The emplacement and integration aspects for the Mark D (and Mark J) bifunctional systems are essentially the same as for the Mark D PODS. This has been discussed previously in detail in the Milestone 30 report.*

10. Parametric Trade-Off

Any one of the candidate destruct systems has certain advantages and disadvantages which have to be taken into consideration in the selection of the most feasible system. The purpose of the parametric trade-off is to evaluate and analyze these various conditions, resulting in the elimination of those least promising systems and the selection of one ejectable ACDS and one bifunctional system for possible future development. From data derived from the ACDS explosive feasibility tests to date it has been concluded that the Mark A and aft-entry Mark D concepts have produced the best core dispersion results for an ACDS, with the Mark D and Mark J concepts indicating the best results for a bifunctional destruct system application. Therefore, the following parametric trade-off evaluation will deal only with those systems.

* Milestone 30 report - REON report RN-S-0033

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a. Ejectable Mark A ACDS

Mounting and ejection provisions for the Mark A ACDS will create some problems since the system surrounds the engine pressure vessel with the vertical components extending from the circumferential upper linear shaped charges the length of the reactor core. In addition, supports must be provided for the conical shaped charges located on the nozzle cone. Since mounting lugs or bosses on the pressure vessel are undesirable, the system will either be supported on the lower engine flange or be suspended from the upper flange.

Such mounting methods are disadvantageous from a dynamic standpoint in that the members will be unsupported over long spans. This is especially true if the longitudinal shaped charges would require either special design or special mounting methods to sustain the acceleration and vibration loads. However, it appears that solutions to these problems can be readily resolved.

The destruct components must clear the engine's external plumbing lines during ejection. To accomplish this, the upper linear shaped charges will either be broken at these clearance points or be oriented so that the members will slip out from under the lines when ejected. The latter may require segmenting the system into two or more parts. This, in turn, may necessitate several separation points, and consequently, a segmented initiation train. The basic jettison principle will probably be effected by storing the required energy in tension or compression springs. The jettison reaction forces will be taken up by the engine pressure vessel as close to the lower (or upper) engine flange as possible. Preliminary investigations indicate that the resultant loads to the pressure vessel are of permissible magnitudes.

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Although this system has some disadvantages, because it will be relatively bulky and its components will extend over the entire pressure vessel, it has a desirable feature in that the members fit closely to the pressure vessel and are mounted in the destruct position, thereby reducing the response time to a practical minimum. A system arranged in this manner is much less susceptible to damage from a collapsing interstage structure than a system with either large protrusions or a greater standoff from the engine. The total system weight is one of the lowest of all candidate systems and the system reliability is favorable. In an overall rating, the Mark A system is considered to be the most promising ejectable ACDS.

b. Ejectable Mark D ACDS

Based on preliminary investigations, the Mark D system appears favorable because of its compact design and its ability to be positioned alongside the nozzle cone and skirt; however, its compactness and relatively high, concentrated weight create problems in mounting and ejection. Since a minimum number of mounting and separation points are desired, the concentrated loads become relatively large at these points. In addition to designing the support members to handle the specified g-loading, vibration loads, etc., consideration must be given to the loads imposed upon the supports during an actual firing of the system's projectile. Although it is not intended to devise the supports to take the total recoil load, they must be sufficiently rigid to maintain the launch tube in the desired orientation until the projectile has started to penetrate the target.

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Further evaluation may indicate a launch-tube assembly of recoilless configuration will be superior to a closed breech configuration. Both methods are effective. However, tests conducted to date indicate that the recoilless concept is probably more practical from the standpoint of design simplicity and total system weight.

Investigations will be conducted to determine the propellant composition needed to obtain necessary projectile velocities consistent with the gun design. For the case of initiation and fast rise-times, it has been found that mortar propellant is probably best; however, due to the high brisance of this pyrotechnic composition, the quantity needed to propel the projectile at the required velocity may not be compatible with gun designs.

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: (1) inclination of target impact, (2) target composition encountered, (3) penetration depth, and (4) permissible deflection during insertion.

A relatively strong ejection force will be required because of the concentrated mass at the outer end of the launch-tube assembly. The design of the nozzle cone and skirt is such that little or no external forces can be exerted on this assembly or damage will occur. It will, therefore, be necessary to devise the ejection mechanism so that these forces are transmitted to reinforced areas as the lower pressure vessel flange. However, this may require overly intricate devices that are not desirable from a reliability or mechanical feasibility standpoint.

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In a minimum-redundancy system, one launch-tube assembly is employed, making the location and interference problems minimal. Although some degree of vehicle imbalance is expected, relocation of a few engine components should adequately compensate for the contributions of the destruct system.

The ejectable Mark D system is considered to be quite vulnerable to damage in the event of adjacent superstructure failure since it protrudes beyond the engine's lateral envelope. The possibility also exists that the launch tube will extend beyond the nozzle skirt (longitudinal envelope), which is objectionable for several reasons; e. g., greater load on gimbaled assembly, vibration problems, etc.

In addition to the undesirable features just discussed, the Mark D system exhibits relatively long response times, and lower levels of reliability. Although the explosive feasibility of the Mark D system is very good, considerable design innovations will be necessary to devise a feasible system. The conclusion reached is that the Mark D system is not too well suited as an independent, ejectable ACDS; however, the system is advantageous when employed as an integral part of the forward-implanted bifunctional destruct system. Further evaluation and analysis will be conducted on this system in an effort to reduce objectionable interrelationships in its application as a bifunctional destruct system.

c. Mark D and Mark J Bifunctional Destruct Systems

Because of the similarity in function of the Mark D and the Mark J bifunctional destruct systems and the fact that sufficient empirical data for these systems have not been established at this time, it

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would be unwise to consider one as being superior to the other. Basically, the same type of launch-tube and projectile assemblies will be used on the Mark D and Mark J bifunctional systems as on the aft-entry, ejectable Mark D ACDS. However, they do utilize projectiles of larger caliber and longer length, as previously discussed. When the ACDS is also used as a part of a bifunctional destruct system, consideration must also be given to the requirements for radiation shielding and cryogenic cooling. The possible deleterious effect of radiation on the Mark J system shaped charge explosive motivated a limited program to determine the feasibility of using a lead conical liner to shape the charge. Since the use of lead cones has been demonstrated to be feasible, it should be possible to reduce the additional shielding requirements and increase the effectiveness of the shaped charge. Investigations were made of 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. From these tests, the shaped charge configuration has been established, and certain refinements have shown that a significant reduction in explosive quantity is possible without sacrificing performance.

Inasmuch as the arrangement of the launch tubes will be practically the same for both the Mark D and the Mark J bifunctional destruct systems, it will be unnecessary to evaluate the advantages and disadvantages of each system in detail. The Mark D bifunctional system appears favorable because its fewer components offer a relatively compact design and fewer mounting problems. In contrast, the Mark J system with its shaped charge housing at its end will be more difficult to integrate due to the limited space available around the outer periphery of the pump housing and control drum actuators. However, the Mark J system is advantageous in

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that lower projectile velocities are required which, in turn, allow shorter launch-tube lengths. The total system weights are comparable, and therefore, factors such as performance, initiation reliability, response time, etc., will in all probability be decisive in determining the optimum system.

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G. DESTRUCT SYSTEM FUNCTIONAL RELATIONSHIPS

The purpose of this study is to evaluate the technical and operational relationships between the destruct system and the NERVA engine.

The preliminary review to determine the flight-test instrumentation required for ACDS and bifunctional destruct systems has been completed. A listing of the anticipated instruments and their range or function is presented in Table 15. The type and the number of instruments required were based on the following assumptions: (1) diagnostic and control inputs only, (2) minimum redundancy, and (3) independent CFS for ACDS and bifunctional destruct system, as applicable.

1. NERVA Engine Destruct System Integration Considerations

The ACDS integration with the NERVA engine will, to a great extent, depend upon the sequencing and ejection mode ultimately used. The destruct systems designed for ejection after stage separation will be either clamped to or attached to the engine. It is anticipated that it will be necessary to provide some mounting lugs, or their equivalent, for support of these systems. Presumably these will be located on either the upper or the lower engine flange. Also, support rods or cables located near the base of the fuel tank superstructure may be required. The external plumbing on the engine offers some interference to ejection; however, it is anticipated that this problem can be overcome through proper mechanical design. No major structural modifications to the engine are anticipated for ejectable ACDS installation.

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Instruments	Quantity	System	Range or Function	Use
Temperature sensors	12	Bifunctional	226° - 846°R	Explosive or casing temperature
	2 to 4	Bifunctional	226° - 700°R	Cryogenic loop and shielding
	24 (max)	Bifunctional	226° - 672°R	Electronic components
Pressure transducers	6	Bifunctional	0 to 30 psia	Combustion chamber - gun (gas evolution)
	6 to 12	Bifunctional	0 to 30 psia	Shaped charge (gas evolution)
	2	Bifunctional	0 to 680 psia	Cryogenic loop
Strain gages	6	Bifunctional	0 to 1×10^{-3} in./in.	Projectile casing
	12	Bifunctional	0 to 1×10^{-2} in./in.	Launch tube and support structure
	8	Bifunctional	0 to 1×10^{-3} in./in.	Cable conduit or harness
	8 (max)	ACDS	0 to 1×10^{-3} in./in.	Casing and support structure
	12	ACDS	0 to 1×10^{-3} in./in.	Cable conduit or harness
Position or event sensors	6	ACDS	Make or break circuit	Successful ejection
	1	ACDS	0 to 10,000 ft	Distance prior to disposal (ranging radar)
	6	ACDS	Radar pickup	Successful disposal
	6	Bifunctional	± 1 in.	Projectile position in launch tube
	6	Bifunctional	Make or break circuits	Launch-tube translation, if aligned with linkage
	16 (max)	ACDS	Make or break circuits	SAFE and ARM
	24 (max)	Bifunctional	Make or break circuits	SAFE and ARM
	16	ACDS	Make or break circuits	Continuity and breakway
	24	Bifunctional	Make or break circuits	Continuity
	16 (max)	ACDS	0 to 17 v dc 0 to 150 ma	Monitor capacitor charge
	24	Bifunctional	0 to 17 v dc 0 to 150 ma	Monitor capacitor charge

Table 15
Flight-Test Instrumentation

The bifunctional destruct systems will require greater integration. To date the Mark D and Mark J concepts appear best suited for bifunctional capability. The launch-tube assemblies on the PODS portion of the bifunctional Mark D and Mark J concepts will require placement through the upper and lower thrust structure. These tubes should be located as close as possible to a vertical position so that the spatial distribution of implanted explosive projectiles will be such as to effect maximum fragmentation of the reactor core. Due to the required length of the launch-tube assemblies, they will also extend above the base of the fuel tank superstructure. Investigations are being conducted to ascertain a method of avoiding this by increasing the insertion angle; however, such an increase, in turn, will entail inefficient explosive application due to diagonal insertion and focal implantment of the explosive charges near the center of the core. Compensating increases in explosive quantity to produce equivalent fragmentation and dispersion performance may not be feasible.

2. CFS Integration

The CFS integration with the NERVA engine may be achieved by one of two basic arrangements: (1) all ACDS CFS electronics installed adjacent to the engine, and (2) All PODS CFS electronics installed in Zone II.

The first arrangement requires electrical cable junction boxes and connectors for: (1) the control cable extending from the destruct relay box in Zone II, and (2) the firing-cable harness installed around the engine. Breakaway (jettison) plus separation of a multiple connector to the mounting system should consist of separation of the 3-wire control-cable connector at its junction box receptacle as described previously, plus separation of a multiple connector to the monitoring system.

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For the second arrangement, individual breakaway connectors will have to be provided for each of the high-voltage firing cables leading to the detonators on the destruct system and the jettison charges.

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H. OPERATIONAL SAFETY CONSIDERATIONS

There are several operational safety requirements that must be considered prior to the selection of the ACDS and the mounting, ejection, and initiation arrangements ultimately employed. For purposes of this discussion, the basic mission is divided into three zones: launch, boost (powered flight), and stages separation, during which these critical conditions could occur.

The safety of an ACDS is concerned not only with the assurance that the destruct system is capable of destroying the reactor during a malfunction; it is also concerned with precluding the occurrence of a premature initiation of any destruct system component which would result in an abortion of the flight. The prevention of premature initiation of an explosive charge is achieved by exclusion from the charge of any energy capable of causing detonation. This is achieved, primarily by the control and firing system which incorporates several safety provisions. One possible control and firing system considered for the NERVA ACDS is based on EBW type initiators which requires that the initiator receives a large quantity of electrical energy before initiation occurs. This permits launch pad check-out of control pad firing circuits using standard test instruments. It is also relatively invulnerable to other sources of voltage in common usage (i.e., 115 vac). The possibility of premature initiation from powerful sources of RF energy (radar, etc.), which has occurred in the past with "hot wire" detonation, is also precluded when an EBW detonator is used.

The destruct systems should be armed prior to the fueling of the vehicle if the ACDS is to be operational on the launch pad. This is recommended in the event that a fire, structural collapse of the vehicle,

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or other malfunction occur during the fueling operation. In addition, should a destruct system initiating malfunction occur during its arming procedure, resultant uncontrolled exposure of the fuel elements to a moderating material could conceivably present a serious nuclear incident. In the event of structural collapse and subsequent explosion or fire on the launch pad prior to fueling, it may be preferred either to destroy or to eject the NERVA engine destruct packages while leaving the reactor relatively intact, thus minimizing the area decontamination problem. In this case, supplementary circuits and devices may be necessary to subvert the destruct package in a manner different from normal operation. To minimize the probability of jet formation, shaped charges should be re-oriented and initiated normal to their intended use, and, should ejection be desired, mechanisms providing removal through the interstage structure would be required.

During fueling, launching, and chemical stage operations, initiation of the stage propellant-dispersion systems subsequent to failure could allow unconfined burning of the large mass of fuel and oxidizer near or surrounding the reactor. If the thermal environment of the core material is below the peritectic dissociation temperature of the fuel particles, the hazards of air pollution in such a situation will be minimal. In thermal environments in excess of this value, the particles will be in a molten state but will be retained within the graphite matrix. The work performed by the Los Alamos Scientific Laboratory indicated negligible loss of uranium from fuel elements heated to this temperature for a number of minutes. However, because of the uncontrolled environments existing within a massive chemical booster-engine fire, no reasonable assurance of reactor-core survival can be given, and initiation of the ACDS might be necessary at the outset of such a conflagration.

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Circumstances could dictate the immediate use of the destruct system before an explosion of the first stage (booster), or before the destruct system is rendered inoperable by interstage structural collapse.

In this case, a system such as the Mark A attached directly to the engine would be less vulnerable to mechanical damage than any ACDS attached to, or supported by, the second stage or in the interstage structure, since partial collapse or local failure of the structure could seriously affect such a system's alignment and function. Also, the Mark A concept, closely integrated with the engine, would not be as susceptible to damage from neighboring parts of a collapsing interstage structure as a system based upon the ACDS Mark D concept because of its lesser bulk and smaller protrusions beyond the engine's envelope.

To ensure optimum reliability, a separate command receiver and CFS may be required within the interstage structure, located in such a manner that the likelihood of damage being imparted to these units will be held to a minimum. Destruct system initiation may be necessitated by any one of several modes of failures. Additional probes to monitor performance and to detect malfunctioning in the destruct component package should be employed. Probes to monitor successful events such as arming, etc., will also be a mandatory requirement in flight. In a bifunctional system, initiation of the ACDS with delayed destruction of the PODS may be a requirement to minimize the probability of an over-kill with subsequent fragment dispersion complications if excessive fragmentation and dispersion is considered detrimental to launch-complex decontamination procedures. Alternately, delayed initiation of the remaining PODS projectiles within their launch tubes during ACDS operation (bifunctional system) may result in better blast energy coupling

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effects within the interstage structure and eliminate the need for interstage removal by special systems provided by the RIFT contractor.

Ejection of ACDS destruct charges early in the NERVA engine startup may be necessary to preclude inadvertent destruction of the engine due to the possible deleterious effects of reactor radiation upon explosives. Studies are being made to predict how long the ACDS could remain attached to the pressure vessel before becoming hazardous. Complications in ACDS ejection during nuclear-stage separation might arise in the event of a separation malfunction. It is possible that the destruct system might be initiated or damaged, while in an armed condition, by impact with, or by applied loads from, the separating structural mass. Although fragment dispersion beyond the Atlantic shelf should not create any serious radiation problems, successful ejection and destruction of the ACDS should be accomplished to eliminate the possibility of damage from the detonating of shaped charges oriented toward the nuclear stage during ejection and disposal of ACDS explosives. Also, it is anticipated that the jet blast of an initiated conical shaped charge could, if properly oriented, cause serious damage to the NERVA engine at distances up to 5000 ft. It will, therefore, be necessary to arrange the postejection destruct devices either so that initiation does not occur within that distance or so that the charges are properly oriented and their point of initiation is at a desired distance prior to self-destruct.

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