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Through Bulkhead Initiator Studies

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ABSTRACT

This report describes recent work done to demonstrate feasibility of a fail-safe Through Bulkhead Initiator with minimum dimensions and suitable for use in cyclical thermal environments. Much of the ground work for a fail-safe TBI was previously done by A. C. Schwartz.[1] This study is an expansion of Schwartz's work to evaluate devices with bulkheads of 304 stainless steel and Inconel 718; explosive donors of PETN, BNCP, and a 0.005 inch thick steel flying plate donor traveling at 2.6 mm/µs; and explosive acceptors of PETN and BNCP. Bulkhead thickness were evaluated in the range of 0.040 to 0.180 inch. The explosive acceptors initiated a small HMX pellet to drive a 0.005 inch thick steel flying plate, and VISAR histories of the HMX-driven flying plates were the measure of acceptable performance. A companion set of samples used a PMMA acceptor to measure the particle velocities at the bulkhead/PMMA interface with VISAR. These data were used to compute the input pressure to the acceptor explosives in an attempt to measure initiation threshold. Unfortunately, the range of bulkhead thicknesses tested did not give any failures, thus the threshold was not determined. It was found that either explosive or the flying plate would perform as a TBI in the bulkhead thickness range tested. The optimum TBI is about 0.060 inches thick, and steel bulkheads seem to be more structurally sound than those made of Inconel. That is, cross section views of the Inconel bulkheads showed it to be more prone to stress cracking than was the 304 stainless steel. Both PETN and BNCP showed good performance when tested at -65°F following thermal cycling of -65°F to +165°F. Analysis of the TBI function times showed that BNCP acceptor explosives were undergoing the classical deflagration to detonation process. The PETN acceptors were undergoing prompt detonation.

ACKNOWLEDGMENTS

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ACRONYMS

CP	pentaamine(5-cyano-2H-tetraazolato-N^2) cobalt(III) perchlorate
BNCP	the Bis Nitro analog of CP: Tetraammine-cis-bis(5-nitro-2H-tetraazolato- N^2) cobalt(III) perchlorate
DDT	Deflagration to Detonation Transfer
EBW	Exploding Bridgewire (usually referring to a type of a detonator)
HMX	High Melting Explosive: octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
LX13	Livermore Explosive #13: a mixture of 20 wt% sylgard binder with PETN
PETN	Pentaerythritol tetranitrate: 2,2-bis[(nitrox)methyl]-1,3-propanediol, dinitrate
PMMA	polymethylmethacrylate: (Romme & Haas Type 2 UVA material)
TBI	Through Bulkhead Initiator
VISAR	Velocity Interferometer System for Any Reflector

Through Bulkhead Initiator Studies

INTRODUCTION

Through-Bulkhead Initiators (TBIs) are used to initiate explosives or pyrotechnics inside vessels that have a need to maintain bulkhead integrity. In the past few years, the emphasis on safety and surety of explosive subsystems, particularly with stray or static electricity, has placed increased emphasis on the desirability of a reliable TBI. Use of a TBI allows initiation inside vessels without electrical paths, thus precluding accidental initiation of explosives inside the vessel by stray lightning or static electricity.

Feasibility of a Fail-Safe TBI was investigated in 1977 by Al Schwartz[1]. His investigations were on a configuration that utilized PETN explosive and 304 stainless steel bulkheads. He noted that TBIs have been developed for several other programs, including the Saturn V Launch Vehicle and the Navy C-4 ordnance for Trident. None of these applications investigated the effects of thermal cycling and operating at cold temperatures. Although not proven, there has been a concern that during thermal cycling, there may be a tendency for donor and acceptor explosives to creep away from the bulkhead. Because functionality of a TBI is dependent on transmittal of a shock from the donor explosive to the acceptor, the presence of small air gaps could be catastrophic.

To address the question of mechanical creep during thermal cycling it was decided to investigate the use of an explosive other than PETN as the donor and acceptor. The alternate explosive was BNCP[2]. This is a relatively new DDT explosive that is a chemical analog of CP which has been used for several years in Sandia designed DDT detonators (for example the MC3614 and MC3990A).[3,4] CP is no longer synthesized primarily because of a low need, but also because the common method of manufacture requires use of hazardous cyanogen gas. BNCP does not require the hazardous process step and has desirable attributes such as a higher detonation pressure and increased sensitivity. Like CP, BNCP is inorganic in nature, and has hard crystals that are not prone to creep. PETN is rather “mushy,” and more likely to take on a permanent mechanical “set” after thermal cycling. Some work has been done to characterize the use of a PETN extrudable explosive (LX13) as the donor. The problem with such extrudables is the lower shock pressure and decreased initiation sensitivity because of the inert binder in the explosive. The use of Inconel 718 was addressed to determine if there was any reason to use an alloy with a higher yield strength than that of 304 stainless steel (the tensile strength of Inconel 718 is about 180 kpsi compared to 85 kpsi for 304 stainless steel).

To address these questions, a study was set up that used a simple TBI explosive configuration like that shown in Figure 1. The nomenclature of the various aspects of a typical TBI design are identified in the simplified sketch shown below in Figure 1. Factors that are considered in TBI designs are the ratio of donor length to bulkhead thickness (L/t), the ratio of donor to acceptor diameters (D/d) and the length to diameter ratios of the explosive columns (L/D and l/d). In this study, D/d was fixed at approximately 2 and l/d was also fixed at approximately 3. The L/D ratio was a variable greater than 2, and the ratio of L/t was varied from 5:1 to 1:2. Also, the radii on the bottom surface of the donor and acceptor counterbores was a minimum of 0.15 inch. It was felt that sharp corners in these regions would enhance crack growth.

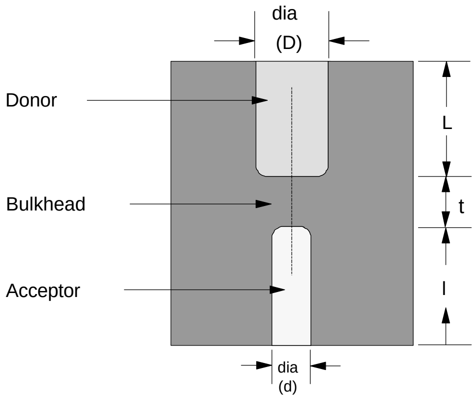

Figure 1. **Typical Explosive Configuration of a Through-Bulkhead Initiator**

There were basically two parts to the study. The first being characterization of the output pressure from the bulkhead as a function of the donor and bulkhead thickness/material. The second part was determining whether or not there was good detonation of the acceptor explosive for the various donor/bulkhead configurations. The work is presented as a series of sketches, tables, and graphs that show the results from each family of samples that were tested.

EXPERIMENTAL RESULTS

EXPLOSIVE CHARACTERIZATION:

The explosives used in this study are as follows:

PETN
This material was Type I PETN, Batch A-110. It was originally prepared by EG&G/Mound for use in EBW detonators and has a mean surface area of 4000 cm^2/g as determined by the Fisher subsieve method. It was used as the donor explosive at a density of 1.6 g/cc and as the acceptor explosive at a density of 1.0 g/cc.

.
BNCP
This material was manufactured by Unidynamics Phoenix Inc. (now Pacific Scientific Corp.), and is lot number EL-94377. This material has a monoclinic structure with a nominal particle size of ~100 µm. The theoretical maximum density of BNCP is 2.03 g/cc. It was used as the donor at a density of 1.8 g/cc and as the acceptor at a density of 1.2 g/cc. A small number of tests were conducted with an acceptor density of 1.0 g/cc.

HMX

The HMX used for the output pellets on the explosive acceptors is Grade II, Class B material that was originally obtained from Los Alamos National Laboratories. The lot number is HOL83L-030-050. The particle size distribution of this HMX was not measured, however Grade II, Class B material has a screening requirement where 75% of the material must pass through a number 325 sieve (44 µm). The HMX was in the form of prepressed pellets weighing 7.3 +/- 0.3 mg. Upon recompaction on the acceptor explosives, the final density of the pellets should have nominally been 1.77 g/cc.

BULKHEAD DONOR CHARACTERIZATION STUDIES

The pressure output of the TBI configurations were characterized using the pressure that was input to a PMMA window. The window was aluminized on the bulkhead contact surface so that the motion of that surface could be measured with fixed-cavity VISAR. The Reynolds RP-2 detonator® was used as the initiation source throughout this investigation.. The RP-2 detonators were always fired at 2000 volts.

® *The RP-2 is an EBW manufactured by Reynolds Industries Inc. The particular units used were part number 167-4379. The detonator uses a 250 mg initiating charge followed by a 365 mg high density RDX output charge. The bridgewire is 0.0015 inch diameter by 0.040 inch long gold. For more information, contact Reynolds Industries Inc., P.O.Box 1179, Marina del Rey, CA, 90291. Telephone 213-823-5491.*

Slightly different configurations were used for the steel and Inconel bulkheads as shown in Figure 2. For steel, the donor explosive was of a fixed length of 0.080 inches.

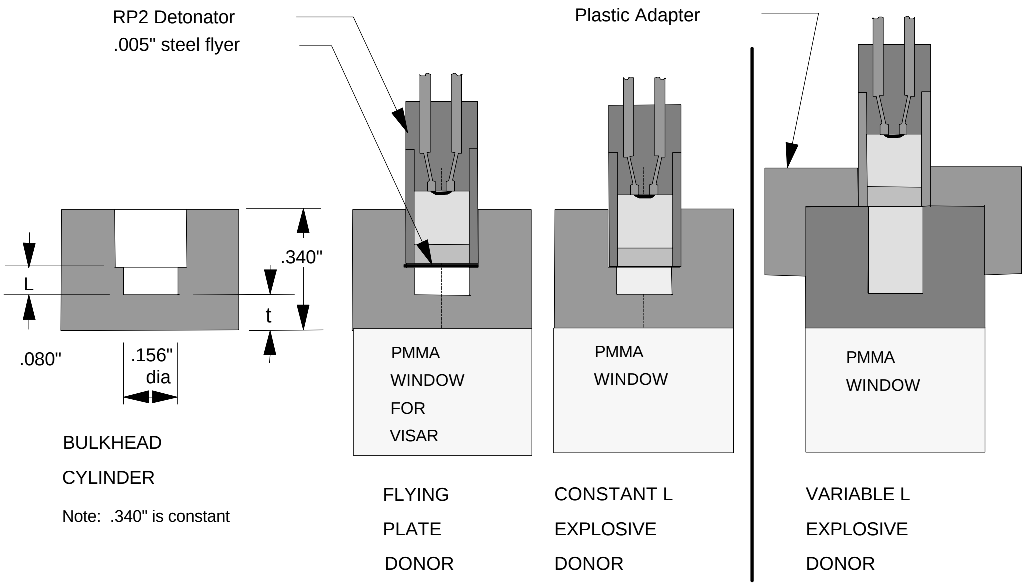

Figure 2. PMMA shock pressure test configurations

By varying the counterbore depth for the RP-2 detonator, the desired bulkhead thickness was obtained. For the majority of the Inconel bulkheads, the donor length varied and the RP-2 detonators were attached to the samples with a plastic adapter. On a few of the steel bulkheads, a 0.005 inch thick steel flying plate was used as the donor as shown in Figure 2. The explosive donors were either PETN at a density of approximately 1.6 g/cc or BNCP at a density of approximately 1.8 g/cc. The actual densities for each test are shown on Table 1 and Table 2 in the Appendix. These tables also give the function time of each test where the function time is the time from the start of current to the RP-2 detonator to the start of motion of the mirrored PMMA surface.

PMMA PRESSURE RESULTS

A third set of tests were conducted at Pantex by Paul Kramer. In those tests, the bulkheads were 304 stainless steel, the donor length was a constant 0.32 inches, and the explosive was LX13. No records of explosive density were maintained since LX13 has a constant density of 1.53 g/cc. The results from all of the PMMA / VISAR tests are shown on Figure 3. All of the PMMA particle velocity results have been converted to the pressure in the steel bulkhead. Inconel data were reduced using the Hugoniot for 304 steel. The data points on Figure 3 are the peak pressures that were obtained. The actual VISAR traces from which Figure 3 was generated are shown in the Appendix, Figures A1, A2, A3, and A4. The straight lines are linear fits to the data.

There are several aspects of Figure 3 that merit discussion. Most obvious is that the highest peak pressures were obtained using the flying plate as the donor. Due to the flyer thickness, and hence the duration of the shock input pulse, the output pulse has a short duration. The second observation is the disagreement between the pressure data for steel / PETN obtained here as compared to obtained by Schwartz[1] for the same materials. This disagreement is probably real and is attributed to the different test configurations. For example, Schwartz used a donor diameter of 0.125 inch, compared to 0.156 inch here. Also, the detonators that initiated the donors were quite different. Schwartz used a detonator with a PETN output from a column that was about 0.1 inches in diameter. The RP-2 on the other hand has an explosive diameter of 0.156 inches and a RDX output pellet. The more brisant donor used here may explain the higher shock pressures that were observed in this study at the bulkhead/PMMA interface. A third observation is in regard to the relative behavior of BNCP versus PETN. When in a steel TBI configuration (with a constant 0.080 inch long donor), the shock pressure for PETN was higher than for BNCP, however when in the Inconel TBI configuration (with much longer donors), the effect was reversed. The longer donor lengths in the Inconel tests may also have had some effect on this result, particularly if the BNCP donors were not reaching full detonation in the shorter lengths. Note also that in Table 1, the density of the shorter BNCP pressings was about 1.73 g/cc in the steel housings. In Table 2, the density in the Inconel housings was about 1.8 g/cc. This density difference may also partially explain the reversal in behavior. Regardless, there is no reason to suspect the data.

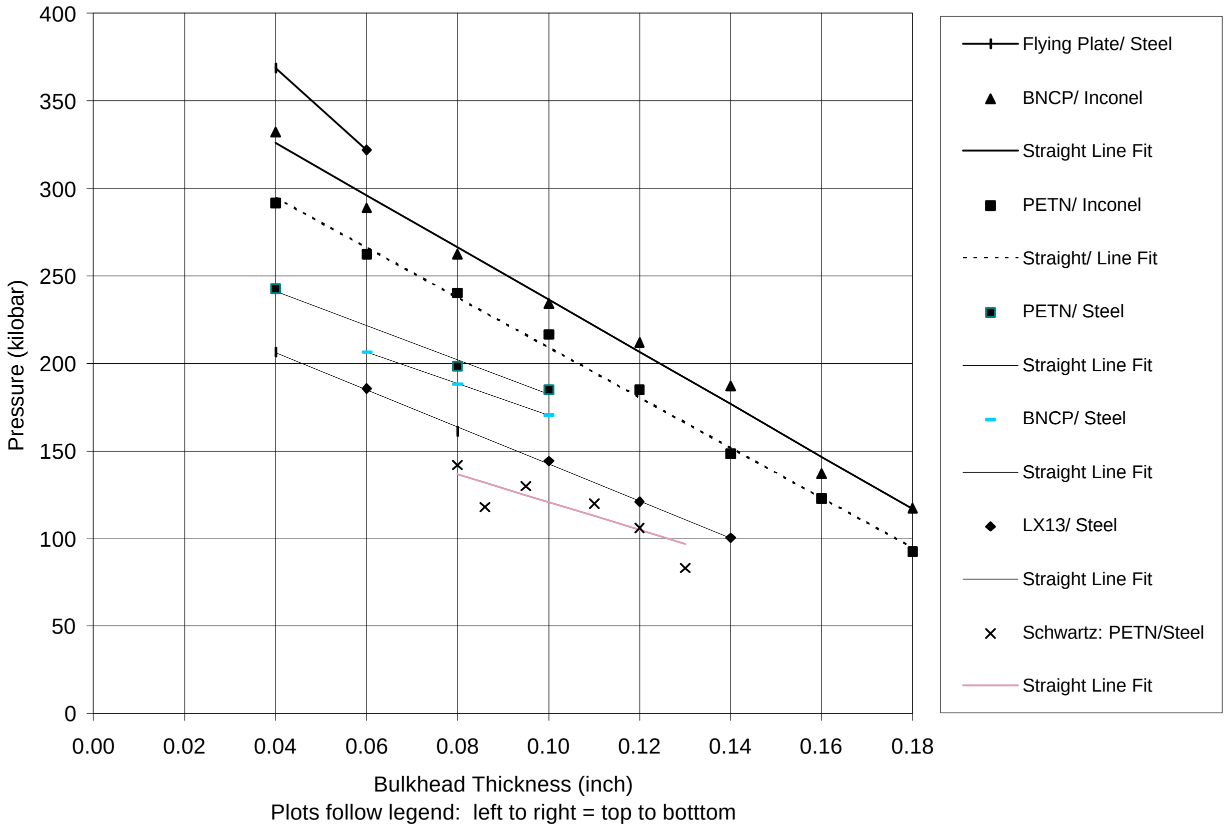

Figure 3. Bulkhead Pressure as a Function of Thickness, Donor, and Material

FUNCTION TIME RESULTS (at the bulkhead)

Another important aspect of a TBI design is consistent and predictable function time. The timing data in Table 1 and Table 2 were analyzed based upon the function time of the detonator, the detonation velocity of the donor explosive, and the shock velocity in the metal bulkhead. The constants chosen for these parameters were selected to provide the best fit to the experimental data. Additional information regarding the calculations is shown in the Appendix, Tables 6, 7, and 8. The RP-2 function time was measured at 2.43 and 2.47 µs, however 2.35 µs was used in the calculations. The reported[5,6] detonation velocity of PETN at a density of 1.6 g/cc is 7.74 mm\ µs. For these calculations however, the velocity chosen was 7.0 mm/µs. Likewise, the BNCP detonation velocity was chosen to be 6.0 mm/µs. The shock velocity in the metal was calculated from the steel Hugoniot data using the measured particle velocity. Note that this velocity is at the bulkhead surface, and not the average velocity across the bulkhead; that is, attenuation was ignored. It is recognized that the shock velocity on this surface is lower than the average velocity, thus the predicted function times are slightly greater than a true prediction, however this contribution to the function time is relatively small. The graphs of these data are shown on Figure 4 and Figure 5. Had the measured RP-2 detonator function time and reported detonation velocities been used for these fits, the predicted lines would have shifted up by 0.1 µs and the slope would have been slightly steeper. Note that the data encompasses a L\t ratio that varies from 0.8 to 7.5.

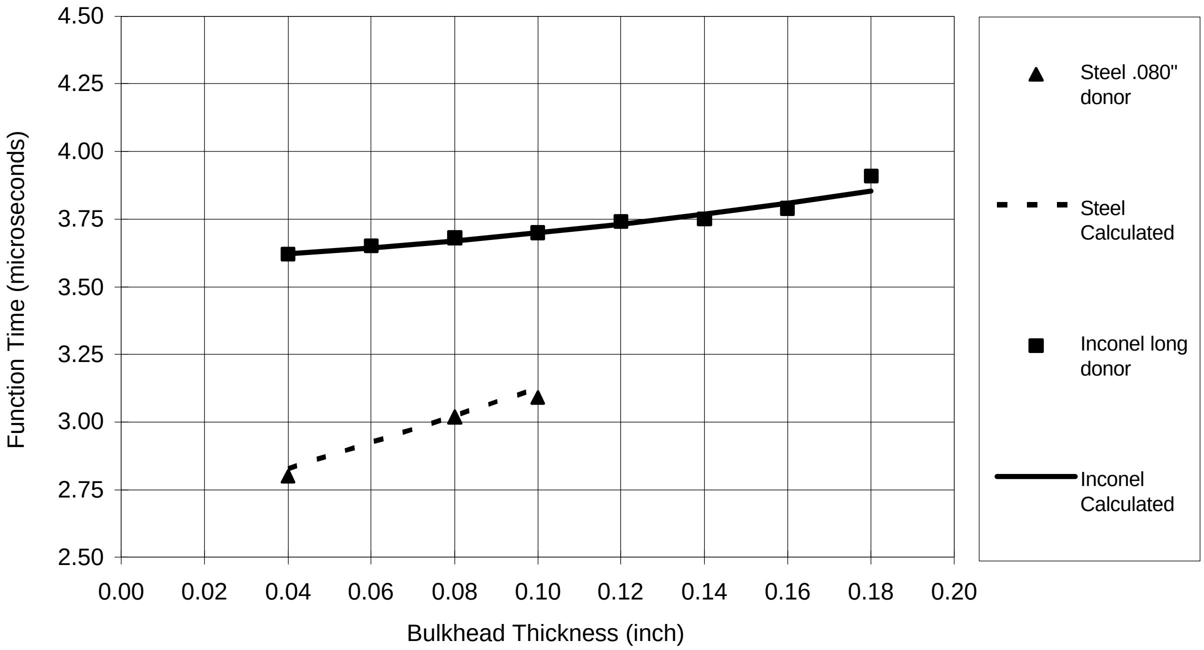

Figure 4. Function Time of the Shock Pulse on the Bulkhead Surfaces with PETN Donors.

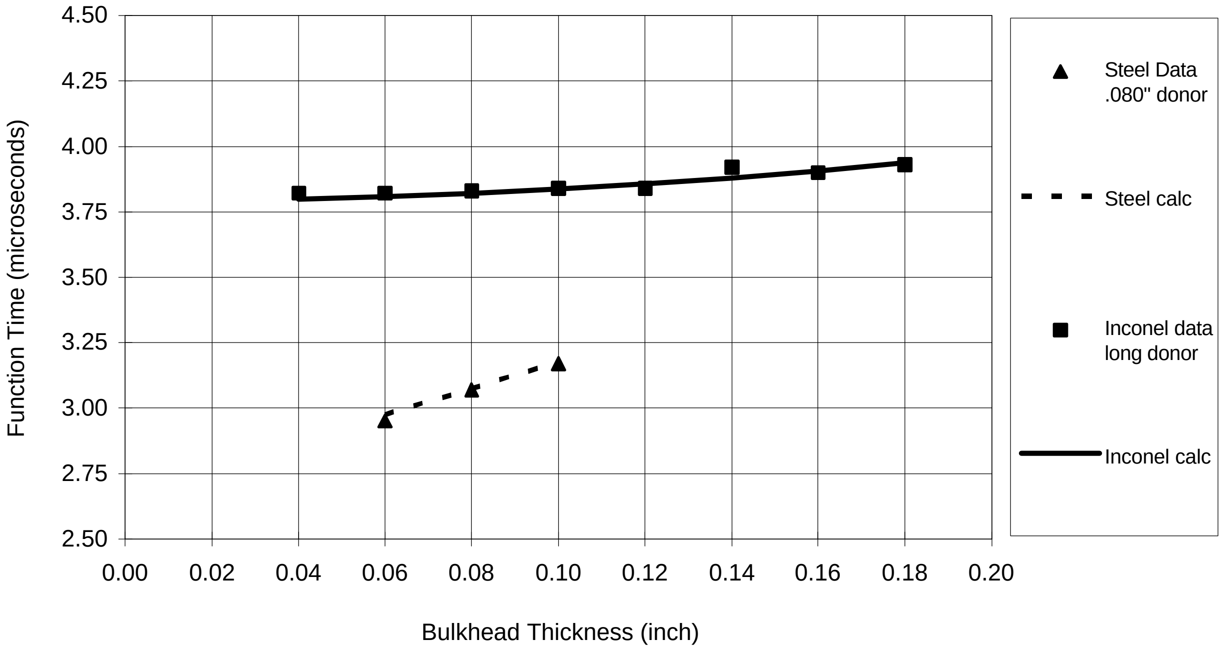

Figure 5. Function Time of the Shock Pulse on the Bulkhead Surface with BNCP Donors.

EXPLOSIVE ACCEPTOR (TBI) CHARACTERIZATION STUDIES.

STEEL BULKHEAD OUTPUT RESULTS

The test samples for the TBI tests are depicticted in Figure 6. The seal disks were 0.25 inch diameter stainless steel disks that were 0.005 inches thick. They were attached to the bulkhead structure with Eastman 910 adhesive. As noted earlier, the measure of performance was the acceleration and final velocity of the flying plate that was sheared from the seal disk. These VISAR traces are shown on Figures 8 through 11. Throughout this study, the operator of the VISAR system experienced low reflected light levels due to poor surface finish of the flying plates. This caused poor signal acquisition after about 0.5 μs of flyer travel on most of the tests. The data is not shown after becoming erratic. This is not an indication of poor TBI behavior, but of an artifact of the VISAR measurement (surface finish of the flyers). On all of the VISAR plots, the data is positioned on the time axis to more clearly show the differences between samples. The location of individual plots from left to right corresponds to the legend identification from top to bottom. The function times of the individual tests are shown in the corresponding Tables in the Appendix (Tables 3, 4, and 5), and will be discussed in a manner like shown earlier with the PMMA bulkhead tests.

The explosive acceptors were either a flying plate, PETN at a density of 1.0 g/cc, or BNCP at a density of 1.2 g/cc. A few tests were conducted with BNCP at a density of 1.0 g/cc in the constant length steel configuration. In all cases, an HMX output pellet was used to accelerate the flying plate. This output pellet was chosen to duplicate that used in the MC3990A Detonator[4] so that results could be compared to a known device. For future reference, the MC3990A accelerates a 0.005 inch thick Hastelloy flyer an average flyer velocity to 2.7 mm/μs (at a distance of 2 mm). Note that in all of these tests, the donor diameter is about twice that of the acceptor and also matches the explosive diameter of the RP-2 detonator. The TBI samples also match the donor configuration of the PMMA / VISAR test specimens.

Figure 7 shows the VISAR data from the 0.005 inch thick donor flying plate from the RP-2 detonator and for the flyers from the steel TBI tests that used the RP-2 flyer as the donor. Figure 8 shows the flyer data for the steel TBI tests that used explosive donors. The BNCP acceptors at 1.2 g/cc showed higher terminal velocities than did the units with BNCP at 1.0 g/cc. No further tests were conducted with the lower density material. Note that all of the TBI samples would have exceeded 2.5 mm/μs. As a point of reference, the acceleration behavior of all the flyers shown on Figures 7 and 8 are well behaved. The reason for the initial jump of the flyer from the RP-2 being slower than that of the TBI units is not known, but may be related to when the flyer was sheared from the bulk of the seal disk, or to the explosive confinement. On both Figures 7 and 8, it is apparent that flyers from PETN TBIs reached terminal velocity quicker than those with BNCP. This is indicative of prompter detonation of PETN.

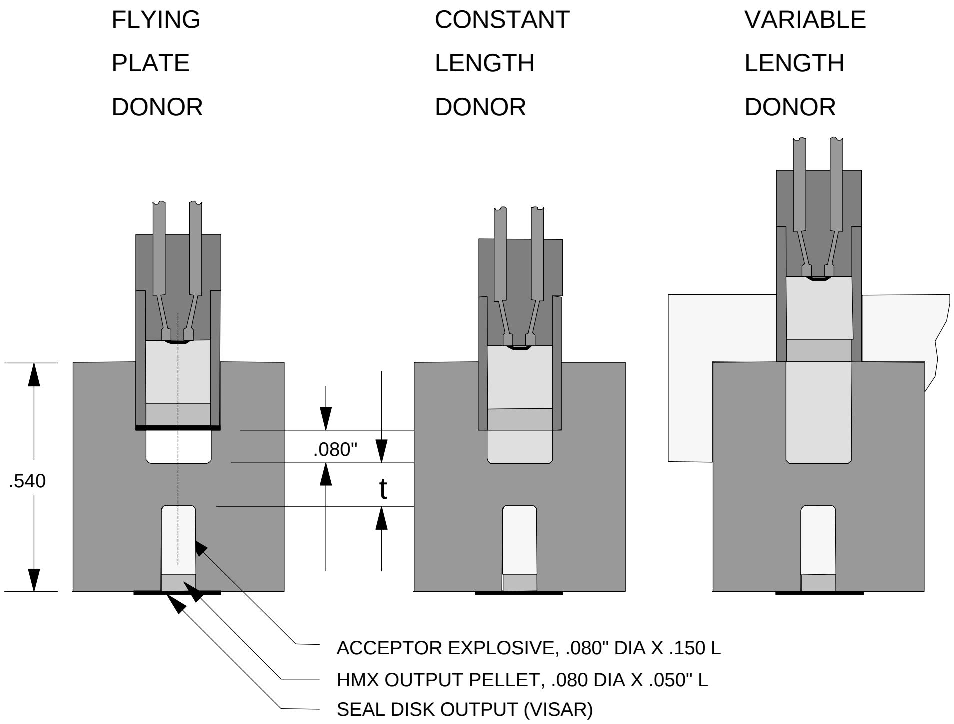

Figure 6. TBI test configurations.

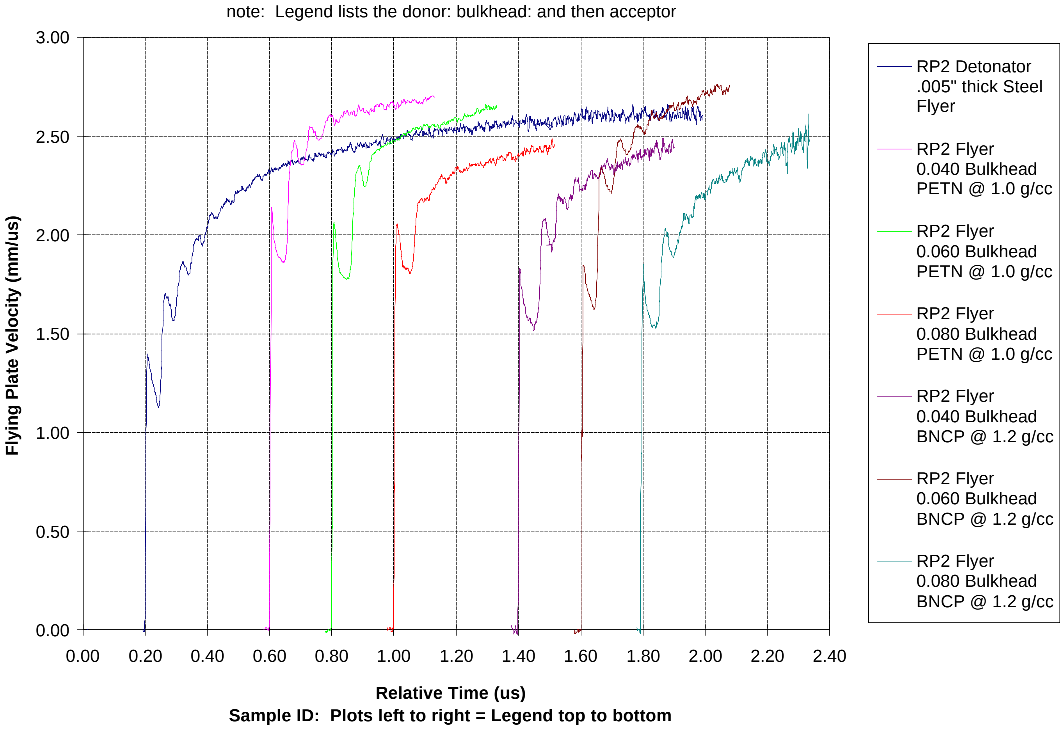

Figure 7. VISAR Traces of the Flying Plate from the RP-2 Detonator and from the Steel Bulkhead TBI Tests with Flying Plate Donors.

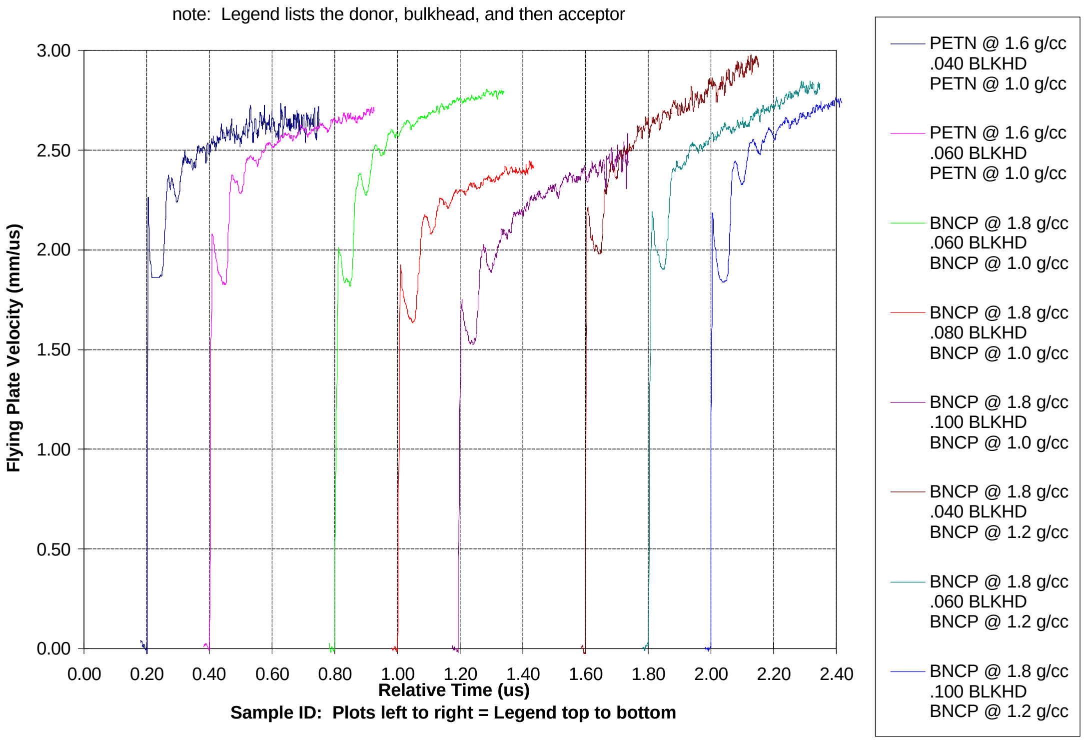

Figure 8. VISAR Traces of Flying Plate Outputs from Steel TBIs with Explosive Donors

INCONEL BULKHEAD OUTPUT RESULTS

The majority of the Inconel 718 bulkhead tests used samples like those shown on the right side of Figure 6 where the donor length was a variable between 0.18 and 0.24 inch. Four tests were conducted with the 0.080 inch long donor, two with PETN and two with BNCP. Table 4 gives the loading data and function times. The samples in Table 4 were tested at ambient temperature, and there was no thermal cycling of the parts. The VISAR results are shown on Figure 9 and Figure 10 for PETN and BNCP respectively. Note that these figures also contain the data for the .060 and .080 inch thick bulkhead units that were thermal cycled and tested at -65°F. Their loading data are in Table 5. Overall, the behavior of the flying plates was quite good, with some of the flying plate velocity profiles staying flat for a microsecond. The units with PETN acceptors tended to reach terminal velocity within 0.1 μs after the initial jump. In contrast, the units with BNCP acceptors were still showing a gradually increasing flyer velocity. This observation was also made with steel bulkhead units and further supports the conclusion that PETN was undergoing prompt detonation off the bulkhead where as the BNCP was not. One anomaly on Figure 9 is the velocity trace for the 0.160 inch thick bulkhead unit with PETN. It's initial acceleration was slower than the rest of the TBIs for reasons unknown. As with the steel TBIs, the BNCP units had higher terminal velocities than did the PETN units.

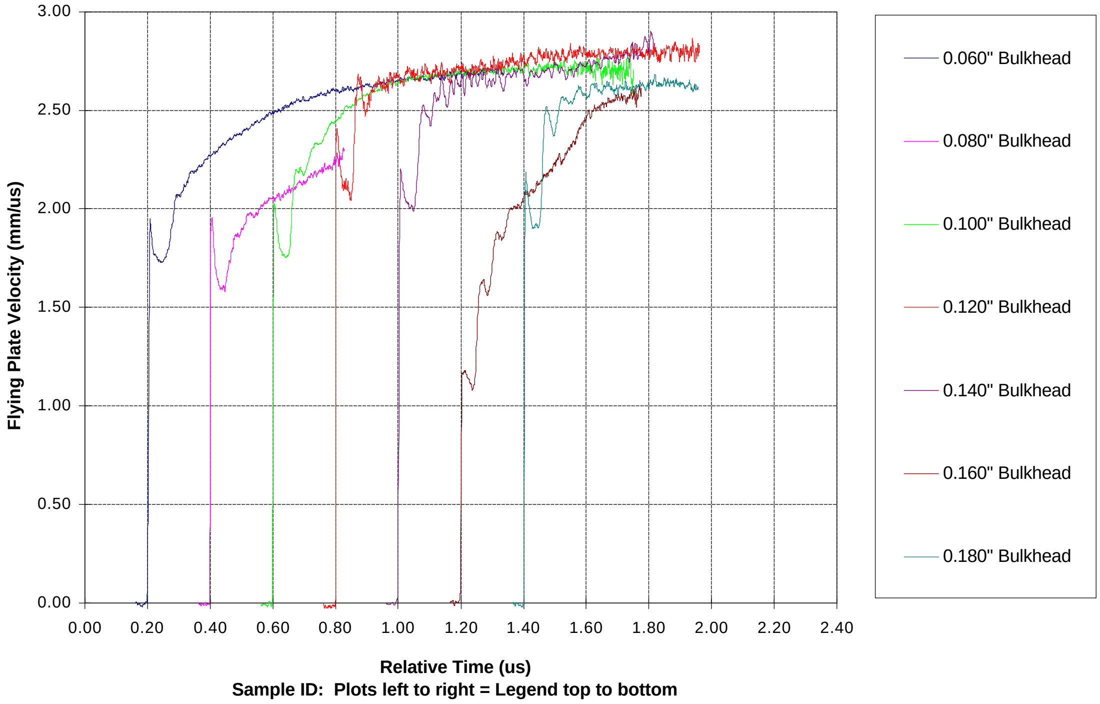

Figure 9. VISAR Traces for the Inconel TBIs with PETN Donors and Acceptors.

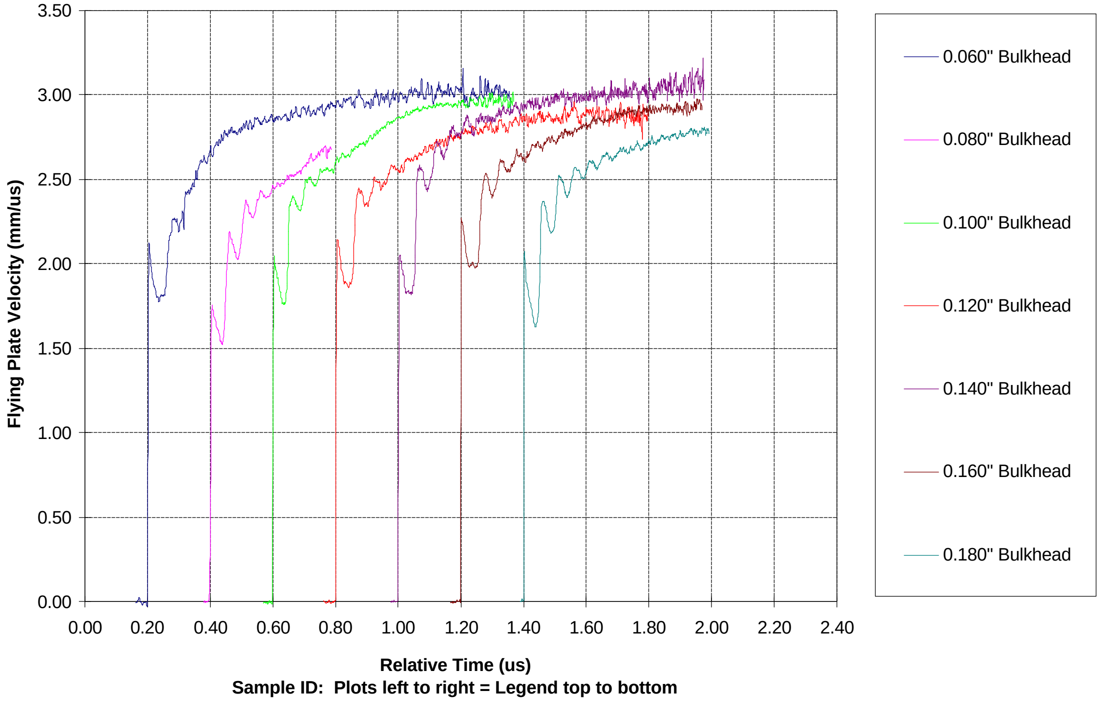

Figure 10. VISAR Traces for Inconel TBIs with BNCP Donors and Acceptors.

The final set of Inconel TBIs were thermal cycled and tested at -65°F. These were units with flying plate donors and 0.080 inch long donors and long donors. The thermal cycling consisted of transporting the samples between thermal chambers that were stabilized at -65°F and +165°F. The samples were left in each thermal chamber for a minimum of 4 hours and the transfer between chambers occurred rapidly so that the units experienced a thermal shock. Four complete cycles of cold to hot to cold were given. The units were then tested at -65°F which is generally considered the worst a severe case for explosive testing. The bulkhead thicknesses in this phase of the study were 0.080 inches and 0.060 inches. The loading data for these samples is shown in Table 5. The VISAR test results for these units are shown on Figure 11. The longer donor results were also shown on Figure 9 and Figure 10.

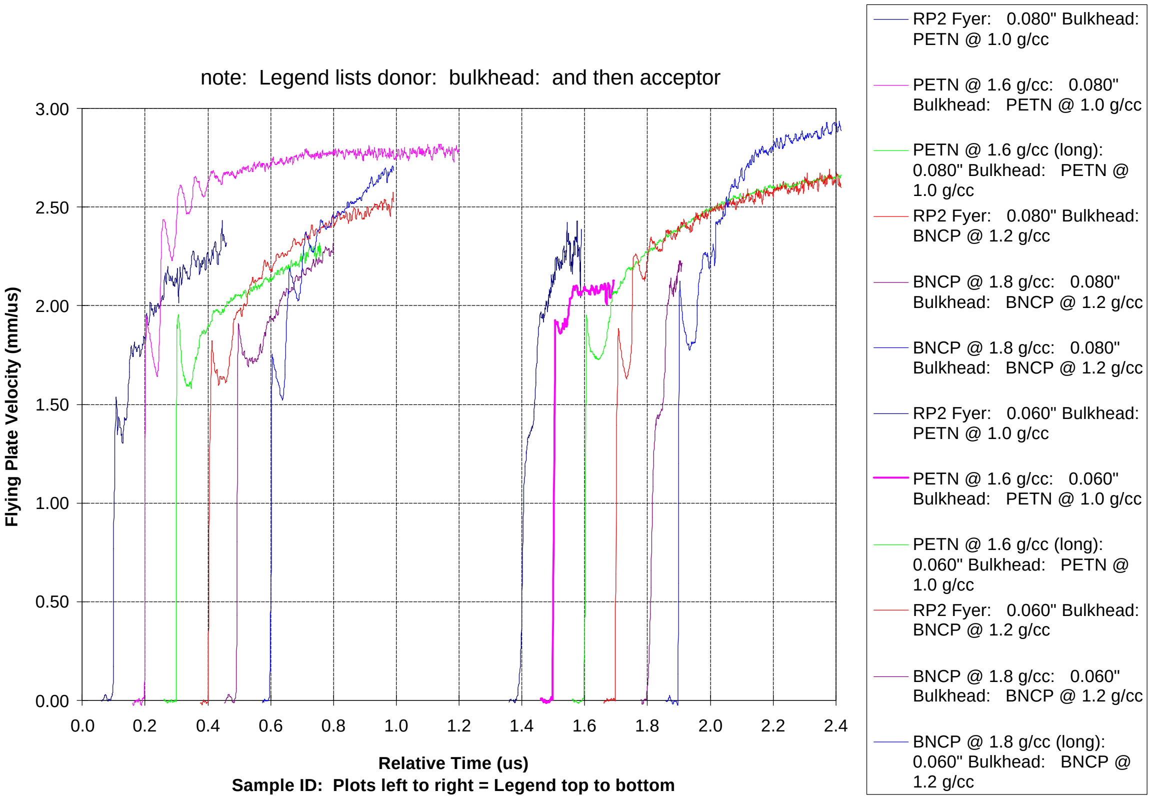

Figure 11. VISAR test results for Inconel TBI units that were thermal cycled and fired at -65F.

Of these twelve tests, only three showed the proper flyer acceleration. The VISAR operator observed that some of the glued flying plates were loose after the thermal cycling, and this could account for the erratic acceleration behavior shown above. The use of the glued seal disks (which became the flying plates) compromised the validity of the thermal cycling stability argument. However, since some of these units did behave properly, thermal cycling should not be a problem, particularly with BNCP explosive units. If the opportunity arises, some portion of this work should be repeated using welded seal disks with good surface finishes.

TBI FUNCTION TIME RESULTS

In Figure 4 and Figure 5, it was shown that the arrival time of the pressure pulse on the bulkhead surface could be accounted for by the detonation velocity of the donor and the shock velocity in the metal. The predicted corresponding function time for first motion of the flying plate output would be the predicted function time calculations used in Figure 4 and Figure 5 increased by the detonation time of the acceptor portion of the TBI sample. The reported detonation velocities of PETN at a density of 1.0 g/cc (5.52 mm\µs[5]) and HMX at a density of 1.89 g/cc (9.1 mm\µs[6]) were used to arrive at an acceptor detonation time of 0.83 µs for the PETN samples. For the BNCP samples, the acceptor detonation time was arbitrarily chosen to be 1.0 µs which equates to a BNCP detonation velocity of 4.4 mm\µs. This value is reasonable for the lower density pressing of BNCP. The results are shown on Figure 12 and Figure 13. On Figure 12, the data point for the 0.08 inch long donor / 0.100 inch thick bulkhead test appears to be faster than expected. The data for the long variable donors appears to be consistently 0.1 µs slower than predicted. This excess transit time is assumed to be a characteristic induction time at the bulkhead/PETN and PETN\HMX interfaces. The data at cold temperatures show longer function times than at ambient, which is an expected result.

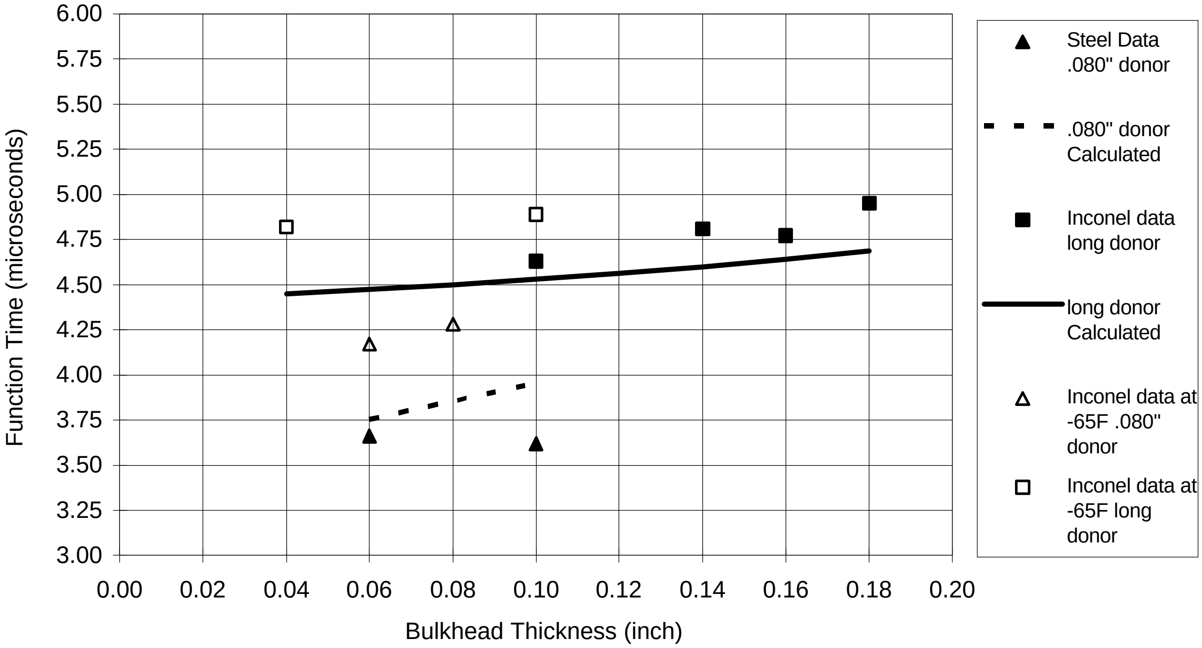

Figure 12. Function Time Data from the TBI Units with PETN donors.

The BNCP data shown on Figure 13 give somewhat different results. There is negligible induction time, particularly with the 0.08 inch long donor tests. With the longer donors however, a similar induction time is observed for the 0.1 inch bulkhead test. Then as the bulkheads become thicker, the excess transit times shows a consistent increase. This phenomenon is consistent with the classic deflagration to detonation transition (DDT) process. The DDT time increases as the bulkhead thickness gets larger since the input pressure to the explosive acceptor is decreasing. Evidence of the occurrence of DDT will be discussed later in the “Bulkhead Integrity” Section of the report. As with the PETN tests, the BNCP cold tests showed longer function times than equivalent tests at ambient.

The function time data from the flying plate donors are plotted on Figure 14. The time for the flyer to travel the 0.08 inch to the bulkhead input surface was found to be 0.9µs. This quantity combined with the detonator function time, bulkhead shock transit time, and acceptor time resulted in the calculated results shown on Figure 14. For the PETN acceptors, there was a small amount of induction time as experienced with the explosive donors. Also, the data taken at -65°F had longer function times than at ambient temperature. The data point for BNCP on a 0.040 inch thick steel bulkhead was not used. Note in Table 3, sample #10, that the measured function time was 6.41 µs, which is clearly out of line. The data for both explosives at -65°F are not only slower than at ambient, but also show a stronger dependence on bulkhead thickness or input pressure. This was not the case with explosive donors (see Figure 12 and Figure 13). It is not known if the stronger bulkhead thickness dependence is real.

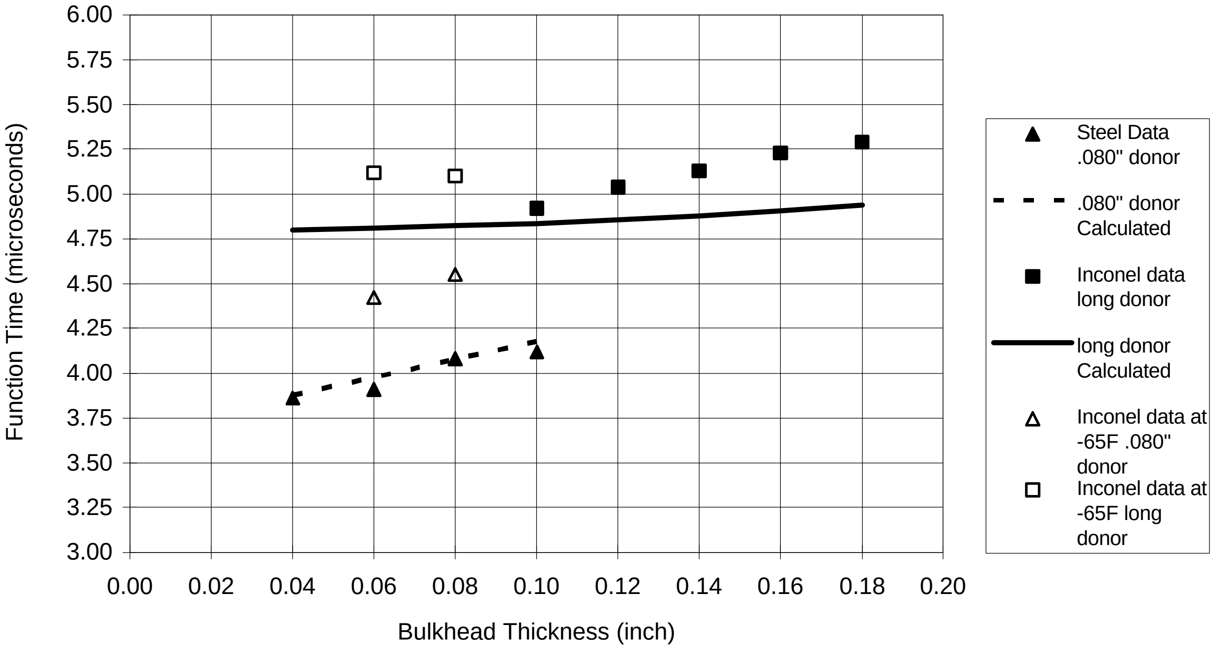

Figure 13. Function Time Data for the BNCP TBI Units.

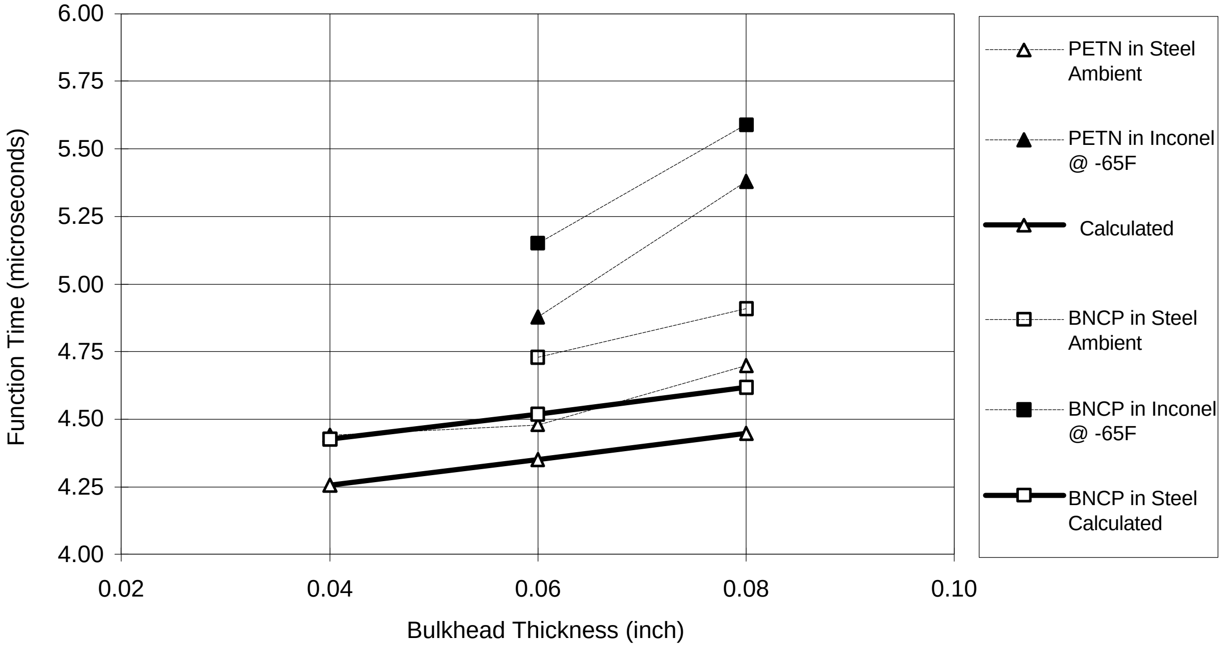

Figure 14. Function Time Results for the Tests That Used Flying Plate Donors.

BULKHEAD INTEGRITY

A few of the bulkheads were sectioned after functioning to study the mechanical integrity of the TBI designs. The records (shown in the APPENDIX, Figures A 5 through A 12) are digitally scanned images of photomicrographs from TBI units that were sectioned. The units were not cut exactly in half, nor are all of the magnifications the same, therefore the size of these images are relative. The aspects of interest are the amount of flaring in the acceptor location and the presence of cracks in the bulkhead. Figure A 5 is from a steel bulkhead PMMA test showing the rupture of the bulkhead when not supported by a detonating acceptor. Figure A 6 is from a 0.040” thick bulkhead with PETN as the donor and acceptor. Note the complete absence of cracks and the straight sidewalls of the acceptor region which indicates relatively prompt detonation of the low density pressing of PETN. Because this sample appeared to be optimum, no other PETN samples were examined. Figure A 7 shows a .080” steel TBI unit that used a BNCP acceptor and a flying plate donor. Note that there appears to be some DDT occurring in the acceptor (flaring) and excellent bulkhead integrity.

Figure A8 shows a 0.060” steel TBI unit that used the 0.080 inch long donor of BNCP and a BNCP acceptor. There was excellent bulkhead integrity in this test, and apparent prompt detonation evidenced by the lack of flaring. Figure A 9 through Figure A 12 show small cracks on the donor surface of the bulkhead. Figure A 8 is like Figure A 9 except for the 0.020 inch increase in bulkhead thickness. The crack in Figure A 9 is barely visible. This is consistent with the concept of equalizing the pressure on both sides of the bulkhead to maintain integrity. Stated otherwise, thinner bulkheads are the better design choice when detonation of both donor and acceptor is present The argument is strengthened when viewing Figure A 10 where the bulkhead thickness is now up to 0.1000 inches (the other parameters are the same). Here the cracking is more evident and the flaring in the acceptor region becomes more pronounced with the increasing bulkhead thickness.

Figure A 11 and Figure A 12 are of the long donor Inconel TBI tests with BNCP. The major difference between these two shots is the donor length. Note that the amount of flaring on the .18 inch bulkhead is greater than on the 0.100 inch bulkhead. This is consistent with the increasing DDT time shown on Figure 13. Note also that there is significant cracking in the TBI structure for the two Inconel tests.

CONCLUSIONS

The overall conclusions are that 304 steel is probably a better choice than Inconel as the TBI structural material, and that if explosive donors are to be used, the longer donor length will decrease the DDT length of the acceptor and probably provide more precision timing, however the function time will be slightly longer due to the increased donor length. If one wishes to significantly reduce the amount of explosive in the component design, the flying plate is quite acceptable as a donor. In any case, the optimum bulkhead thickness is probably in the range of 0.060 to 0.080 inches. At greater thicknesses, the later detonation time (hence greater pressure differential) of the acceptor allows the donor to cause cracks in the bulkhead.

As noted earlier, the use of glued flyers compromised the integrity of the data that was taken on the thermal cycled units. A few of the flyers had to be reattached prior to test. Thus, movement of the acceptor explosive during the thermal cycling was not constrained as it would have been in a welded configuration. The donor explosives were constrained during the thermal cycling with no apparent degradation in performance. It is believed that thermal cycling is not a concern as originally postulated, however the thermal cycling tests should be repeated with steel bulkheads and welded flying plates with optimum surface finishes for VISAR diagnostics. Also, bulkhead integrity should be addressed in a reverse detonation scenario. That is, an ideal fail-safe TBI configuration would maintain bulkhead integrity regardless of the direction of detonation. This aspect of the TBI design was not tested.

REFERENCES

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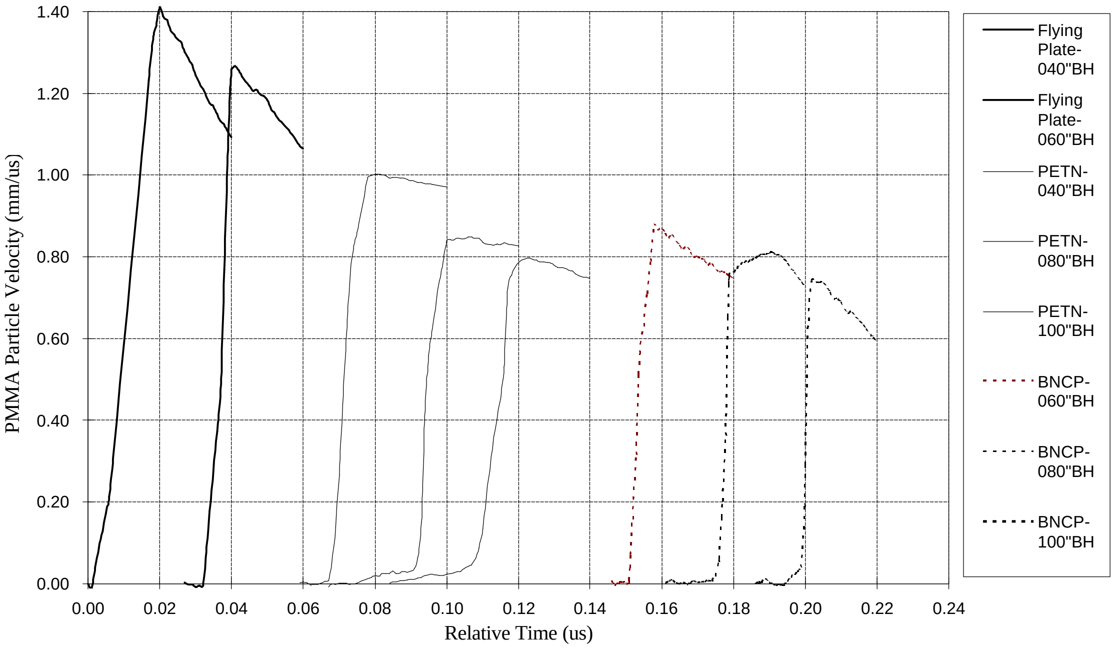
APPENDIX

Table 1. Loading Data for Donor Tests with Steel Bulkheads.

PMMA PRESSURE STUDIES: MATERIAL: 304L S. STL.
OVERALL LENGTH=.340" CONSTANT (.080") DONOR LENGTH

SERIAL #		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
BULKHEAD THICKNESS	(inch)	0.040	0.060	0.080	0.100	0.040	0.060	0.080	0.100
RP2 COUNTERBORE	(inch)	0.220	0.200	0.180	0.160	0.220	0.200	0.180	0.160
DONOR EXPLOSIVE	(ρ)	NONE	NONE	PETN (1.6)	PETN (1.6)	PETN (1.6)	BNCP(1.8	BNCP(1.8)	BNCP(1.8)
TARE + EXPLOSIVE	(gram)	0.005"	0.005"	7.7560	7.8430	7.5984	7.6846	7.7567	7.8460
TARE	(gram)	FLYING	FLYING	7.7178	7.8040	7.5599	7.6409	7.7137	7.8025
EXPLOSIVE WEIGHT	(gram)	PLATE	PLATE	0.0382	0.0390	0.0385	0.0437	0.0430	0.0435
DENSITY	(g/cc)			1.52	1.56	1.54	1.74	1.72	1.74
FUNCTION TIME	(æs)	3.55	3.57	3.02	3.09	2.80	2.95	3.07	3.17



Sample IDs: Plots left to right = Legend top to bottom

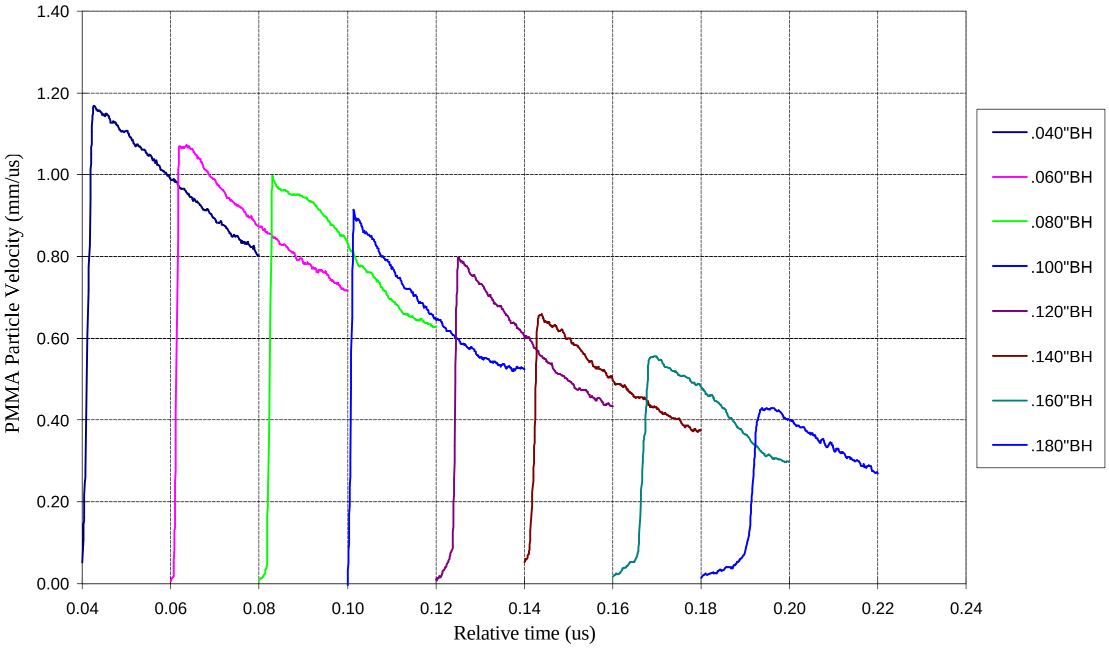
Figure A 1. Particle Velocities from the Steel Bulkheads with Various Donors.

Table 2. Loading Data for Donor Tests with Inconel Bulkheads

PMMA PRESSURE STUDIES: MATERIAL: INCONEL 417
LENGTH=.340" VARIABLE DONOR LENGTHS

SERIAL #		*I-1*	*I-2*	*I-3*	*I-4*	*I-5*	*I-6*	*I-7*	*I-8*
BULKHEAD THICKNESS	(inch)	0.180	0.180	0.160	0.160	0.140	0.140	0.120	0.120
DONOR LENGTH	(inch)	0.160	0.160	0.180	0.180	0.200	0.200	0.220	0.220
DONOR EXPLOSIVE	(ρ)	PETN (1.6)	BNCP (1.8)	PETN (1.6)	BNCP (1.8)	PETN (1.6)	BNCP (1.8)	PETN (1.6)	BNCP (1.8)
TARE + EXPLOSIVE	(gram)	8.6715	8.7042	8.6257	8.6391	8.5943	8.6042	8.5596	8.5884
TARE	(gram)	8.5971	8.6192	8.5421	8.5448	8.4998	8.4974	8.4555	8.4717
EXPLOSIVE WEIGHT	(gram)	0.0744	0.0850	0.0836	0.0943	0.0945	0.1068	0.1041	0.1167
DENSITY	(g/cc)	1.58	1.81	1.58	1.79	1.61	1.82	1.61	1.81
FUNCTION TIME	(æs)	3.91	3.93	3.79	3.90	3.75	3.92	3.74	3.84

SERIAL #		*I-9*	*I-10*	*I-11*	*I-12*	*I-13*	*I-14*	*I-15*	*I-16*
BULKHEAD THICKNESS	(inch)	0.100	0.100	0.080	0.080	0.060	0.060	0.040	0.040
DONOR LENGTH	(inch)	0.240	0.240	0.260	0.260	0.280	0.280	0.300	0.300
DONOR EXPLOSIVE	(ρ)	PETN (1.6)	BNCP (1.8)	PETN (1.6)	BNCP (1.8)	PETN (1.6)	BNCP (1.8)	PETN (1.6)	BNCP (1.8)
TARE + EXPLOSIVE	(gram)	8.5253	8.5276	8.4972	8.5122	8.4620	8.4592	8.4193	8.4309
TARE	(gram)	8.4108	8.4003	8.3758	8.3745	8.3300	8.3117	8.2786	8.2721
EXPLOSIVE WEIGHT	(gram)	0.1145	0.1273	0.1214	0.1377	0.1320	0.1475	0.1407	0.1588
DENSITY	(g/cc)	1.63	1.81	1.59	1.80	1.61	1.80	1.60	1.80
FUNCTION TIME	(æs)	3.70	3.84	3.68	4.09?	3.65	3.82	3.62	3.82



Sample ID: Plots left to right = Legend top to bottom

Figure A 2. Particle Velocities from Inconel Bulkheads with PETN donors.

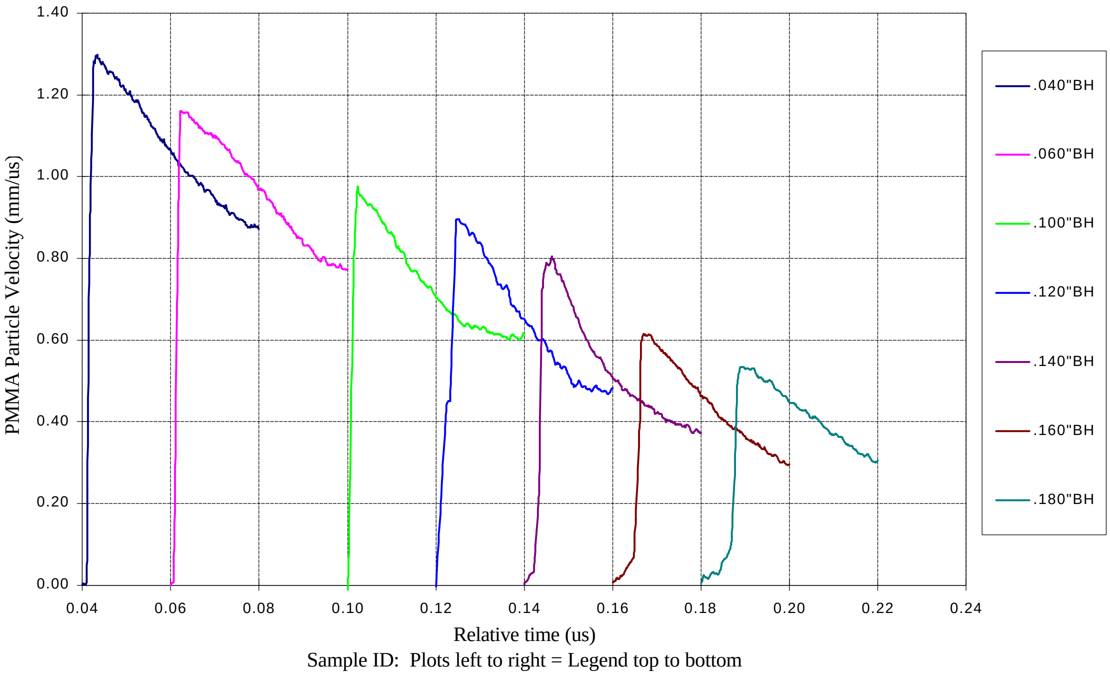


Figure A 3. Particle Velocities from Inconel Bulkheads with BNCP Donors.

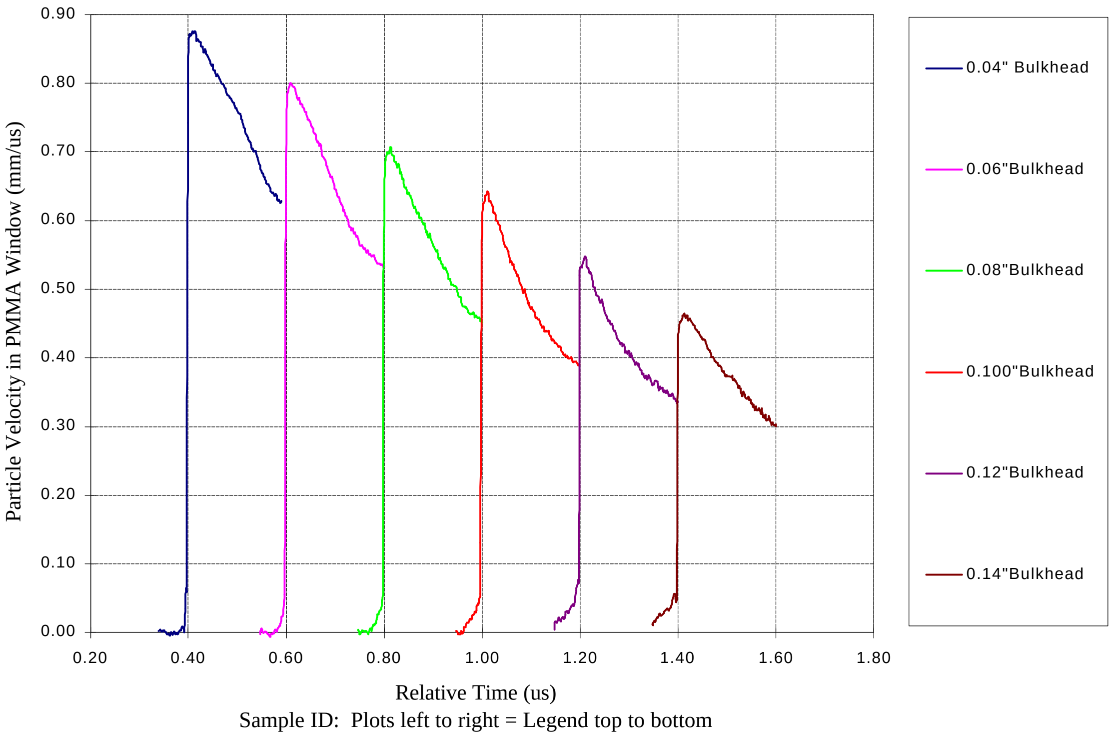


Figure A 4. Particle Velocities in Steel Bulkheads with LX13 Donors

Table 3. Loading Data for Steel TBI tests.

TBI VISAR TEST SAMPLES MATERIAL: 304L S. STL.
OVERALL LENGTH=.540" CONSTANT DONOR (.080") & ACCEPTOR (.200') LENGTHS

SERIAL #		*9*	*10*	*11*	*12*	*13*	*14*	*15*
BULKHEAD THICKNESS	(inch)	0.040	0.040	0.040	0.040	0.060	0.060	0.060
RP2 CB Depth	(inch)	0.220	0.220	0.220	0.220	0.200	0.200	0.200
DONOR EXPLOSIVE	(ρ)	NONE	NONE	PETN (1.6)	BNCP (1.8)	NONE	NONE	PETN(1.6)
TARE + EXPLOSIVE	(gram)	0.005"	0.005"	12.5537	12.5644	0.005"	0.005"	12.6288
TARE	(gram)	FLYING	FLYING	12.5166	12.5224	FLYING	FLYING	12.5909
EXPLOSIVE WEIGHT	(gram)	PLATE	PLATE	0.0371	0.0420	PLATE	PLATE	0.0379
DENSITY	(g/cc)			1.58	1.79			1.61
ACCEPTOR EXPLOSIVE	(ρ)	PETN (1.0)	BNCP (1.2)	PETN (1.0)	BNCP (1.2)	PETN (1.0)	BNCP (1.2)	PETN (1.0)
TARE + EXPLOSIVE	(gram)	12.5148	12.5358	12.5678	12.5814	12.5990	12.6147	12.6419
TARE	(gram)	12.5008	12.5208	12.5537	12.5649	12.5854	12.5978	12.6288
EXPLOSIVE WEIGHT	(gram)	0.0140	0.0150	0.0141	0.0165	0.0136	0.0169	0.0131
DENSITY	(g/cc)	1.11	1.18	1.11	1.30	1.07	1.33	1.03
HMX PELLET WEIGHT	(gram)	0.0076	0.0073	0.0070	0.0071	0.0070	0.0073	0.0075
FUNCTION TIME	(æs)	4.44	6.41	3.66	3.86	4.48	4.73	3.62

SERIAL #		*16*	*17*	*19*	*20*	*22*	*23*	*25*	*26*
BULKHEAD THICKNESS	(inch)	0.060	0.060	0.080	0.080	0.080	0.080	0.100	0.100
RP2 COUNTERBORE	(inch)	0.200	0.200	0.180	0.180	0.180	0.180	0.160	0.160
DONOR EXPLOSIVE	(ρ)	BNCP (1.8)	BNCP (1.8)	NONE	NONE	BNCP (1.8)	BNCP (1.8)	BNCP (1.8)	BNCP (1.8)
TARE + EXPLOSIVE	(gram)	12.6324	12.6336	0.005"	0.005"	12.7099	12.7099	12.7809	12.7967
TARE	(gram)	12.5894	12.5908	FLYING	FLYING	12.6642	12.6675	12.7386	12.7544
EXPLOSIVE WEIGHT	(gram)	0.0430	0.0428	PLATE	PLATE	0.0457	0.0424	0.0423	0.0423
DENSITY	(g/cc)	1.83	1.82			1.95	1.81	1.80	1.80
ACCEPTOR EXPLOSIVE	(ρ)	BNCP (1.0)	BNCP (1.2)	PETN (1.0)	BNCP (1.2)	BNCP (1.0)	BNCP (1.2)	BNCP (1.0)	BNCP (1.2)
TARE + EXPLOSIVE	(gram)	12.6453	12.6500	12.6780	12.6861	12.7207	12.7250	12.7940	12.8125
TARE	(gram)	12.6325	12.6340	12.6655	12.6696	12.7073	12.7100	12.7808	12.7967
EXPLOSIVE WEIGHT	(gram)	0.0128	0.0160	0.0125	0.0165	0.0134	0.0150	0.0132	0.0158
DENSITY	(g/cc)	1.01	1.26	0.99	1.30	1.06	1.18	1.04	1.25
HMX PELLET WEIGHT	(gram)	0.0072	0.0072	0.0072	0.0071	0.0072	0.0073	0.0071	0.0075
FUNCTION TIME	(æs)	4.70	3.91	4.70	4.91	4.08	4.08	4.43	4.12

Table 4. Loading Data for Inconel TBI tests.

TBI VISAR TEST SAMPLES MATERIAL: INCONEL 718
OVERALL LENGTH=.540" VARIABLE DONOR (.080") & CONSTANT ACCEPTOR LENGTHS (.200")

SERIAL #		*I-1-1*	*I-1-2*	*I-2-1*	*I-2-2*	*I-3-1*	*I-3-2*
BULKHEAD THICKNESS	(inch)	0.180	0.180	0.160	0.160	0.140	0.140
RP2 COUNTERBORE	(inch)	0.160	0.160	0.180	0.180	0.200	0.200
DONOR EXPLOSIVE	(ρ)	PETN (1.6)	BNCP (1.8)	PETN (1.6)	BNCP (1.8)	PETN (1.6)	BNCP (1.8)
TARE + EXPLOSIVE	(gram)	13.8308	13.8280	13.7857	13.8058	13.7647	13.7745
TARE	(gram)	13.7558	13.7436	13.7002	13.7105	13.6701	13.6687
EXPLOSIVE WEIGHT	(gram)	0.0750	0.0844	0.0855	0.0953	0.0946	0.1058
DENSITY	(g/cc)	1.60	1.80	1.62	1.80	1.61	1.80
ACCEPTOR EXPLOSIVE	(ρ)	PETN (1.0)	BNCP (1.2)	PETN (1.0)	BNCP (1.2)	PETN (1.0)	BNCP (1.2)
TARE + EXPLOSIVE	(gram)	13.8443	13.8437	13.7983	13.8211	13.7773	13.7894
TARE	(gram)	13.8308	13.8280	13.7857	13.8058	13.7647	13.7745
EXPLOSIVE WEIGHT	(gram)	0.0135	0.0157	0.0126	0.0153	0.0126	0.0149
DENSITY	(g/cc)	1.09	1.27	1.02	1.24	1.02	1.21
HMX PELLET WEIGHT	(gram)	0.0076	0.0077	0.0073	0.0072	0.0075	0.0073
FUNCTION TIME	(æs)	4.95	5.29	4.77	5.23	4.81	5.13

SERIAL #		*I-4-1*	*I-4-2*	*I-5-1*	*I-5-2*
BULKHEAD THICKNESS	(inch)	0.120	0.120	0.100	0.100
RP2 COUNTERBORE	(inch)	0.220	0.220	0.240	0.240
DONOR EXPLOSIVE	(ρ)	PETN (1.6)	BNCP (1.8)	PETN (1.6)	BNCP (1.8)
TARE + EXPLOSIVE	(gram)	13.7178	13.7393	13.6683	13.6795
TARE	(gram)	13.6135	13.6233	13.5552	13.5526
EXPLOSIVE WEIGHT	(gram)	0.1043	0.1160	0.1131	0.1269
DENSITY	(g/cc)	1.62	1.80	1.61	1.80
ACCEPTOR EXPLOSIVE	(ρ)	PETN (1.0)	BNCP (1.2)	PETN (1.0)	BNCP (1.2)
TARE + EXPLOSIVE	(gram)	13.7303	13.7548	13.6808	13.6950
TARE	(gram)	13.7178	13.7393	13.6683	13.6795
EXPLOSIVE WEIGHT	(gram)	0.0125	0.0155	0.0125	0.0155
DENSITY	(g/cc)	1.01	1.25	1.01	1.25
HMX PELLET WEIGHT	(gram)	0.0073	0.0074	0.0072	0.0072
FUNCTION TIME	(æs)	9.26?	5.04	4.63	4.92

Table 5. Loading data for Thermal Cycled Inconel TBI Tests

TBI VISAR TEST SAMPLES
OVERALL LENGTH=.540"
.060" & .080" BULKHEADS

MATERIAL: INCONEL 718
MISCELLANEOUS DONORS
THERMAL CYCLED & TESTED @ -65 Deg F

SERIAL #	*I-6-1*	*I-6-2*	*I-6-3*	*I-6-4*	*I-6-5*	*I-6-6*
BULKHEAD THICKNESS (inch)	0.080	0.080	0.080	0.080	0.080	0.080
RP2 CB Depth (inch)	0.080	0.080	0.260	0.080	0.080	0.260
DONOR EXPLOSIVE (ρ)	FP	PETN (1.6)	PETN (1.6)	FP	BNCP (1.8)	BNCP (1.8)
TARE + EXPLOSIVE (gram)		13.2031	13.6435		13.1688	13.6574
TARE (gram)		13.1654	13.5214		13.1262	13.5199
EXPLOSIVE WEIGHT (gram)		0.0377	0.1221		0.0426	0.1375
DENSITY (g/cc)		1.61	1.60		1.81	1.80
ACCEPTOR EXPLOSIVE (ρ)	PETN (1.0)	PETN (1.0)	PETN (1.0)	BNCP (1.2)	BNCP (1.2)	BNCP (1.2)
TARE + EXPLOSIVE (gram)	13.1635	13.2158	13.6560	13.1629	13.1841	13.6724
TARE (gram)	13.1510	13.2031	13.6435	13.1477	13.1688	13.6574
EXPLOSIVE WEIGHT (gram)	0.0125	0.0127	0.0125	0.0152	0.0153	0.0150
DENSITY (g/cc)	1.01	1.03	1.01	1.23	1.24	1.21
HMX PELLET WEIGHT (gram)	0.0076	0.0077	0.0073	0.0076	0.0074	0.0074
FUNCTION TIME (æs)	5.38	4.28	4.82	5.59	4.55	5.1

SERIAL #	*I-7-1*	*I-7-2*	*I-7-3*	*I-7-4*	*I-7-5*	*I-7-6*
BULKHEAD THICKNESS (inch)	0.060	0.060	0.060	0.060	0.060	0.06
RP2 COUNTERBORE (inch)	FP	0.080	0.280	FP	0.080	0.28
DONOR EXPLOSIVE (ρ)	PETN (1.6)	PETN (1.6)	PETN (1.6)	BNCP (1.8)	BNCP (1.8)	BNCP (1.8)
TARE + EXPLOSIVE (gram)	0.005"	13.09990	13.59430	0.005"	13.09380	13.59020
TARE (gram)	FLYING	13.06370	13.46410	FLYING	13.05300	13.44400
EXPLOSIVE WEIGHT (gram)	PLATE	0.03620	0.13020	PLATE	0.04080	0.14620
DENSITY (g/cc)		1.54	1.58		1.74	1.78
ACCEPTOR EXPLOSIVE (ρ)	PETN (1.0)	PETN (1.0)	PETN (1.0)	BNCP (1.2)	BNCP (1.2)	BNCP (1.2)
TARE + EXPLOSIVE (gram)	13.0570	13.1126	13.6071	13.0747	13.1092	13.6055
TARE (gram)	13.0441	13.0999	13.5943	13.0594	13.0938	13.5902
EXPLOSIVE WEIGHT (gram)	0.0129	0.0127	0.0128	0.0153	0.0154	0.0153
DENSITY (g/cc)	1.04	1.03	1.04	1.24	1.25	1.24
HMX PELLET WEIGHT (gram)	0.0075	0.0076	0.0074	0.0074	0.0077	0.0075
FUNCTION TIME (æs)	4.88	4.17	4.89	5.15	4.42	5.12

Table 6. Straight Line Fit Coefficients to Bulkhead Pressure Data.

Explosive	PETN	PETN	BNCP	BNCP	LX13	Schwartz
Bulkhead	Steel	Inconel	Inconel	Steel	Steel	Steel
a	280.5	352.0	385.8	260.4	248.5	200.3
t (inch)	-980.0	-1428.6	-1493.9	-900.0	-1059.3	-795.4

In Table 6, P is in kilobars and t is the bulkhead thickness in inches. P=a + bt
See Figure 3 for the plot of the pressure data.

Table 7. Hugoniot Constants[7] for Calculating Shock Pressures

material		steel	PMMA
density	ρ	7.89	1.186
slope	S	1.49	1.516
intercept	C_o	4.58	2.598

$P = \sigma U_S U_p$
$U_S = C + S U_p$
$P = \sigma C U_p + \sigma S U^2_p$

Table 8. Constants used to Compute the Predicted Function Times.

(U_D) PETN donor detonation velocity	7.0 mm/μs
(U_D) BNCP donor detonation velocity	6.0 mm/μs
(U_D) PETN acceptor detonation velocity	5.52 mm/μs
(U_D) BNCP acceptor detonation velocity	4.43 mm/μs
(U_D) HMX acceptor detonation velocity	9.1 mm/μs
(t_D) RP-2 Detonator function time	2.35 μs

t_f (at bulkhead) = $t_D + t_{EXP} + t_B$
where $t_{EXP\ (d)}$ = donor length ÷ u_D
t_D = bulkhead thickness ÷ U_S (computed using Hugoniot data)

t_f (at flyer) = tf (at bulkhead) + $t_{EXP\ (a)}$
(acceptor explosives are either low density PETN or BNCP plus the HMX pellet)

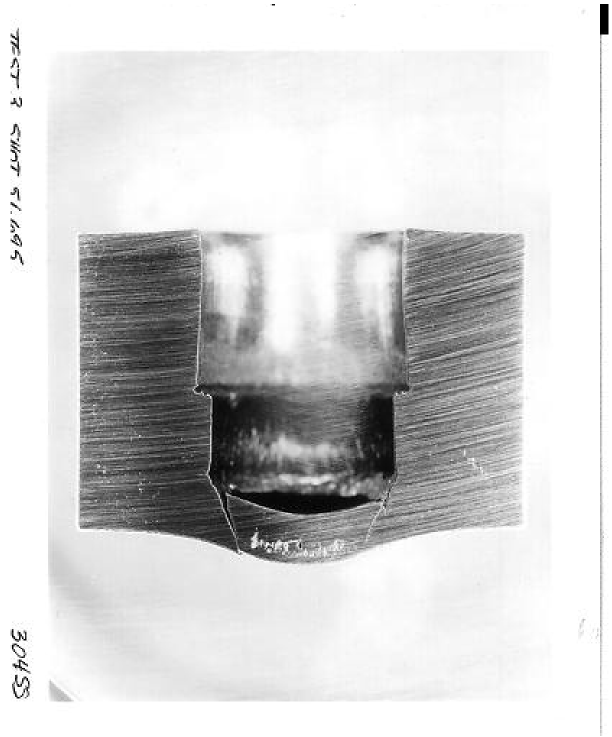


Figure A 5. Test #3: PETN Donor to 0.080” Steel, (PMMA test)

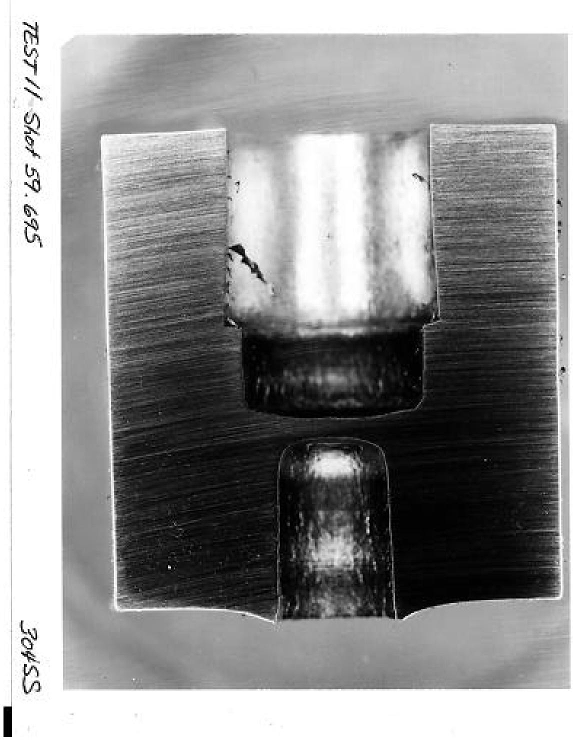


Figure A 6. Test #11: PETN Donor to 0.040” Steel, PETN Acceptor at 1.0 g/cc

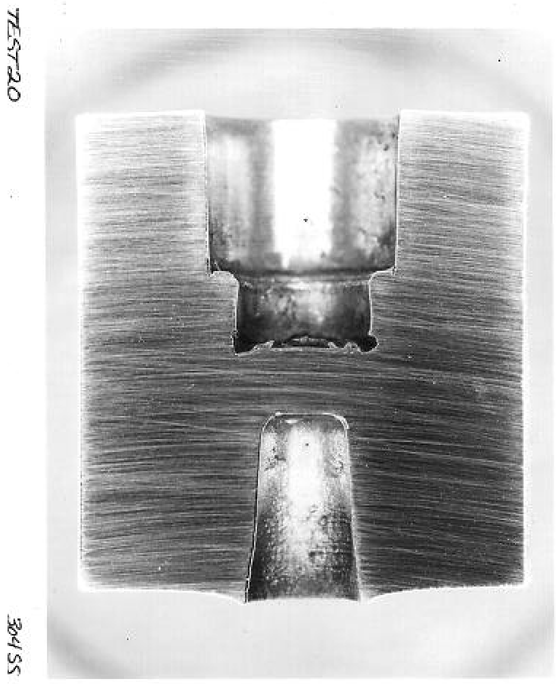


Figure A 7. Test #20: Flying Plate to 0.080” Steel, BNCP Acceptor at 1.2 g/cc.

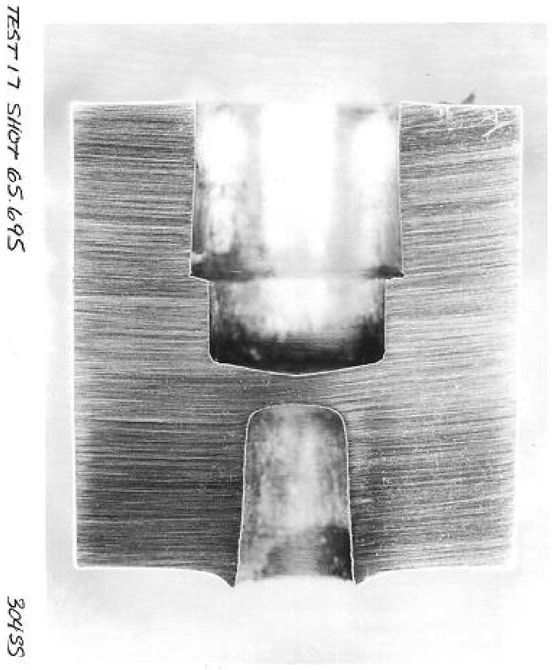


Figure A 8. Test# 17: BNCP Donor to 0.060” Steel, BNCP Acceptor at 1.2 g/cc

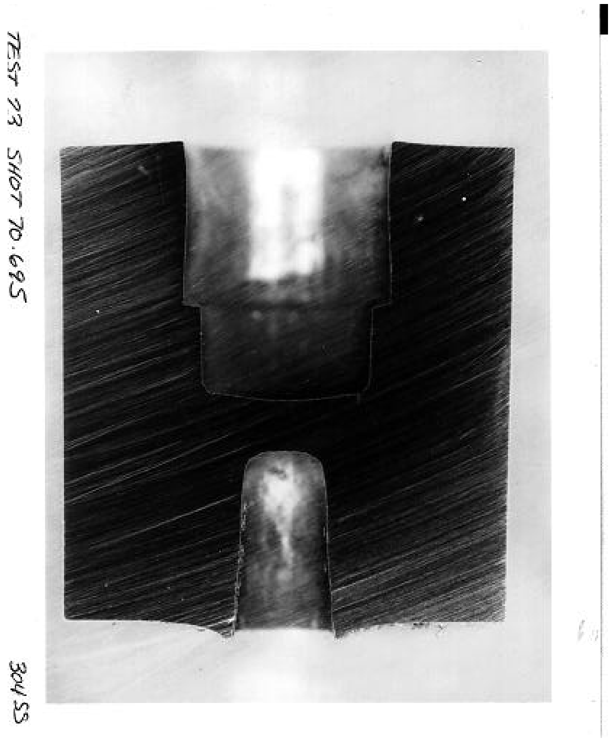


Figure A 9. Test # 23: BNCP to 0.080” Steel, BNCP Acceptor at1.2 g/cc

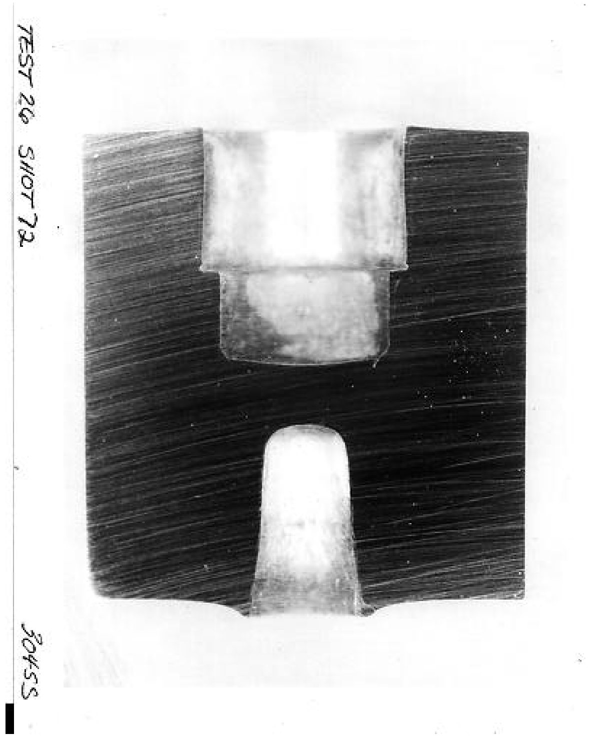


Figure A 10. Test #26: BNCP to 0.100” Steel, BNCP Acceptor at 1.2 g/cc

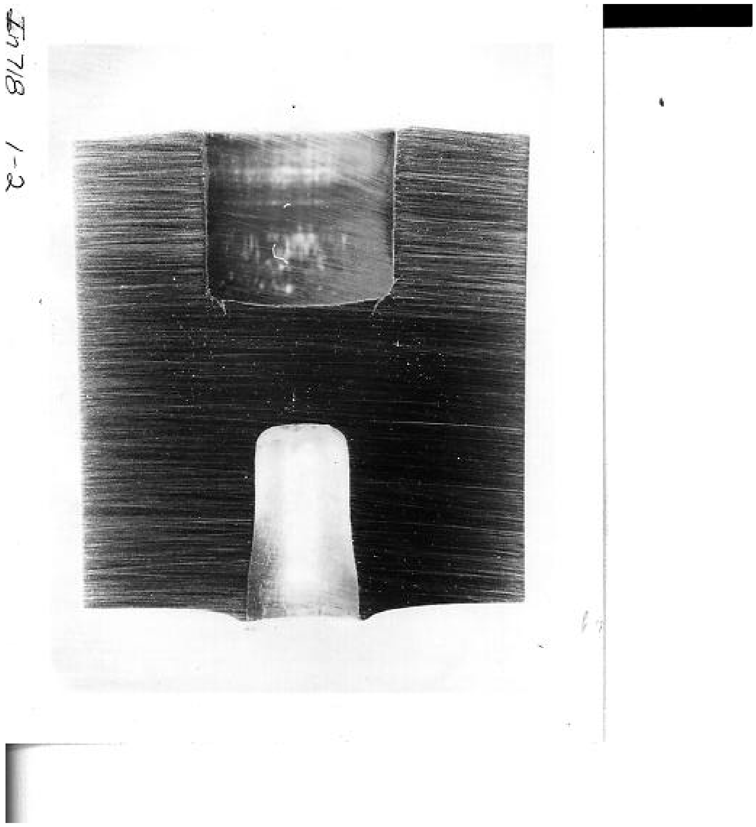


Figure A 11. Test # 1-2: BNCP to 0.180” Inconel, BNCP Acceptor at 1.27 g/cc

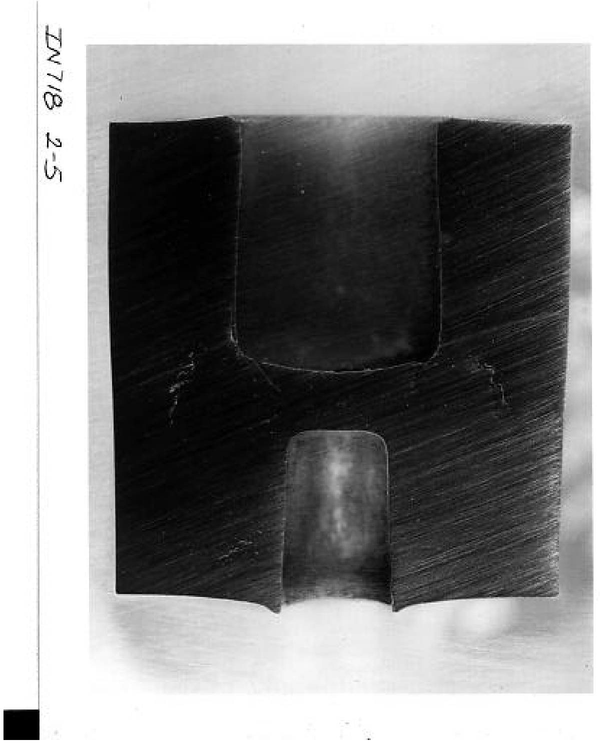


Figure A 12. Test # 2-5: BNCP to 0.100” Inconel, BNCP Acceptor at 1.25 g/cc.

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