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QUANTITATIVE UNDERSTANDING OF EXPLOSIVE STIMULUS TRANSFER

by M. L. Schimmel

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16. Abstract

THE PURPOSE OF THIS STUDY WAS TO DEVELOP AND DEMONSTRATE AN UNDERSTANDING OF THE MECHANISMS OF DETONATION TRANSFER ACROSS HERMETICALLY SEALED INTERFACES CREATED BY NECESSARY INTERRUPTIONS IN HIGH EXPLOSIVE TRAINS, SUCH AS AT DETONATORS TO EXPLOSIVE COLUMNS, FIELD JOINTS IN EXPLOSIVE COLUMNS, AND COMPONENTS OF MUNITIONS FUSE TRAINS. RELIABILITY OF DETONATION TRANSFER IS LIMITED BY MINIMIZING EXPLOSIVE QUANTITIES, THE USE OF INSENSITIVE EXPLOSIVES FOR SAFETY, AND REQUIREMENTS TO PROPAGATE ACROSS GAPS AND ANGLES DICTATED BY INSTALLATION AND PRODUCTION RESTRAINTS. THE MAJOR DETONATION TRANSFER VARIABLES STUDIED IN THIS PROGRAM WERE: EXPLOSIVE QUANTITY, SENSITIVITY, AND PARTICLE SIZE, LOADING DENSITY, CONFINEMENT, CLOSURE MATERIALS, AND THICKNESSES, AND THE SEPARATION DISTANCES BETWEEN DONOR AND ACCEPTOR EXPLOSIVES.

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QUANTITATIVE UNDERSTANDING OF EXPLOSIVE STIMULUS TRANSFER

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SUMMARY

The primary objective of this test program was to answer the fundamental question: "How is detonation transfer accomplished?" This information is needed to optimize initiation designs for such critical applications as staging, structural severance, escape systems, and explosive trains.

Five different explosives and two basic donor and acceptor configurations were evaluated. Three of the explosives and the donor/acceptor designs were selected because of their extensive aerospace usage. The remaining two acceptor explosives were included to extend the range of sensitivities tested. The donor design variables studied were size, confinement, closure material, explosive quantity and explosive compaction pressure. Changing these parameters controlled the amount of energy in the donor closure fragments and in the gaseous detonation products. The effect on detonation transfer was studied by adjusting the separation air gap between donor and acceptor, and also by varying five acceptor parameters. These were: explosive sensitivity, particle size, closure thickness, closure density, and confinement. For each configuration tested, an approximate 50%-fire point was determined. From these data the following detonation transfer principles are indicated:

(1) The amount of energy supplied by a donor, compared to that required by an acceptor for initiation, determines whether detonation transfer takes place.

(2) Donor energy sources are high-velocity closure fragments, gaseous detonation products, or a combination of the two. Experimental methods developed for measuring donor energy are described.

(3) Energy reaching the acceptor explosive is reduced with increases in air gap, acceptor closure thickness, or density. These parameters attenuate gaseous energy more severely than fragment energy.

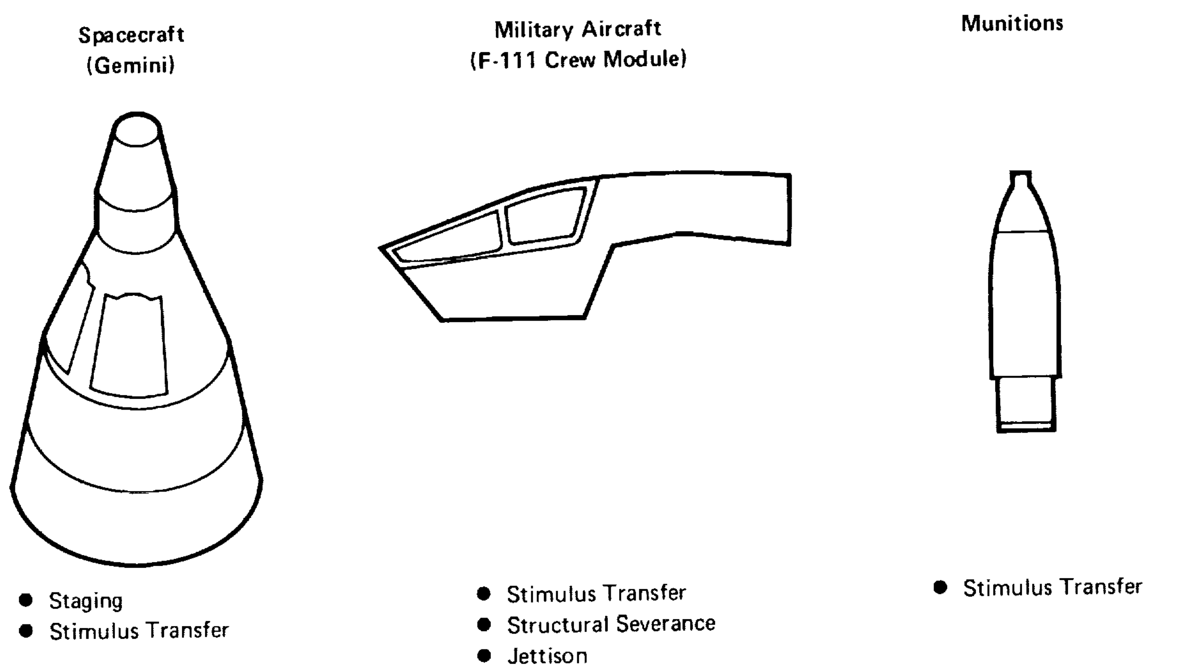
(4) Initiation energy requirements of acceptor explosives are indicated by gap test sensitivity results.

INTRODUCTION

This program, "Quantitative Understanding of Explosive Stimulus Transfer (QUEST)," sought to provide data which are basic to the use of high explosives in spacecraft and military aircraft, or as part of an explosive train. Examples of these applications are given in Figure 1, and include staging, stimulus transfer, structural severance, and jettison. Initiation of all of these functions is normally accomplished by means of a detonator separated by an air gap from an explosive acceptor. For most flight applications, successful initiation is compromised by the requirements to:

(1) minimize the quantity of explosives used
(2) ensure handling safety by employing relatively insensitive explosives
(3) provide environmentally protected assemblies
(4) propagate over gaps and at angles dictated by installation and production restraints

FIGURE 1 APPLICATIONS OF DETONATION TRANSFER



Despite the critical uses of aerospace explosive systems, and the untold millions of explosive trains that have been built, tests of detonation transfer have been confined primarily to empirical measurements for determining whether a proposed design is sufficiently reliable for the intended use. While these measurements do not provide the kind of information needed to optimize designs, they have generally resulted in flightworthy hardware. Thus, the limitations of currently used methods are described merely to illustrate the problem for which this program sought to provide better understanding.

The most common method of demonstrating reliability of detonation transfer involves testing at gaps greater than permitted by actual installation, with analysis by the Bruceton technique (ref. 1). Another approach to the problem is the VARICOMP technique developed at the Naval Ordnance Laboratory, White Oak, Maryland (ref. 2). In this method, production geometry is maintained during testing, but explosive output or sensitivity is varied. A statistical analysis is then performed to determine probability of propagation. Both tests are conducted in such a manner that propagation failures are expected. These failures are treated statistically as caused by being fired over too large a gap, or at too insensitive an acceptor. As a result, a marginal donor, which should be cause for lot rejection or design modification, may be missed. This is a serious deficiency from the standpoint of aerospace applications where relatively few tests are conducted because of high unit cost, and yet extremely high reliability is required. A more basic shortcoming of these methods is that they do not disclose the precise reason for failing to initiate detonation. Thus, they do not clearly point the way to better designs.

The only military standards dealing with detonator output involve dent tests (ref. 3). While the stated purpose is "---to measure output and check uniformity of performance---," they do so only with respect to gaseous detonation products. These tests do not measure the effect of the detonator closure. With respect to accomplishing detonation transfer, the energy available from closure fragments was shown to be significantly greater than that from gaseous detonation products for all donor configurations tested in the QUEST program.

The specific design variables studied during this program are illustrated

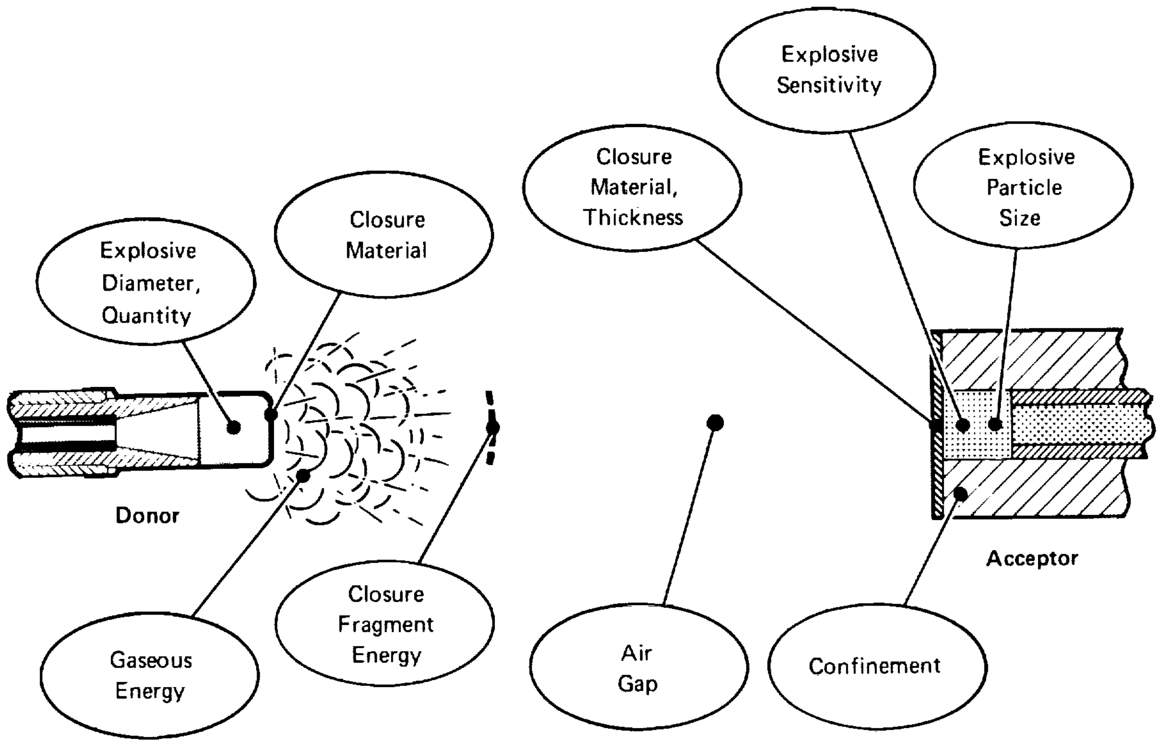


FIGURE 2 VARIABLES STUDIED

in Figure 2. The initial approach was to measure velocity of donor closure fragments, compute the pressure that would be induced in an acceptor explosive, and compare this value to the pressure known to be required for acceptor initiation from Small Scale Gap Test (SSGT) results (ref. 4). This test measures the sensitivity of an acceptor in terms of the thickness of polymethyl methacrylate that can be interposed between it and a standardized, precisely controlled donor, and still accomplish detonation transfer. The greater the thickness of plastic, the lower the pressure that reaches the acceptor. Originally, acceptor sensitivity was reported in arbitrary units based on this thickness. More recently, this test has been calibrated so that results can be expressed in units of pressure (ref. 5), and such sensitivity values have been reported for most explosives of aerospace interest, (ref. 6).

Although it was recognized that the time of pressure application by the

SSGT would be exceedingly long in comparison to the application time for pressure generated by thin donor fragments, the significance of this difference was unknown. When the initial QUEST tests were run, it was learned that this difference was crucial. That is, even when the pressure calculated to have been induced in an acceptor explosive by donor closure fragments was substantially greater than that shown to be required by SSGT results, propagation did not take place. The reason for this apparent contradiction has been established by Walker and Wasley (ref. 7). They showed that the energy induced in an acceptor explosive is the critical parameter for initiation, not the pressure. Thus, for the initial tests with thin donor closure fragments, and the resulting short time of application, the amount of energy induced in the acceptor explosive was less than from the SSGT, even though the pressure was greater.

While the critical energy concept was developed based on experiments with very large driver plates and acceptor charges, test results show that this concept can also be applied to small explosive devices used for aerospace applications. Further, it appears that there is a relationship between critical energy of initiation and SSGT sensitivities for a wide range of explosives. Therefore, an estimate of the required initiation energy is available for most acceptor explosives. Thus, the QUEST program suggests a new approach to the problem of determining reliability of detonation transfer by measuring only donor parameters. These measurements of both donor fragment and gaseous product energy should also show how detonator designs can be optimized from the standpoint of output.

APPARATUS

All experiments were performed at the McDonnell Aircraft Company, Solid Propellant and Explosive Devices Test Laboratory. The apparatus consisted of donors and acceptors designed for investigation of specific parameters, explosives with a wide range of sensitivities, and test fixtures for determining propagation and donor fragment characteristics.

Donor Configurations

The two basic donor designs selected for this study are illustrated in Figure 3. The flight configuration type was chosen because of its widespread usage in aerospace programs, including Apollo, F-111 crew module, F-14, F-15, and B-1 escape systems. A simplified experimental configuration was used to obtain a lower-cost test part. The detonating cord consisted of 5.3 mg/cm (2.5 grains per foot) of hexanitrostilbene (HNS-II) in aluminum sheathing. Ferrule and output charges were HNS-I. The closure cup was 0.38 cm (0.15 inch) in diameter, and 0.010 cm (0.004 inch) thick stainless steel. An electric blasting cap was used to initiate the detonating cord. Upon detonation, the closure cup breaks into a predictable pattern of high velocity fragments. Details concerning development of this design are given in References 8 and 9.

The experimental configuration donor, also shown in Figure 3, was used to permit design parameters to be varied more easily than with the cup configuration. Because the output charge was loaded into a brass bushing, it provided more confinement than the cup configuration. The bushing was 1.91 cm (0.75 inch) long, with an outside diameter of 1.27 cm (0.50 inch) and an inside diameter of 0.38 cm (0.15 inch). Since no ferrule charge was used, the detonating cord size was increased to 42.4 mg/cm (20 grains per foot) of RDX in lead sheathing.

In order to obtain donors with different output levels, the cup configuration donor size was maintained, but the quantity and loading pressure of the explosive in the ferrule and closure cup were reduced, resulting in lowered fragment velocity. Loading pressure units are given in newtons per square centimeter (N/cm^2) as well as pounds per square inch. A summary of the

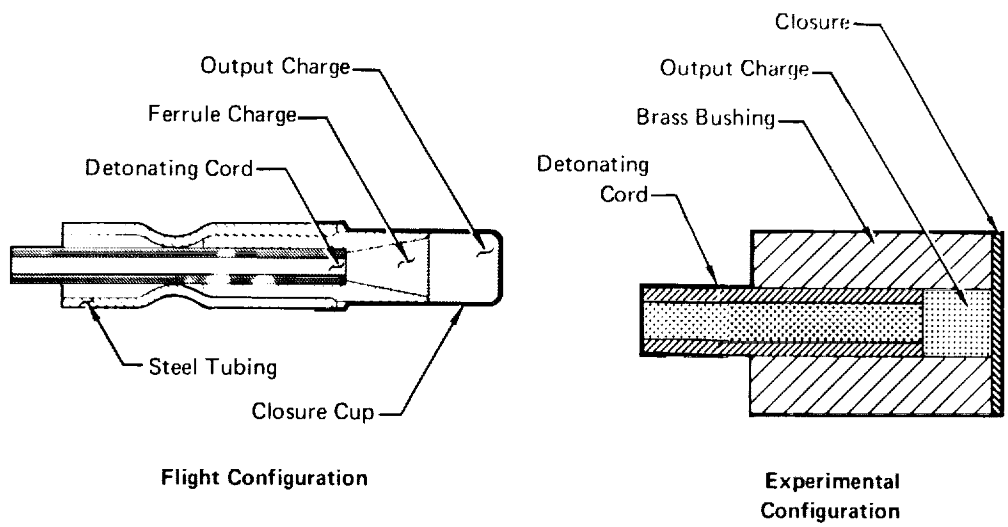


FIGURE 3 DONOR DESIGNS

performance of donor cup configurations is given in Table 1. The velocity of the cup bottom fragments was measured experimentally. Energy per unit area was calculated as:

$$\frac{KE}{A} = \frac{MV^2}{2A}$$

where

$\frac{KE}{A}$ = fragment kinetic energy per unit area

M = mass of fragments

V = measured fragment velocity

A = area of cup bottom

Acceptor Configurations

Acceptor designs, shown in Figure 4, are essentially mirror-images of the donors. Again, the cup design provided light confinement; the bushing configuration, heavy confinement and easier variation of design parameters. Both acceptor types used 42.4 mg/cm (20 grains per foot) of lead sheathed RDX detonating cord butted against the compacted acceptor explosive to provide a positive indication of acceptor detonation. The cup configuration contained 65 mg of explosive in a stainless steel cup which was 0.38 cm (0.15 inch) in diameter, and 0.010 cm (0.004) inch thick. For the acceptor with heavy confinement, the closure was bonded to the bushing prior to explosive loading. Except for the one series of tests in which size was varied, the acceptor contained 65 mg of explosive with a column diameter of 0.28 cm (0.15 inch).

Acceptor explosives.- Because acceptor explosive sensitivity was considered to be of major importance in determining detonation transfer probability, materials for which this information was available were procured from Naval Ordnance Laboratory, White Oak, Maryland. The listing of explosives in Table 2 illustrates the wide range of SSGT sensitivities investigated in this program. Photomicrographs of these explosives are shown in Figure 5.

TABLE 1 DONOR PERFORMANCE
(Cup Configurations)

Donor Group	Loading Pressure, N/cm^2 (psi)	Weight of HNS-I (±2 mg)		Cup Bottom Fragments	
		Ferrule	Output	Average Velocity, cm/μsec (ft/sec)	Average Energy/Area (cal/cm^2)
–1	22,000 (32,000)	37	63	0.276 (9040)	72
–2	11,000 (16,000)	32	57	0.263 (8620)	66
–3	5,600 (8,000)	28	50	0.244 (8000)	56
–4	2,800 (4,000)	25	44	0.203 (6640)	39
–5	1,400 (2,000)	22	39	0.189 (6200)	34
–6	700 (1,000)	19	37	0.175 (5750)	29

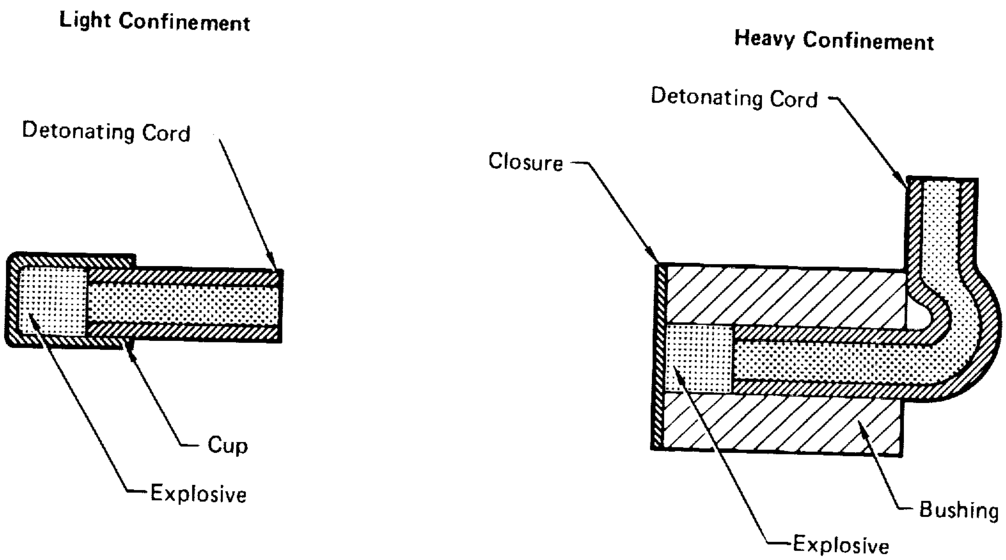


FIGURE 4 ACCEPTOR CONFIGURATIONS

TABLE 2 ACCEPTOR EXPLOSIVE SENSITIVITIES

Explosive	Naval Ordnance Lab Lot Number	SSGT Sensitivity (kbar) at 11,000 N/cm^2 Loading Pressure
RDX (Cyclotrimethylenetrinitramine)	189	11
HNS-II (2,2′, 4,4′, 6,6′ - Hexanitrostilbene)	528	15
HNS-I (2,2′, 4,4′, 6,6′ - Hexanitrostilbene)	537	21
DATB (1,4-Diamino-2,4,6-Trinitrobenzene)	315	39
TATB (1,3,5-Triamino-2,4,6-Trinitrobenzene)	398	74

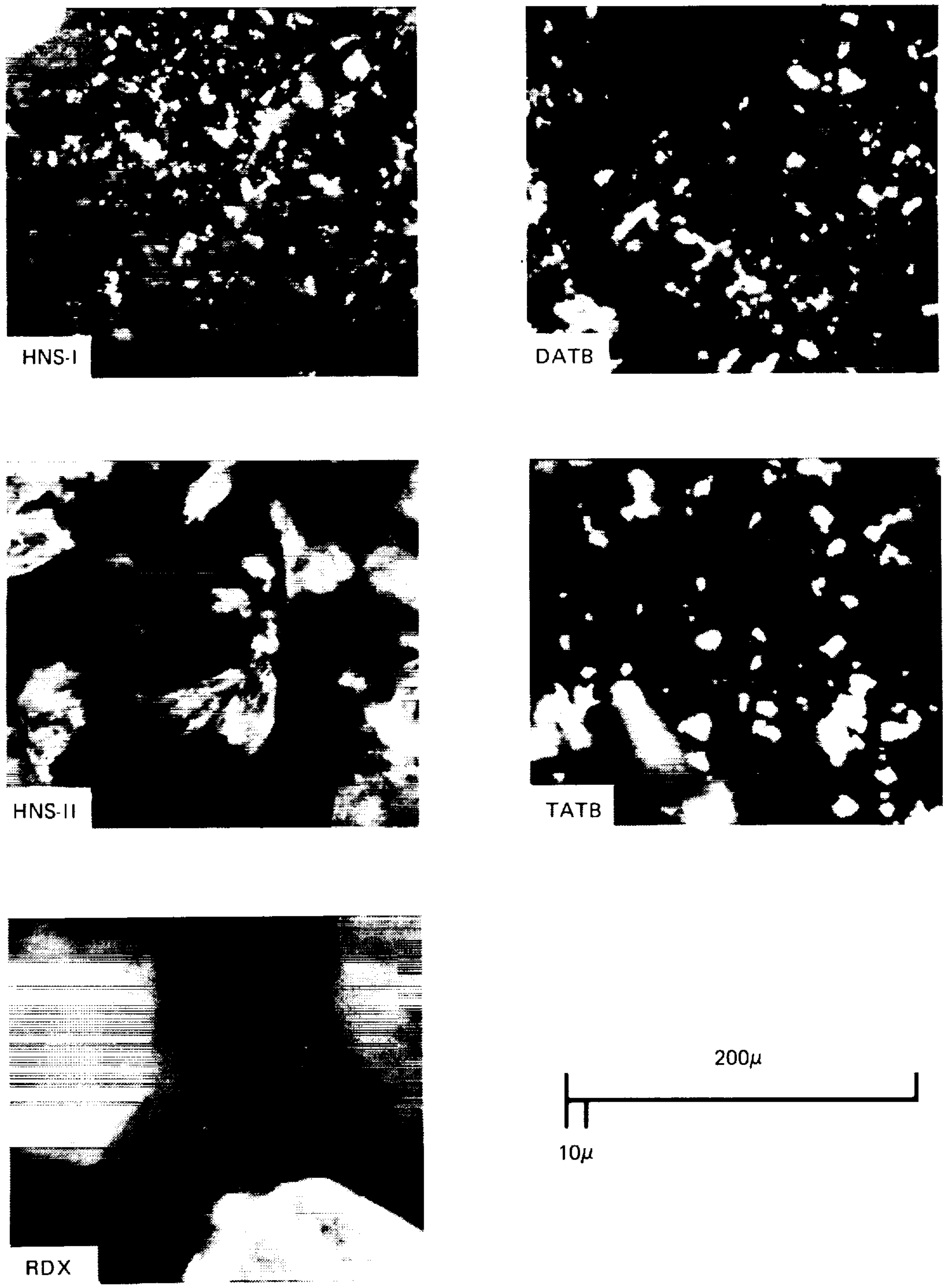


FIGURE 5 ACCEPTOR EXPLOSIVE PHOTOMICROGRAPHS

Test Fixtures

Proper alignment of donor and acceptor for propagation tests was accomplished with a Vee-block fixture, Figure 6. For simultaneous measurement of donor end and side fragment velocity, the test fixture illustrated in Figure 7 was used. The witness blocks were Lucite, and they provided an indication of fragment pattern, as well as a passive check (by the extent of crazing) on velocity measurements. Because it was found that foil switches would affect propagation results, it was necessary to develop the "partial-foil" switch shown in Figure 8. This switch is triggered by fragments at the outer edge of the pattern, and permits all of the center fragments to pass through unaffected. Figure 9 is a circuit diagram of the electronic instrumentation used in conjunction with the switches and the fragment velocity test fixture.

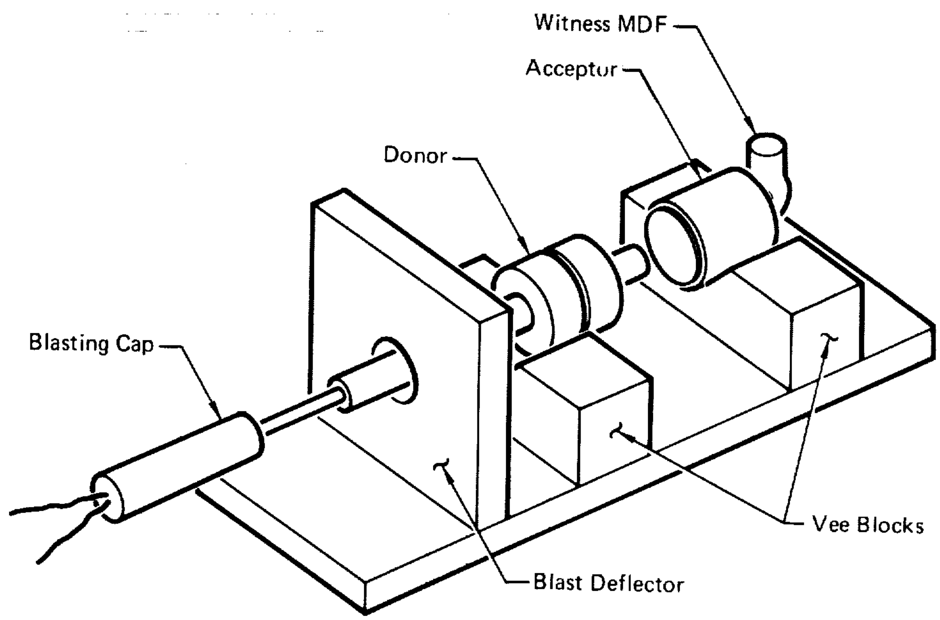


FIGURE 6 PROPAGATION TEST FIXTURE

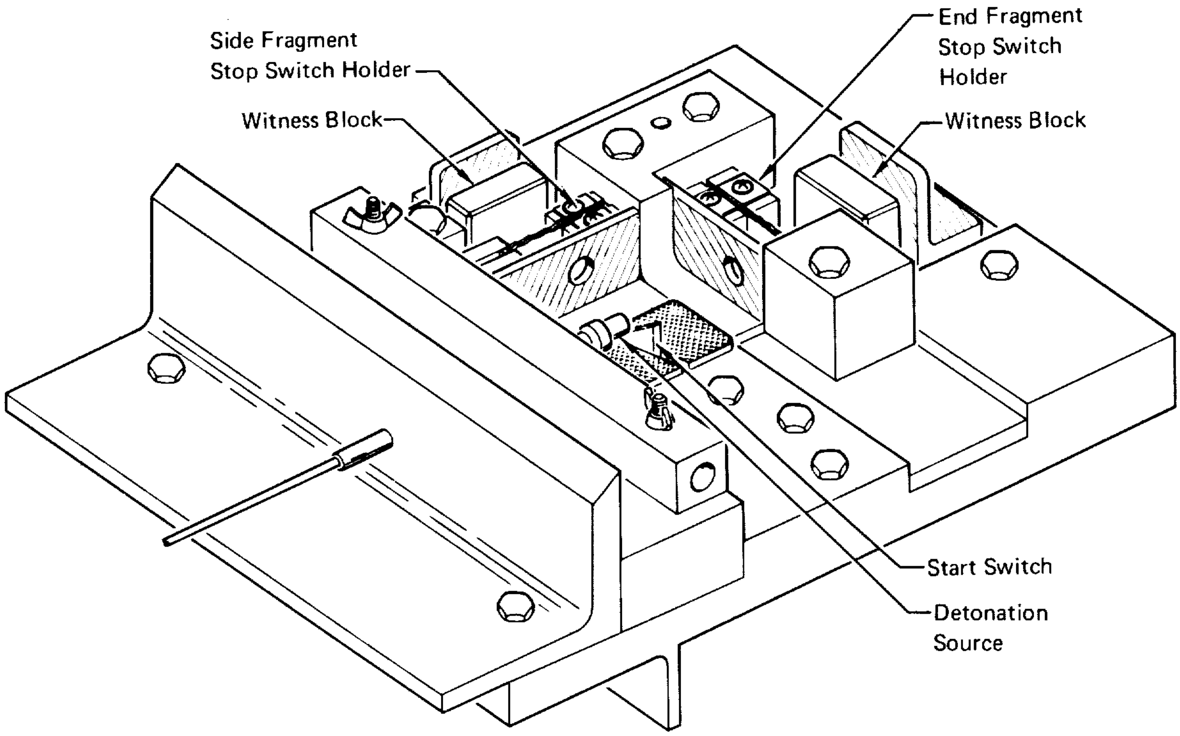


FIGURE 7 TEST FIXTURE FOR FRAGMENT VELOCITY MEASUREMENT

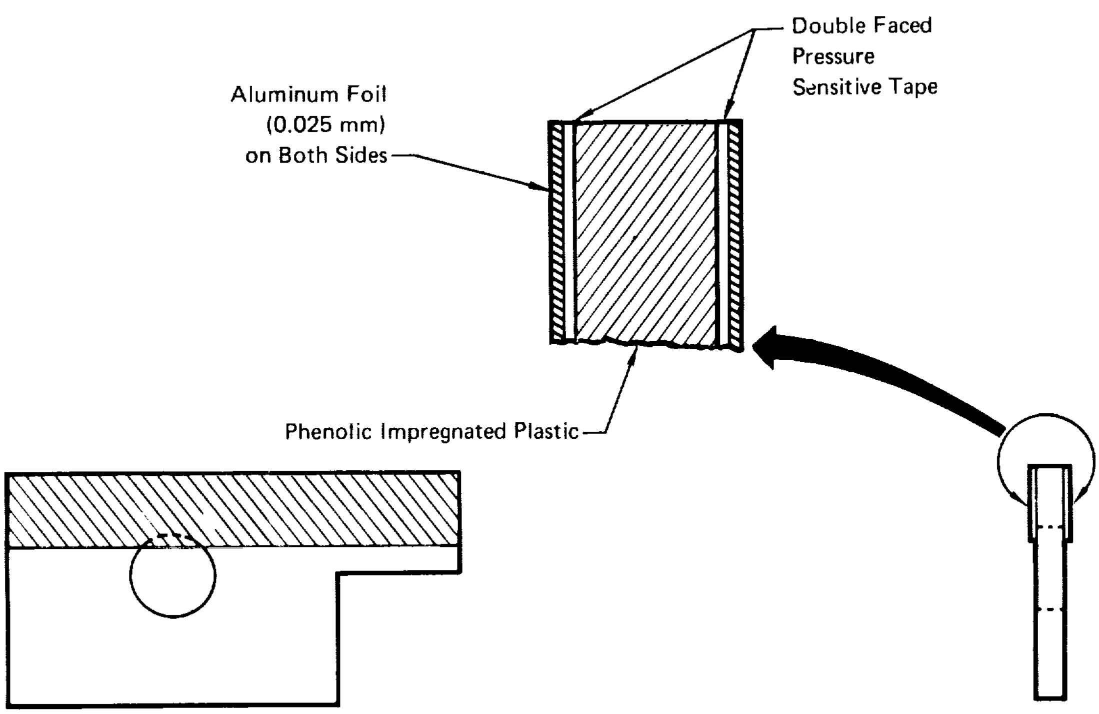


FIGURE 8 "PARTIAL-FOIL" SWITCH ASSEMBLY

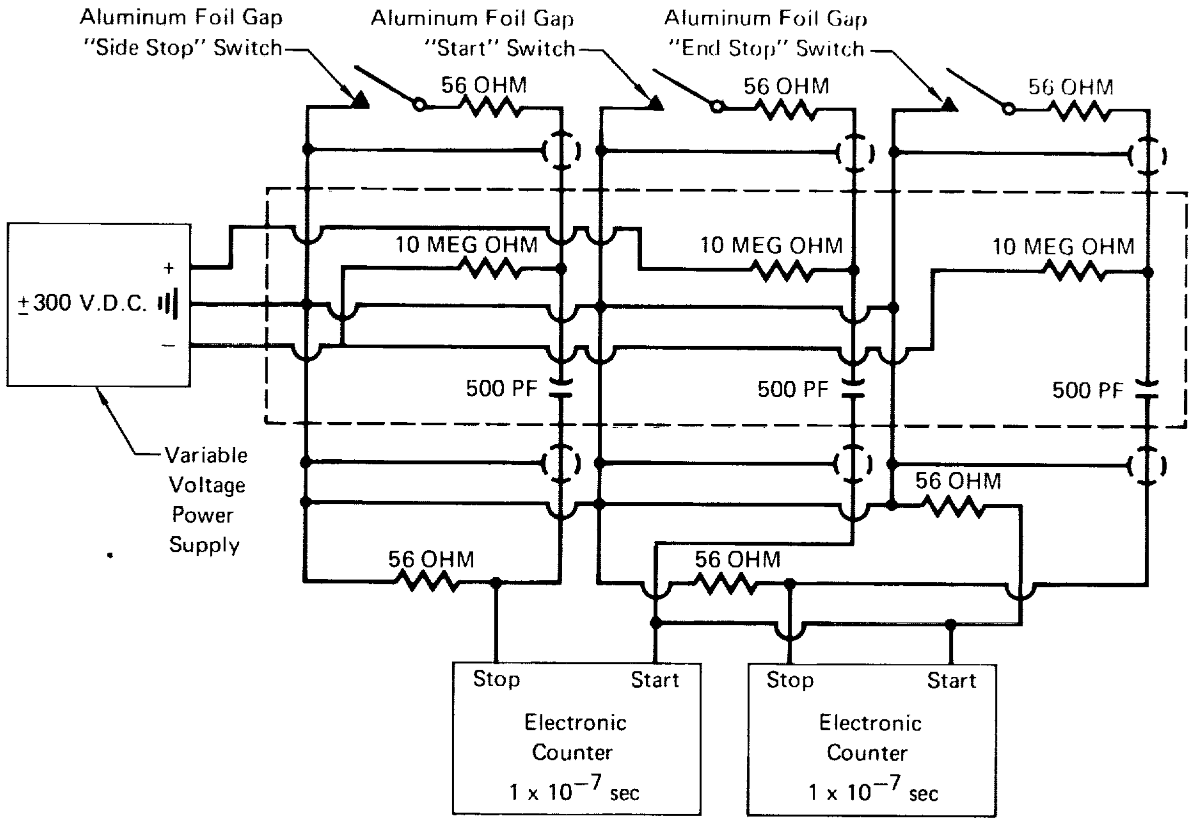


FIGURE 9 FRAGMENT VELOCITY MEASUREMENT CIRCUIT DIAGRAM

TEST PROCEDURE

Estimation of 50%-Fire Point

Because the objective of this program was to investigate a wide range of variables involved in detonation transfer rather than any specific design, a procedure was used which permitted determination of approximate 50%-fire configurations with relatively few tests, usually only four or five. For example, if the variable being investigated was air gap between donor and acceptor, a separation distance was selected for the first test. If successful propagation resulted, the gap was doubled for the next test; a propagation failure resulted in running the second test at one-half the separation gap. Successive tests were then conducted at gaps midway between the last success and failure. The approximate 50%-fire point reported is the mid-point between the smallest propagation fail gap and the largest successful propagation gap.

Donor Output Determination

Measurements were made of the effects of donor fragments alone, gaseous detonation products alone, or the combined effects of the two. This was accomplished by selection of air gap distance between donor and acceptor. For gaps of 1.27 cm (0.50 inch), or more, it was assumed that energy from gaseous products was negligible (tests later proved this assumption valid), and the acceptor was affected only by donor fragments. For those tests in which donor fragment velocity and propagation were measured simultaneously, it was necessary to use separation air gaps of as much as 7.62 cm (3.0 inches). This large a gap was needed to ensure that the stop switch was triggered by fragments rather than by detonation gases. Lucite impact patterns showed that donor fragments were not significantly dispersed in spite of this large gap. In order to measure the effect of gaseous energy alone, the bottom of the donor closure cup was cut off, or no closure was used on the bushing, thus eliminating end fragments. For measurements of the combined effects of donor fragments and gases, tests were conducted at a 0.38 cm (0.15 inch) air gap.

Experimental Conditions

Throughout the program, all experiments were performed at ambient temperature and pressure. All propagation testing was in open air; that is, while the fixture provided alignment, there was no confinement in the peripheral area between the donor and acceptor.

TEST RESULTS

This section presents results of experiments with donor/acceptor variables, and discusses both their theoretical and practical significance. A program summary is given by task, to show how the program developed, and to provide a convenient tabulation of results for each variable tested. Then, significant aspects from each phase, grouped as donor or acceptor variables, are mentioned. Finally, the results are discussed functionally based on the effect of donor high-velocity fragments, gaseous detonation products, and the combined action of both.

Throughout the tabulation and discussion, certain terms are used interchangeably; i.e., "propagation," "initiation," and "fire" all refer to detonation of the acceptor explosive as evidenced by initiation of the RDX detonating cord, and the resulting metal erosion. Also, the term, "shock initiation," is applied to those tests in which only the effect of donor gaseous detonation products was being evaluted.

Summary of Results

The information presented in Table 3 summarizes the results obtained in tasks 1 through 6 of Contract NAS 1-9903, and tasks 7 through 12 of Contract NAS 1-10762 in chronological order.

Donor variables.-

Fragment velocity (task 1): this series of tests used donors from the six groups listed in Table 1. Each of these donors was the same physical size, and all detonated. However, because the quantity and compaction pressure of the explosive was varied, donor output decreased in discrete increments between the upper (-1 donor) and lower (-6 donor) limits. Failure of fragments from a -1 donor to initiate TATB was contrary to expectations, based on a pressure comparison of SSGT sensitivity and that computed as induced by donor fragments. However, reducing the air gap between the donor and acceptor to 0.38 cm (0.15 inch), where gaseous energy was superimposed on fragment energy, resulted in

TABLE 3 TEST PROGRAM RESULTS SUMMARY

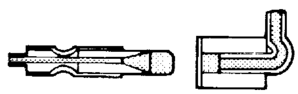
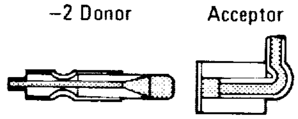
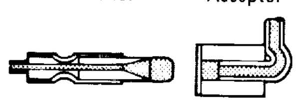
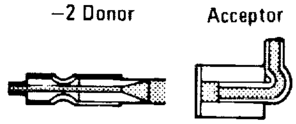
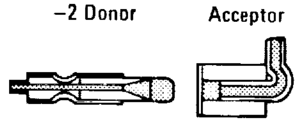
Task No. Variable	Test Setup	Results
1. Donor Fragment Velocity	Donor Acceptor 	1. Fragment energy alone, even from –1 Donor would not initiate TATB at 11,000 N/cm^2 2. At a 0.38 cm air gap, –1 and –2 Donors produced All Fires; –3 fired 1 of 5; –4, –5, –6 gave No Fires 3. Fragment energy alone from –2, –3, –4 Donors initiated DATB at 22,000 N/cm^2; –5 Donors gave No Fires
2. Acceptor Confinement	Donor Acceptor  Air Gap = 0.38 cm Acceptor Explosive: TATB at 11,000 N/cm^2	1. –1, –2 Donors produced All Fires, –3, –4 Donors gave No Fires
3. Acceptor Closure Thickness	–2 Donor Acceptor  Air Gap = 0.38 cm Acceptor Closure: Steel Acceptor Explosive: TATB	TATB Compaction Pressure (N/cm^2) / Approximate 50% Fire Acceptor Closure Thickness (cm) 11,000 .... 0.015 5,500 .... 0.020 2,800 .... 0.020
4. Acceptor Explosive	–2 Donor Acceptor  Air Gap = 0.38 cm Acceptor Closure: Steel	Acceptor Explosives 22,000 N/cm^2 Compaction / Approximate 50% Fire Acceptor Closure Thickness (cm) DATB .... 0.033 HNS-I .... 0.064 RDX 0.064
5. Acceptor Explosive Particle Size	–2 Donor Acceptor  Acceptor Closure = 0.010 cm Steel	Shock Initiation (Donor Cup Buttom Removed) Acceptor Explosive 22,000 N/cm^2 Compaction / Approximate 50% Fire Air Gap (cm) HNS-I .... 0.20 HNS-II 0.22
	–2 Donor Acceptor  Air Gap = 1.27 cm Acceptor Closure: Steel	Fragment Initiation Acceptor Explosive 22,000 N/cm^2 Compaction / Approximate 50% Fire Acceptor Closure Thickness (cm) HNS-I .... 0.064 HNS-II 0.028

TABLE 3 (Continued)
TEST PROGRAM RESULTS SUMMARY

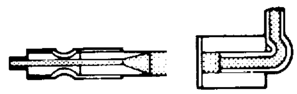
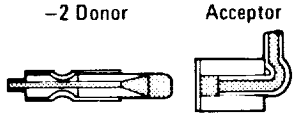
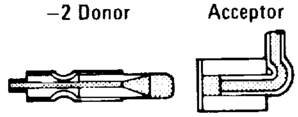
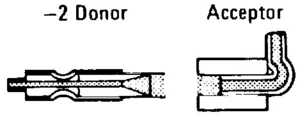
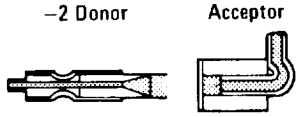
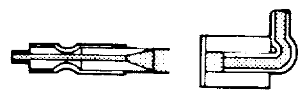
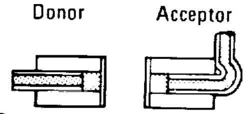
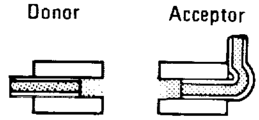
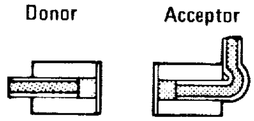
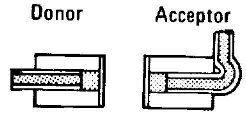
Task No. Variable	Test Setup	Results	
6. Acceptor Closure Materials	−2 Donor Acceptor  Acceptor Explosive: HNS-I at 22,000 N/cm^2	Shock Initiation (Donor Cup Bottom Removed)	
		Acceptor Closure Material and Thickness (cm)	Approximate 50% Fire Air Gap (cm)
		No Closure	0.356
		Aluminum, 0.028	0.240
		Lead, 0.036	0.048
	−2 Donor Acceptor  Air Gap = 1.27 cm Acceptor Explosive: HNS-II at 22,000 N/cm^2	Fragment Initiation	
		Acceptor Closure Material	Approximate 50% Fire Closure Thickness (cm)
		Lead	0.033
		Steel	0.028 (Task No. 5)
	−2 Donor Acceptor  Acceptor Explosive: TATB at 11,000 N/cm^2	Combined Shock and Fragment Initiation	
		Acceptor Closure Material and Thickness (cm)	Approximate 50% Fire Air Gap (cm)
		No Closure	1.04
		Aluminum, 0.028	0.35
		Steel, 0.010	0.51 (Task No. 1, −1 Donor)
7. Separation Air Gap	−2 Donor Acceptor  No Closure on Donor or Acceptor	Acceptor Explosive, Compaction Pressure (N/cm^2), SSGT Sensitivity (kbar)	Approximate 50% Fire Air Gap (cm)
		RDX at 22,000, 14	0.325
		HNS-I at 5,500, 20	0.649
		HNS-I at 22,000, 25	0.356 (Task No. 6)
		DATB at 6,900, 36	0.183
		TATB at 5,500, 53	0.086
		TATB at 11,000, 74	0.198
8. Acceptor Closure Thickness	−2 Donor Acceptor  Acceptor Explosive: HNS-I at 22,000 N/cm^2 Acceptor Closure: Steel	Acceptor Closure Thickness (cm)	Approximate 50% Fire Air Gap (cm)
		0	0.356 (Task No. 6)
		0.013	0.236
		0.020	0.112
		0.030	0.056
		0.051	0.008
		0.081	0
		0.013 (HNS-I at 5,500 N/cm^2)	0.427

TABLE 3 (Continued)
TEST PROGRAM RESULTS SUMMARY

Task No. Variable	Test Setup	Results	
9. Acceptor Closure Materials	−2 Donor Acceptor  Acceptor Explosive: HNS-I at 22,000 N/cm^2 Acceptor Closure Thickness: 0.030 cm	**Acceptor Closure Material Density (g/cm^3)** Lead, 11.3 Brass, 8.5 Steel, 7.9 Aluminum, 2.6 PMMA, 1.2	**Approximate 50% Fire Air Gap (cm)** 0.061 0.066 0.058 0.173 0.188
10. Donor Fragment Energy	Donor Acceptor  Air Gap = 7.6 cm Donor, Acceptor Closure: 0.010 cm Steel Acceptor Explosive: TATB at 11,000 N/cm^2	**Average Donor Fragment Velocity (cm/μsec), Energy (cal/cm^2)** 0.286, 78 0.274, 71 0.200, 38	**Propagation Frequency** 9 of 9 3 of 6 2 of 5
11. Donor Size	Donor Acceptor  Donor Explosive: HNS-I at 11,000 N/cm^2 Acceptor Explosive: HNS-I at 22,000 N/cm^2 Column Length: 0.51 cm	**Shock Initiation** **Explosive Column Diameter (cm)** 0.381 0.318 0.254 0.191	 **Approximate 50% Fire Air Gap (cm)** 0.340 0.193 0.140 0.117
	Donor Acceptor  Air Gap = 1.27 cm Donor Closure = 0.010 cm Steel Acceptor Closure: Steel	**Fragment Initiation** **Explosive Column Diameter (cm)** 0.381 0.318 0.254 0.191	 **Approximate 50% Fire Acceptor Closure Thickness (cm)** 0.094 0.094 0.018 0.066
12. Donor Closure Material	Donor Acceptor  Air Gap = 1.27 cm Donor Explosive: HNS-I at 11,000 N/cm^2 Acceptor Explosive: HNS-I at 22,000 N/cm^2 Acceptor Closure: Steel	**Donor Closure Material, Thickness (cm)** Steel, 0.010 Titanium, 0.020 Brass, 0.010 Aluminum, 0.030	**Approximate 50% Fire Acceptor Closure Thickness (cm)** 0.094 0.094 0.066 0.046

initiation of TATB with the more powerful donors. Substitution of a more sensitive acceptor explosive, DATB, resulted in successful initiation using only donor fragments.

Fragment energy (task 10): in order to provide more donor fragment energy than that available in task 1, an experimental configuration donor, which provided greater sidewall confinement, was used. Using a donor containing 100 mg of HNS-I compacted at 22,000 N/cm^2 (32,000 psi) resulted in an average fragment energy of 78 cal/cm^2. This donor consistently initiated a TATB acceptor across a 7.6 cm (3 inch) air gap. Reducing the quantity of donor explosive and the compaction pressure, resulted in less fragment energy and reduced frequency of propagation.

Size (task 11): donors and acceptors with the four explosive column diameters shown in Table 3 were tested for detonation transfer by shock and fragment initiation. For shock initiation, the 50%-fire air gap decreased significantly as explosive column diameter was reduced. In contrast, for fragment initiation, successful propagation occurred over large air gaps and through thick acceptor closures, even when the explosive column diameter was significantly reduced. The quantity of explosive used in the donors tested was 89, 60, 46, and 20 mg, respectively. Plate dent tests were conducted on the 0.381 cm (0.15 inch) donor, with and without an end closure, and essentially identical results were obtained, in spite of the marked difference in propagation ability. The design significance of this observation is discussed in "APPLICATION OF RESULTS" section.

Closure material (task 12): for donor closures with approximately equal weight per unit area, the materials tested have the following performance ranking: titanium, steel, brass, and aluminum. This is based on measurements of donor fragment velocity and pattern, as well as ability to transfer detonation.

Acceptor variables.-

Confinement (task 2): substitution of the bushing for the cup configuration acceptor resulted in substantially increased explosive confinement.

However, propagation results were not affected, and the bushing configuration acceptor was used in tasks 2 through 12 because it provided a more convenient means of varying design parameters.

Closure thickness (tasks 3, 8): in task 3, the donors used were all -2 type, containing 89 mg HNS-I compacted at 11,000 N/cm^2 (16,000 psi). The TATB acceptor explosive was compacted at reduced pressures to increase its sensitivity. The approximate 50%-fire acceptor closure thickness increased with increasing acceptor sensitivity. Task 8 differed from, and extended the investigation of, task 3 in that the donor cup bottom was removed. This permitted the measurement of donor shock energy attenuation by varying the thickness of steel acceptor closures. Test data show that the 50%-fire air gap decreases as acceptor closure thickness increases. The result with HNS-I at 5,500 N/cm^2 (8000 psi) shows initiation over a substantially larger gap than would be expected from the remainder of the data of this task.

Closure materials (tasks 6, 9): in task 6 the effects of having no acceptor closure, as well as having closures of aluminum, steel, and lead were evaluated with respect to initiation by shock, fragments, or a combination of the two. Best propagation was obtained with no acceptor closure. Attenuation of detonation transfer was related to acceptor closure mass. Task 9 extended the work of task 6 with respect to shock energy attenuation. Five different acceptor closure materials were used. These had a wide range of densities, but a constant thickness. Results confirmed that attenuation was related to acceptor closure mass.

Explosive material (task 4): this task was essentially a continuation of task 3. Still more sensitive acceptors were tested by selection of the indicated explosives. Again, the more sensitive the explosive, the thicker the acceptor closure through which propagation could be accomplished.

Explosive particle size (task 5): the effect of explosive particle size was investigated, using HNS-I (under 5 microns) and HNS-II (under 50 microns). Table 3 results show HNS-II to be more sensitive to shock initiation, and HNS-I to be more sensitive to fragment initiation. This apparent sensitivity reversal is significant from the standpoint of hardware design, and is discussed in "APPLICATION OF RESULTS."

Sensitivity (task 7): the decay in donor shock energy was measured, using acceptor explosives of various sensitivities. Generally, the more sensitive acceptor explosives could be initiated over larger air gaps. HNS-I at 5,500 N/cm^2 (8000 psi) was initiated over substantially larger gaps than would be expected from the remainder of the data of this task.

Discussion of Results

Even a cursory review of Table 3 shows the marked contrast of the initiating ability of donors with and without end closures. The presence of high-velocity, high-energy donor fragments made it possible to initiate using test gaps of 7.6 cm (3 inches). Without such fragments, the successful gaps were less than 0.7 cm (0.25 inch). In addition, donors with end closures initiated through thicker and more dense acceptor closures, and transferred detonation to less sensitive explosives. In Figure 10 these results are illustrated conceptually. It shows that the energy sources, which are discussed in this section, consist of fragments, gaseous products, or a total of the two. QUEST donors produced a concentrated pattern of high-velocity fragments. There was only a small decrease in fragment energy, even out to the maximum test gap of 7.6 cm (3 inches). On the other hand, the energy decay from donor gaseous

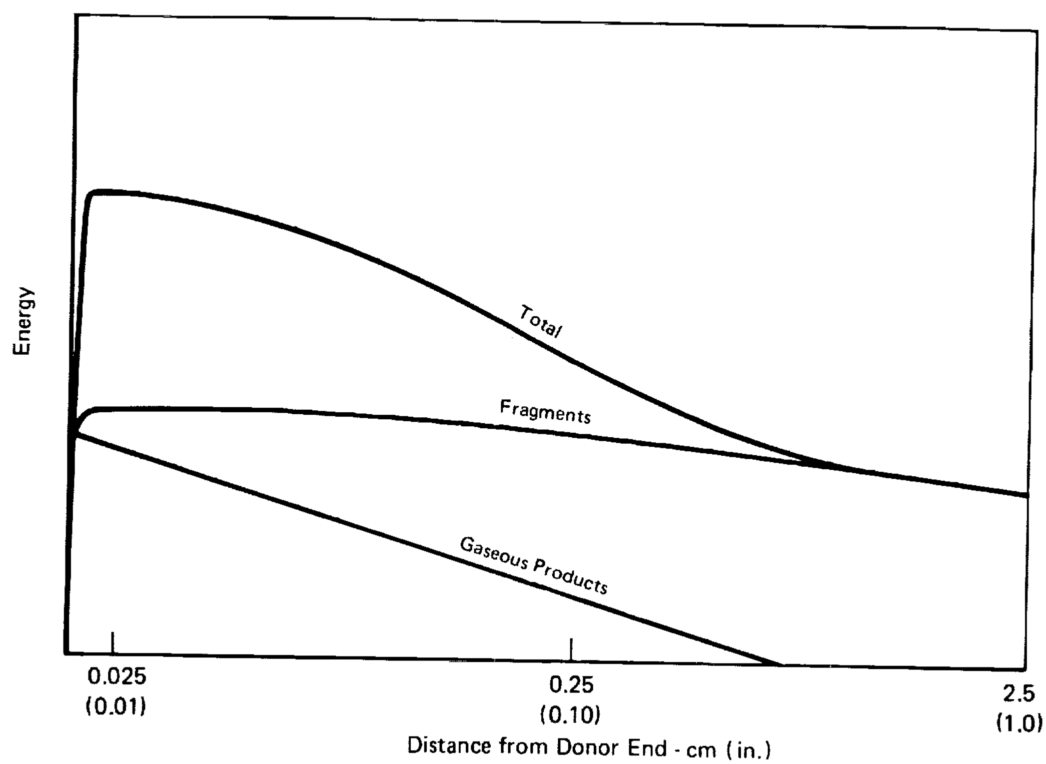


FIGURE 10 ENERGY AVAILABLE FROM A QUEST DONOR AS A FUNCTION OF DISTANCE

products was so rapid that at gaps greater than 0.7 cm (0.25 inch), the gaseous energy was insufficient to initiate the secondary explosives studied. Measurements of the combined effect of fragments and gaseous products were made at a gap of 0.38 cm (0.15 inch). At this distance, which coincidentally is a typical aerospace production gap, it is estimated that only about 30% of the energy is derived from the gaseous products.

Donor fragment energy. - Experimental results of task 1 showed that donor fragments with an average velocity of 0.276 cm/usec (9040 ft/sec), equivalent to energy of 72 cal/cm^2, would not initiate a TATB acceptor compacted at 11,000 N/cm^2 (16,000 psi) in a 0.010 cm (0.004 inch) thick stainless steel cup. This results was contrary to that expected, based on the pressure induced in the acceptor explosive computed by the Hugoniot method to be approximately 200 Kbar, compared to the 74 Kbar SSGT sensitivity measured for the TATB acceptor explosive, (ref. 6). This difference is explained by the work of Walker and Wasley (ref. 7), which showed that the critical parameter for initiation is the energy, not the pressure, induced in each of three acceptor explosives which they studied. Based on the critical energy concept of initiation, an explanation of task 1 results is given conceptually

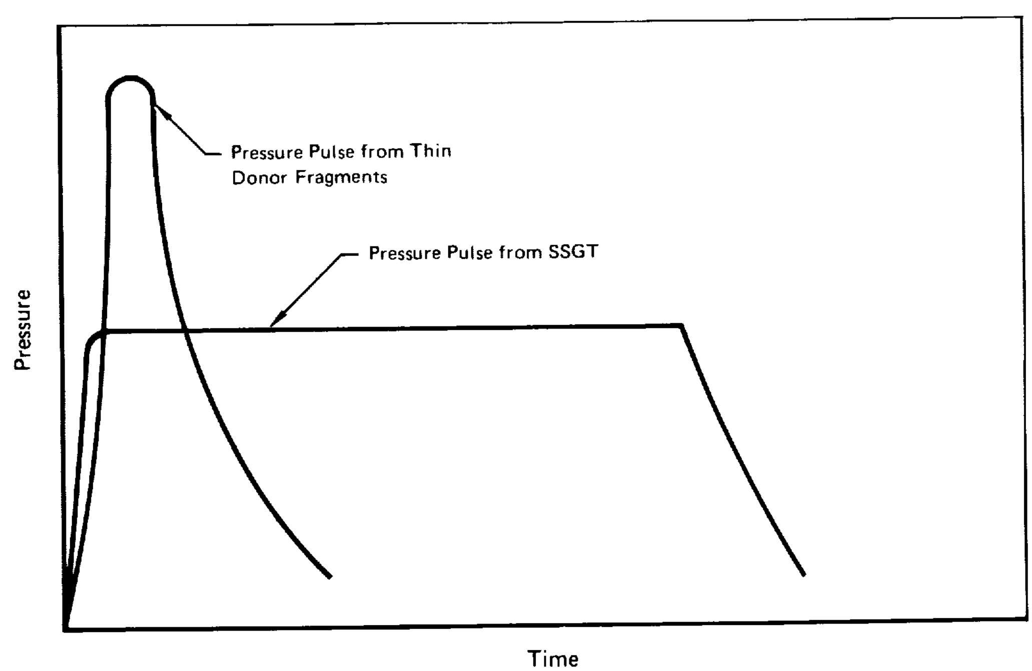


FIGURE 11 PRESSURE vs ENERGY CONCEPTS OF INITIATION

in Figure 11. Even though the pressure induced in the TATB acceptor was substantially higher than the pressure measured as required by SSGT testing, the time of pressure application with thin, 0.010 cm (0.004 inch), donor fragments is substantially less than that for the Lucite spacer, 0.28 cm (0.11 inch) for the SSGT 50%-fire point for TATB at 11,000 N/cm^2 (16,000 psi). Accordingly, less energy, corresponding to the area under the pressure-time curve, is induced by fragments than by the gap test.

A summary of fragment energy initiation tests is given in Table 4. These tests were conducted at air gaps of 1.27 to 7.62 cm (0.50 to 3.0 inches), so that the effect of donor gaseous detonation products is negligible. The donor fragment energy, expressed in cal/cm^2, is computed from the fragment velocity, mass, and area. The amount of energy actually transferred to the acceptor explosive is less than that shown in column 1 of Table 4 because of: (1) slight donor fragment spreading (some fragments miss the acceptor), (2) the presence of acceptor closures (a portion of the donor energy is transferred to this closure), and (3) the donor fragments retain some kinetic energy after impact. Examination of Table 4 shows that when the donor energy, expressed in cal/cm^2, was greater numerically than the acceptor explosive sensitivity expressed in kilobars, then initiation took place, even through acceptor closures of various thicknesses. When donor fragment energy was less, initiation did not take place, except for the -4 donor which initiated DATB in task 1. In this instance, as well as in the tests in task 10 where partial success was achieved, damage to the acceptor bushing was less than normal. This suggests the possibility that the acceptor explosive had not completely detonated, even though the RDX detonating cord was initiated.

The above numerical comparison between quantities of pressure and energy may seem incongruous. However, it should be noted that although SSGT sensitivity results are expressed in pressure units, they actually indicate the energy transmitted to the acceptor explosive. This is because pressure induced in the acceptor and the time of application are both functions of the plastic attenuator thickness.

Further background on the relationship between explosive sensitivity and critical energy is given in Table 5. The flyer plate experiments of Gittings (ref. 10), and Walker and Wasley (ref. 7), as well as the computations of Price (ref. 11) indicate a reasonable correlation between the initiation energy

TABLE 4 FRAGMENT ENERGY INITIATION TESTS

Air Gaps - 1.27 to 7.62 cm

Donor, Fragment Energy (cal/cm^2)	Acceptor, SSGT Sensitivity (kbar)	Propagation Acceptor Closure Thickness (cm)	Task No.
−1, (72)	TATB, (74)	No-Fire (0.010SS)	1
−4, (39)	DATB, (45)	Fire (0.010SS)	1
−5, (34)	DATB, (45)	No-Fire (0.010SS)	1
−2, (66)	HNS-I, (25)	50% - Fire (0.064SS)	5
−2, (66)	HNS-II (19)	50% - Fire (0.028SS)	5
−2, (66)	HNS-II (19)	50% - Fire (0.033Pb)	6
(78)	TATB, (74)	Fire (0.010SS)	10
(32)	HNS-I (25)	Fire (0.094SS)	11
(32)	HNS-I, (25)	Fire (0.094SS)	12

induced in an acceptor explosive and its gap test sensitivity. The work by McDonnell Aircraft Company on the Manned Orbital Laboratory (MOL) and QUEST involved the use of small donors in which the energy source was high-velocity closure fragments. For this method also, the fragment energy for successful initiation was also indicated by gap test sensitivity. Table 5 shows the correlation for a group of explosives with an extremely wide range of sensitivities, from 13 to 74 kilobars. While the QUEST program primarily used steel cups or closures as the source of donor fragment energy, other materials, including brass, titanium, and aluminum, were also tested. A comparison of these four closure materials is shown in Figure 12. These equivalent-mass closures all show a relatively concentrated impact pattern at a gap of 7.62 cm (3 inches). Qualitative examination of the Lucite witness blocks shows the following efficiency ranking of these materials in terms of energy delivery: (1) titanium, (2) steel, (3) brass, and (4) aluminum.

Donor gaseous energy.- The ability of donor gaseous energy to propagate detonation was evaluated by the use of donors with no end closures, thus eliminating fragment energy. Using a single donor configuration (the -2 group

TABLE 5 RELATIONSHIP BETWEEN EXPLOSIVE SENSITIVITY AND CRITICAL ENERGY

Explosive	Density (g/cm^3)	Gap Test Sensitivity, Pressure (kbar)	Critcal Energy, Ec (cal/cm^2)	Investigator, or Program
PBX-9404	1.840	13	12	Gittings[10]
LX-04	1.860	25	26	Walker, Wasley[7]
HNS-I	1.555	25	Ec < 34	MOL
TNT	1.620	29	32	Price[11]
TNT	1.645	–	34	Walker, Wasley[7]
DATB	1.676	45	39	QUEST
TATB	1.762	74	72 < Ec < 78	QUEST

Closure Material	Steel	Brass	Titanium	Aluminum
Closure Thickness (cm)	0.010	0.010	0.020	0.030
Velocity (cm/μsec)	0.228	0.192	0.305	0.201

Fragment Pattern at 7.62 cm

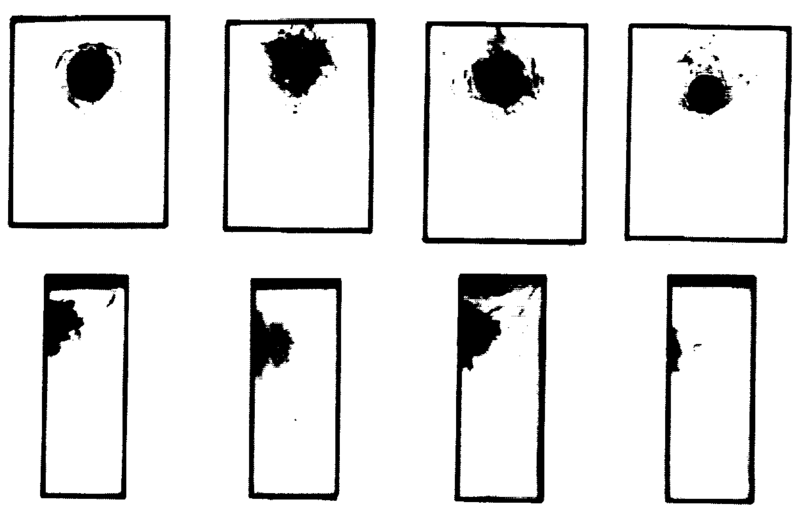


FIGURE 12 FRAGMENT PATTERNS FROM VARIOUS CLOSURE MATERIALS

of Table 1 with the closure cup bottom cut away) 50%-fire air gaps were measured in terms of acceptor explosive sensitivity, closure thickness, and density. The results are plotted in Figures 13, 14, and 15, respectively. In addition, the effect of donor explosive diameter on 50%-fire air gap was also evaluated, and these results are presented in Figure 16. The most significant result with respect to gaseous energy initiation, as shown by those four figures, is that propagation could be successfully accomplished only across very small gaps, in marked contrast to the large propagation gaps for donor fragments.

The effect of acceptor explosive sensitivity on gaseous energy initiation was evaluated, using the acceptors shown in Figure 13. These explosives, at the indicated compaction pressures, were selected to cover a wide range of SSGT sensitivities from 14 kilobars, for RDX compacted at 22,000 N/cm^2 (32,000 psi), to 74 kilobars, for TATB compacted at 11,000 N/cm^2 (16,000 psi). The 50%-fire air gap generally decreases with decreasing SSGT sensitivity (i.e., increasing pressure in kilobars required for initiation), with one marked exception. HNS-I, compacted at 5,500 N/cm^2 (8,000 psi) with an SSGT sensitivity of 20 kilobars, had a 50%-fire air gap of 0.649 cm (0.255 inch). This gap is substantially greater than would be expected from the remainder of the data. For example, the corresponding gap for RDX compacted at 22,000 N/cm^2 (32,000 psi) with a sensitivity of 14 kilobars, was only 0.325 cm (0.128 inch). One possible explanation for the large HNS-I gap is that the combination of extremely small particle size and relatively low compaction pressure resulted in building to detonation within the acceptor charge.

Both Figures 14 and 15 give the extent of decrease of 50%-fire air gap with increasing closure mass, the former as a result of increasing thickness of steel closure, and the latter due to increasing the density of closure materials with a constant 0.030 cm (0.012 inch) thickness. The significance of these results from a design standpoint is discussed in the "APPLICATION OF RESULTS" section.

The Figure 16 curve shows that as explosive diameter increases, there is a corresponding increase in 50%-fire air gap. This result correlates with previous small-scale air gap testing reported by other investigators (ref. 12). However, the small gaps reported in the literature and obtained in QUEST testing of gaseous energy initiation are in marked contrast to the fragment

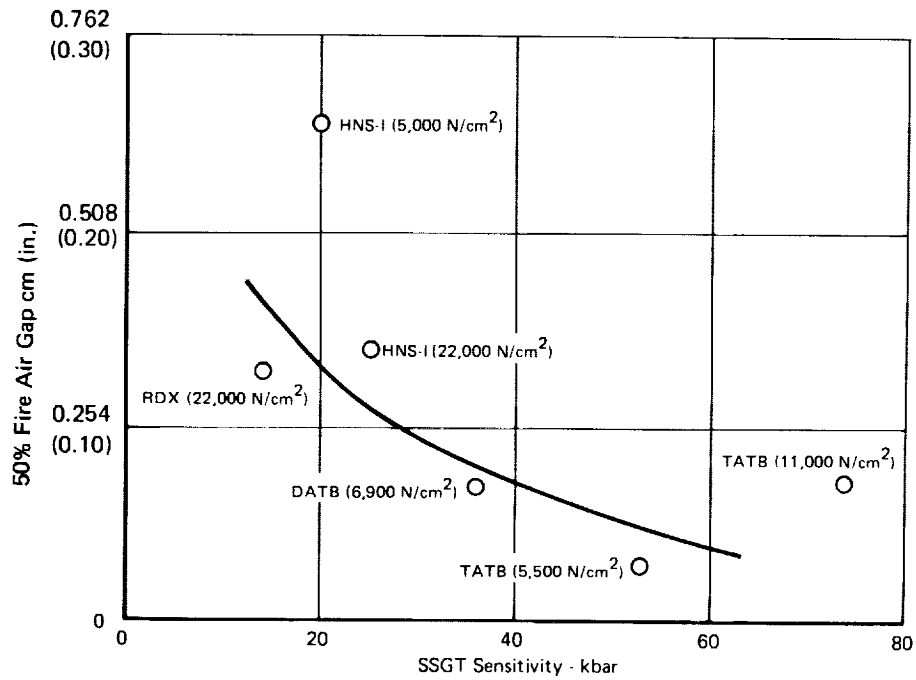


FIGURE 13 GASEOUS ENERGY INITIATION, EFFECT OF ACCEPTOR SENSITIVITY
(Task No. 7)

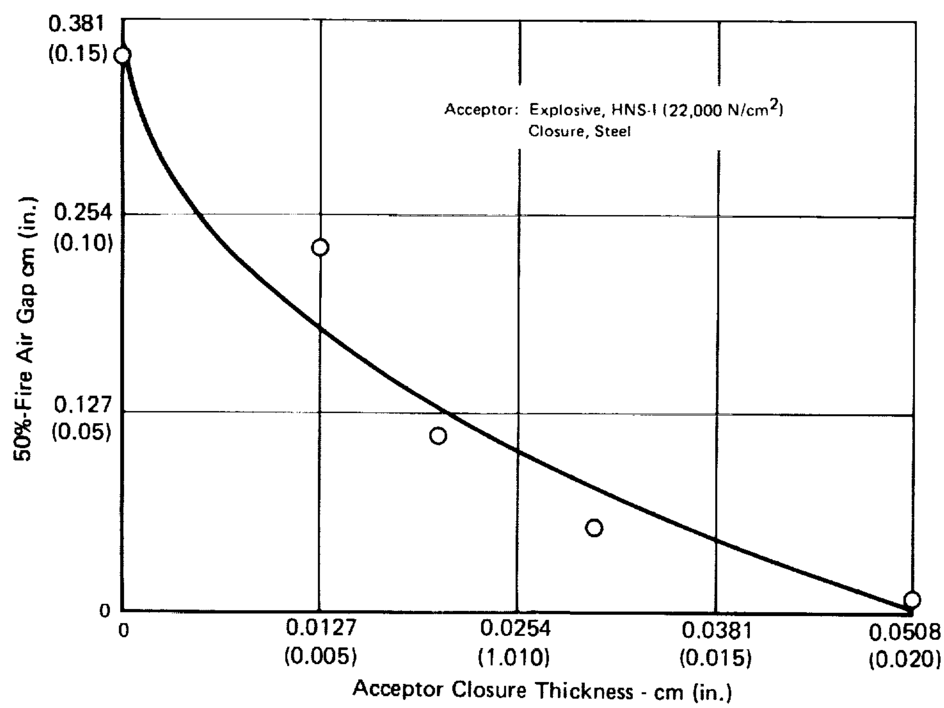


FIGURE 14 GASEOUS ENERGY INITIATION, EFFECT OF ACCEPTOR CLOSURE THICKNESS
(Task No. 8)

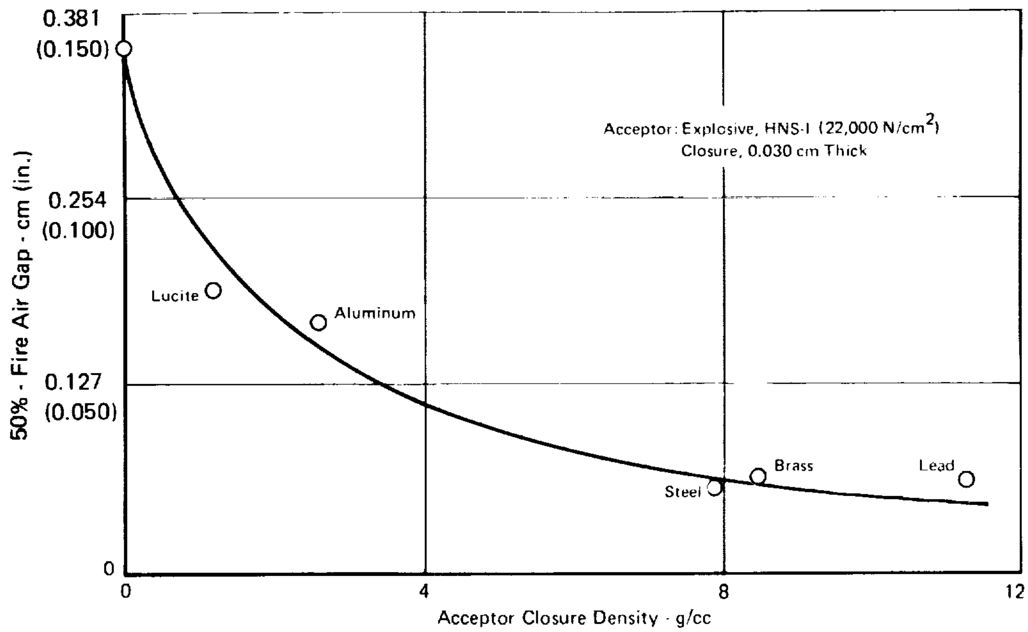


FIGURE 15 GASEOUS ENERGY INITIATION, EFFECT OF ACCEPTOR CLOSURE DENSITY
(Task No. 9)

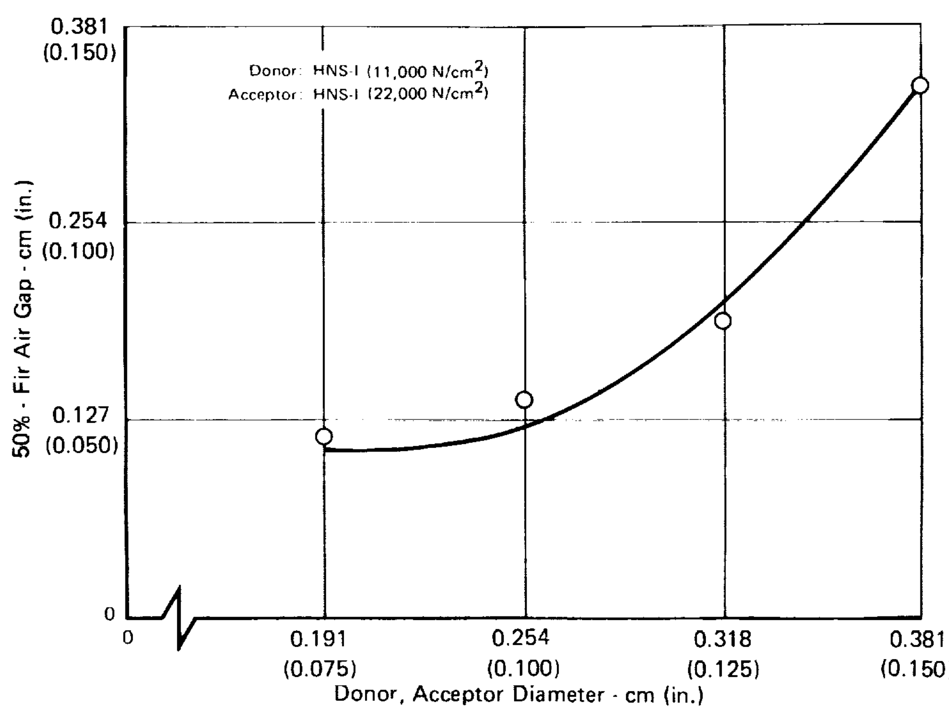


FIGURE 16 GASEOUS ENERGY INITIATION, EFFECT OF EXPLOSIVE DIAMETER
(Task No. 11)

initiation results throughout the program and particularly those obtained in Task 11, when small diameter donors were tested using end closures. An example of this difference is the result obtained with the smallest explosive diameter, 0.191 cm (0.075 inch) for both donor and acceptor. With no closure on either the donor or acceptor, the 50%-fire air gap was 0.117 cm (0.046 inch); on the other hand, with a 0.010 cm (0.004 inch) steel donor closure and an air gap of 1.27 cm (0.50 inch), the 50%-fire acceptor closure was 0.066 cm (0.026 inch) thick steel. The design significance of this striking difference is discussed in "Application of Results."

Combined fragment and gaseous energy initiation. - When initial tests of fragment initiation of TATB at gaps more than 2.54 cm (1.0 inch) proved unsuccessful in task #1, the experimental approach used was to reduce the separation air gap so that donor gaseous energy would be superimposed on that from the fragments. At an air gap of 0.381 cm (0.15 inch), when the same TATB acceptor was tested with the six groups of donors listed in Table 1, the two most powerful donors resulted in all-fires; the -3 group, in partial fires; and the three weakest donors, in no-fires. These results are summarized in Table 6. For each donor group the fragment, gaseous, and total energy are listed in cal/cm^2. For example, the -1 donor has 72 cal/cm^2 fragment energy (from Table 1) and 23 cal/cm^2 gaseous energy for a total of 95 cal/cm^2. The gaseous energy figure is an estimate based on: (1) the numerical relationship shown between critical energy and SSGT sensitivity, and (2) the initiation results obtained in task 6 with gaseous energy resulting in a 50%-fire gap of 0.35 cm (0.14 inch) with a bare acceptor of HNS-I compacted to 22,000 N/cm^2 (32,000 psi) and whose SSGT sensitivity is 25 kbar. The Table 6 results show that if the donor total energy is significantly greater than the acceptor explosive sensitivity in kilobars, detonation transfer takes place. When the donor energy was substantially less than this value, there were no-fires; when these values were about equal, a partial fire condition occurred. These experimental results are illustrated in Figure 17. The Lucite witness block shows the fragment impact pattern from donor and acceptor. For the most powerful donor (the -1 at the far right), note the strong pattern from the donor cup and ferrule fragments. The acceptor cup fragment pattern shows that the acceptor

TABLE 6 COMBINED FRAGMENT AND GASEOUS ENERGY INITIATION BY VARIOUS STRENGTH DONORS

Air Gap - 0.381 cm

Donor; Energy - Fragment, Gaseous, (Total, cal./cm^2)	Acceptor, Compaction, SSGT Sensitivity (kbar)	Propagation	Task No.
−1; 72, 23, (95)	TATB, 16,000, (74)	All-Fire	1
−2; 66, 22, (88)		All-Fire	
−3; 56, 20, (76)		1 of 5 Fired	
−4; 39, 18, (57)		No-Fire	
−5; 34, 17 (51)		No-Fire	
−6; 29, 16, (45)		No-Fire	

charge detonated. The decreasing donor strength is visible in the donor fragment patterns looking from right to left (-1 to -6). While all of the donors detonated, the cup fragment patterns become progressively weaker, and for the -4, -5 and -6 donors, the ferrule fragments are not accelerated at sufficient speed to give a significant impact pattern. This is because the ferrule fragments are much heavier than the cup fragments, and therefore more sensitive to the decrease in donor output. With respect to acceptor cup fragment patterns, note that in addition to -1 donor test, uniform acceptor fragment patterns indicate initiation for the three -2 donors, and for one of five of the -3 donors (test 36). On the remainder of the tests, detonation transfer did not take place, as shown by the irregular or missing acceptor pattern. This was further confirmed by the failure of the acceptor charge to initiate the witness detonating cord.

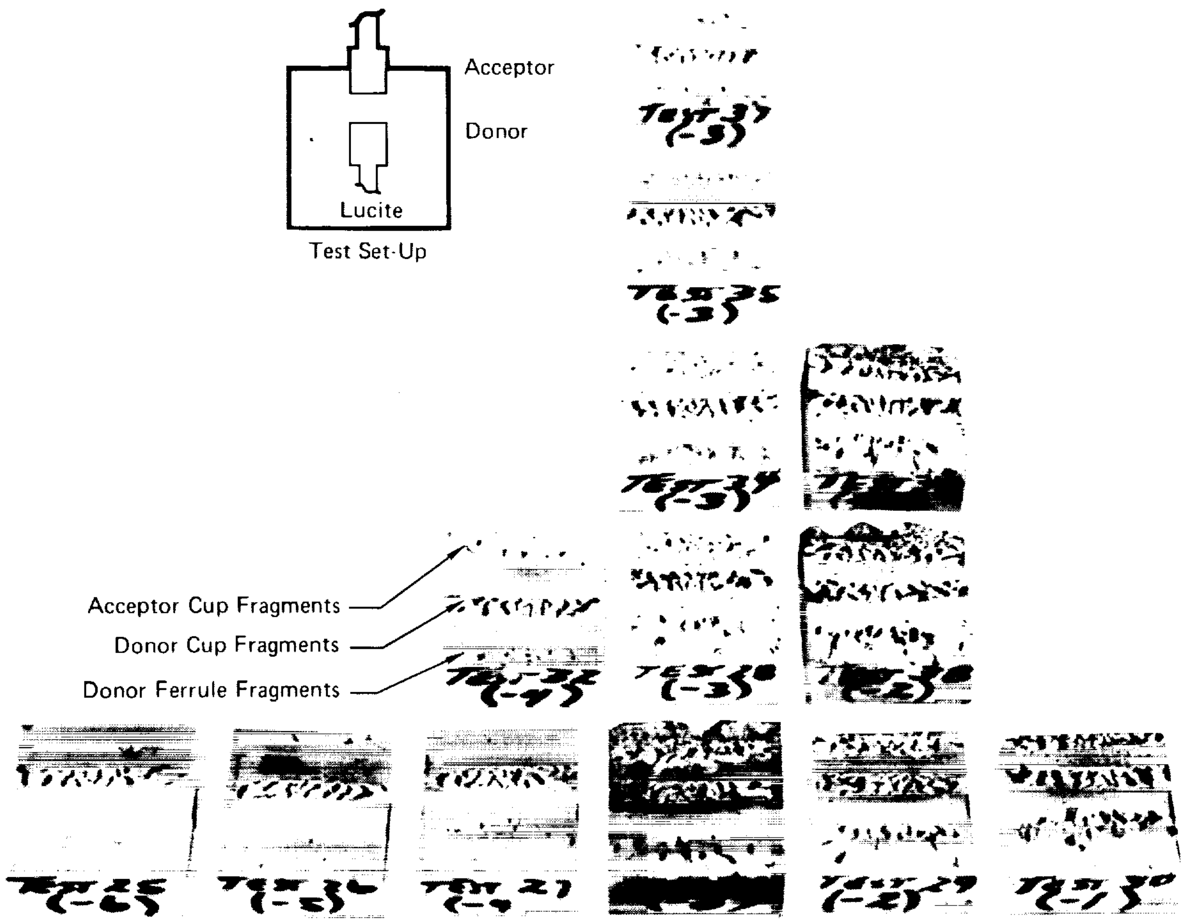


FIGURE 17 FRAGMENT PATTERNS FROM VARIOUS STRENGTH DONORS

Additional test results on combined fragment and gaseous initiation are summarized in Table 7. This compilation is for a single-donor configuration, but using acceptor explosives of various sensitivities. This table indicates that when total donor energy exceeded acceptor SSGT sensitivity, initiation took place; and the greater the difference, the thicker the acceptor closure for a 50%-fire condition. These results correlate with those obtained for fragment energy alone (Table 4).

TABLE 7 COMBINED FRAGMENT AND GASEOUS ENERGY INITIATION

Air Gap (0.381 cm, Except as Noted)

Donor; Energy - Fragment, Gaseous, (Total, Cal/cm^2)	Acceptor, SSGT Sensitivity (kbar)	50% - Fire Steel Acceptor Closure, cm (in.)	Task No.
−2; 66, 22 (88)	TATB, (74) TATB, (53) TATB, (43)	0.015 (0.006) 0.020 (0.008) 0.020 (0.008)	3
−2; 66, 22 (88)	DATB, (45) HNS-I, (25) RDX, (14)	0.033 (0.013) 0.064 (0.025) 0.064 (0.025)	4
−2; 66, 22 (88)	TATB, (74)	No Acceptor Closure, 1.04 cm Air Gap	6

APPLICATION OF RESULTS

Results of this program suggest a new approach to the problem of determining probability of detonation transfer. In addition, from a system reliability standpoint, the significance of the following parameters was determined: acceptor explosive particle size, acceptor closure material, and donor design. Finally, the limitation of the plate dent test as a means of determining detonation transfer capability was demonstrated.

Reliability concept. - As discussed in the Introduction, the methods presently used to determine reliability of detonation transfer include penalty gap testing, the VARICOMP method, and plate dent tests. The QUEST program results suggest another approach as illustrated in Figure 18. Experimentally, this approach can be accomplished as follows:

(1) Fire a sample group of donors, measure the fragment velocity, and compute fragment energy and standard deviation.

(2) Fire a second group of donors with the end closures removed, and at the maximum required air gap determine gaseous energy alone, using bare acceptor explosives of various sensitivities.

(3) Add measured fragment and gaseous energy to obtain total, and standard deviation.

(4) Since the acceptor explosive and its compaction pressure are known, the energy required and its standard deviation will be indicated by SSGT sensitivity results. The additional energy required because of attenuation by acceptor closure mass can be determined from QUEST results.

(5) Statistical comparison of energy supplied with that required will give probability of detonation transfer.

It should be emphasized that there are limitations and uncertainties to the above approach. First, the critical energy concept of Walker and Wasley (ref. 7) is based on the energy actually induced in the acceptor explosive. Only a portion of the donor fragment energy would be transferred. Secondly, while QUEST results show that SSGT sensitivity is an indication of energy required for initiation, no exact correlation has been established. From the standpoint of designing reliable initiation systems, these are not considered

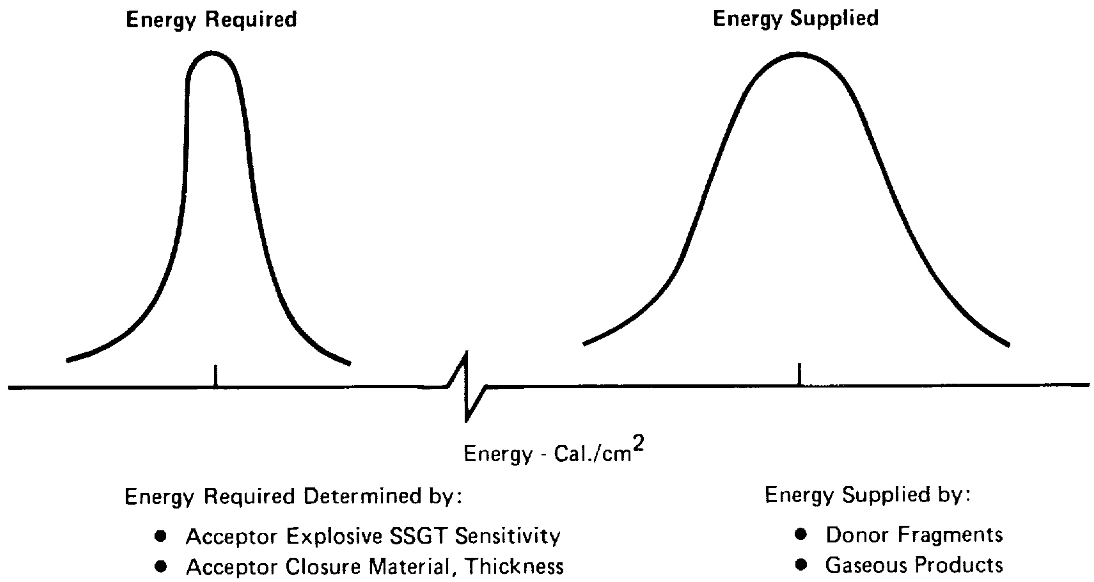


FIGURE 18 RELIABILITY CONCEPT

serious limitations. For example, in task 10 it was demonstrated that a small donor containing 100 mg of HNS-1, with a 0.381 cm (0.15 inch) explosive diameter and a 0.010 cm (0.004 inch) thick steel closure could repeatedly initiate a TATB acceptor with a SSGT sensitivity of 74 kilobars across a 7.6 cm (3 inch) air gap. Since the SSGT sensitivities of generally used aerospace acceptor explosives are less than 25 kilobars, at normal production gaps a properly designed small detonator should be capable of supplying many times the quantity of energy needed for initiation.

Acceptor explosive particle size.- The results of task 5, showing that HNS-II is more sensitive to gaseous energy but that HNS-I is more sensitive to fragments, appear to be a sensitivity reversal for a single explosive. However, these results are consistent with those obtained by other investigators. For example, the SSGT sensitivity of HNS-II at 22,000 N/cm^2 (32,000 psi) is 19 kilobars, while that of HNS-I at the same pressure is 25 kilobars. Thus, HNS-II is more sensitive to shock initiation through polymethyl methacrylate, just as in the QUEST work it was more sensitive to gaseous energy attenuated by an air gap. On the other hand, Kilmer (ref. 13), and Chamberlain and Stresau (ref. 14), conducted shock initiation tests on HNS-I and HNS-II using detonating cords between 5.3 and 10.6 mg/cm (2.5 to 5 grains per foot). With this small initiation stimulus, these investigators found HNS-I to be more sensitive than HNS-II. Thus, it appears that the stimulus provided by fragment initiation under task 5 conditions corresponds to the shock stimulus from small coreload detonating cord.

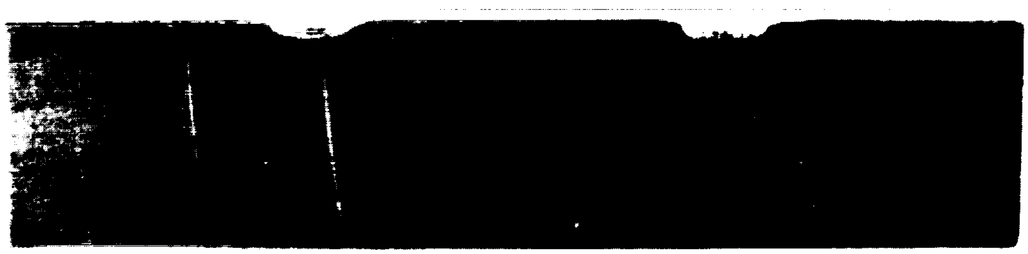
From the standpoint of hardware design, these results show that for miniature devices, such as detonating cord end boosters which must be initiated by either low coreload detonating cord or by fragments, the choice of a small particle size explosive, such as HNS-I, is indicated. However, for the output charge of a detonator initiated by a booster charge of about 0.38 cm (0.15 inch) in diameter, the larger particle size HNS-II would be preferable.

Acceptor closure mass. - In most designs, acceptor closures are required to provide an environmental seal. QUEST results show that as acceptor closure mass is increased, detonation transfer capability is correspondingly decreased, both by gaseous energy (Figures 14 and 15) and by fragment energy (Table 4). This can be explained, based on the critical energy concept of initiation, as resulting from a portion of the available donor energy being transferred to the acceptor closure material. The greater the closure mass, the more energy that is absorbed, and the less available for the acceptor explosive. For system design involving detonating cord, the experiments involving acceptor closure mass show that the practice of initiation through the side of high density metallic sheathing would cause attenuation of a substantial portion of the detonator energy. For a given detonator, improved detonation transfer would be achieved by the use of an acceptor booster charge compacted in a thin-walled cup at the point of initiation.

Donor design. - During task 11, donor explosive column diameter was reduced in increments, from 0.381 cm (0.15 inch) to 0.191 cm (0.075 inch). For gaseous energy initiation, the 50%-fire air gap decreased significantly as explosive column was reduced, as shown in Figure 16. This effect did not occur for fragment initiation, as shown in Table 3. This indicates that there is a design alternative to the practice of increasing the size of the donor output charge to increase detonation transfer capability. By designing the donor closure so that high-energy fragments are impacted on the acceptor, effective detonation transfer can be achieved without the undesirable blast effects associated with a large detonator. Of the three most common donor closure metals, task 12 results showed steel to be most effective for transferring this energy, followed by brass, and aluminum. A practical example of the importance of these findings involves the design of miniature detonators. One such commercially available detonator, which is 0.23 cm (0.09 inch) outside diameter and contains 35 mg of high explosive, has an aluminum case. The manufacturer states that this detonator is capable of initiating tetryl over a 0.089 cm (0.035 inch) air gap. In contrast, the 0.191 cm (0.075 inch) inside diameter donor of task 11, with a 0.010 cm (0.004 inch) thick steel closure, contained only 20 mg explosive output charge. Yet, it initiated HNS-1 (less sensitive than tetryl) compacted at 22,000 N/cm^2 (32,000 psi) against a 0.051 cm (0.020 inch) thick steel acceptor closure, over a 1.27 cm (0.50 inch) air gap. From the above data, it appears that the aluminum case fragments of the commercial detonator do not appreciably enhance its ability to propagate detonation, and that for this detonator substitution of a higher density case could be expected to improve this aspect of performance.

Plate dent test limitations. - QUEST results indicate that the plate dent test has serious limitations as an index of detonator gap jumping ability. Figure 19 compares dents obtained on two donors, which were identical except that one had a 0.010 cm thick steel closure, while the other had no closure. Essentially equal plate dents were obtained, despite the enormous difference the closure made in ability to propagate detonation over air gaps. This result

Closure **No Closure**



	Propagation Ability
Donor With Closure:	Detonated HNS-I (22,000 N/cm^2) at 1.27 cm Air Gap Through 0.081 cm Steel Acceptor Closure
Donor Without Closure:	Detonated HNS-I (22,000 K/cm^2) at 0.317 cm Air Gap With No Acceptor Closure

FIGURE 19 PLATE DENT TEST

is in direct contradiction to the underlined portion of the following quotation from the U.S. Army publication, titled "Explosive Trains" (ref. 12):

> "Most experimental determination of the relative effectivess of explosive charges in initiating other charges has been done as part of a study of a specific system. Hence, the variables are generally so intermingled as to make generalizations from such data difficult. However, the evidence that the volume of dent which a charge makes in a steel block is nearly proportional to its effectiveness as an initiator, combined with relatively broad and interpretable plate-dent data, makes it possible to derive relationships which appear to have relatively broad applicability."

Dent tests have received much emphasis because they are the only performance tests for detonators in the basic Department of Defense Military Standard on fuzes (ref. 3). Yet, these tests do not adequately define detonator performance because they measure only the effect of gaseous detonation products at "zero" air gap. QUEST results show that for the air gaps required on most aerospace applications, there is significantly more energy available from the case or closure fragments of a properly designed detonator. From an applications standpoint, this means that a group of detonators can give uniform plate dent results, and yet have substantially different ability to initiate detonation. The critical importance of the case or closure must be recognized and controlled.

CONCLUSIONS

A complete analysis of detonation transfer probability must include evaluation of the amount of energy:

- o Supplied by donor fragments and gaseous detonation products
- o Attenuated by the air gap separating the donor and acceptor, and by the acceptor closure mass
- o Required for initiation of the acceptor explosive, as indicated by gap test sensitivity results

For the configurations tested in this program, the following may be concluded:

(1) Detonation transfer can be accomplished by donor fragments, gaseous detonation products, or a combination of the two.

(2) Donor fragments proved to be substantially more effective than gaseous products for initiation of secondary explosives.

(3) For a given configuration, variation of donor output was the most significant parameter affecting probability of detonation transfer.

(4) The principle of accomplishing detonation transfer based on supplying a critical amount of energy to the acceptor explosive was shown to be valid for detonators and closures of typical aerospace design.

RECOMMENDATIONS FOR FUTURE WORK

The following items are suggested as having merit for further investigation:

(1) The demonstrated efficiency of fragment initiation should be investigated for military explosive trains. An example would be the achievement of Safe/Arm fuzing capability with no moving parts by controlling the direction of donor fragments.

(2) The surprisingly high sensitivity demonstrated by HNS-I at low compaction pressure should be studied further because of the widespread aerospace usage of this explosive.

(3) Detonator design should be studied from the standpoint of improvements that can be achieved by taking full advantage of the energy generated by donor fragments. Efforts in this area should lead to significant reduction in detonator size, while at the same time achieving improved detonation transfer capability.

(4) Since most aerospace detonators are built and tested to military specifications, additional work is needed on these documents to assure that detonation transfer capability is adequately measured.

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