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Pressure Amplification Off High Impedance Barriers in DDT

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1 Introduction

The Deflagration-to-Detonation Transition (DDT) in one-dimensional porous explosive, where combustion in an explosive transitions to detonation, can be described by the following model [1]. This simplified model proceeds in five steps, as follows: 1) Ignition of the explosive, surface burning. 2) Convective burning, with the flame front penetrating through the porous network of the explosive. This proceeds until the pressure grows high enough to result in choked flow in the pores restricting the convective burn. 3) The choked flow results in the formation of a high-density compact of explosive. This compact is driven into undisturbed material by the pressure of the burning explosive. See Figure1. 4) The compression of the undisturbed porous explosive by the compact leads to the ignition of a compressive burn. This builds in pressure until a supported shock forms. 5) The shock builds in pressure until detonation occurs. See Figure 2 for an overview streak of the proceeding steps.

The physical distance from ignition to detonation is referred to as the run length. The run length depends on a variety of factors, such as the type of explosive, the porosity of the explosive and the physical configuration. Factors which influence run length has important implications for the safety of an explosive during an abnormal thermal event. It is hypothesized that the presence of a high-impedance barrier in the flow of step 3 or 4 of the previously described mechanism could lead to an increase in pressure via reflection off the barrier. It is expected that the reflection of the building pressure wave off the high-impedance barrier back onto to itself will lead to an increase in pressure which might be enough to initiate detonation and give rise to a shorten run length. There has been several 1-D and 2-D DDT tests performed by Gary Parker [3] which suggest that this occurs.

In order to test this hypothesis a series of 1-D DDT tests were performed where PBX 9501 was thermal damaged and ignited on one end. In the col-

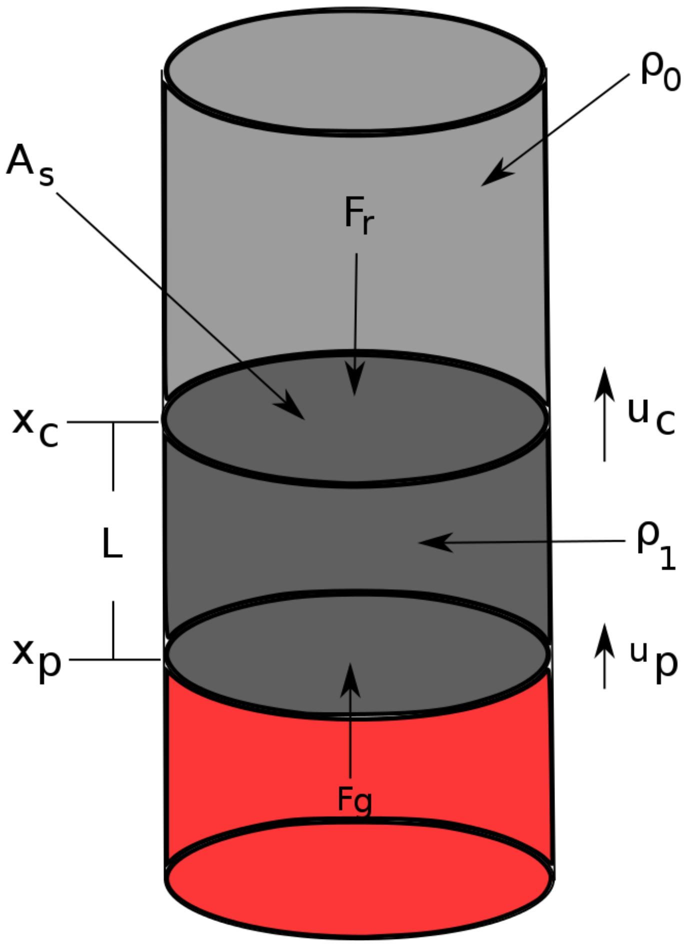


Figure 1: Overview of the simple 1-D DDT model. The burning explosive push the high-density (ρ_1) compact of explosive into the lower density (ρ_0) undisturbed material with force F_g. The compact of length, L, moves at a velocity u_p, with the leading edge of the compact moving at u_c.

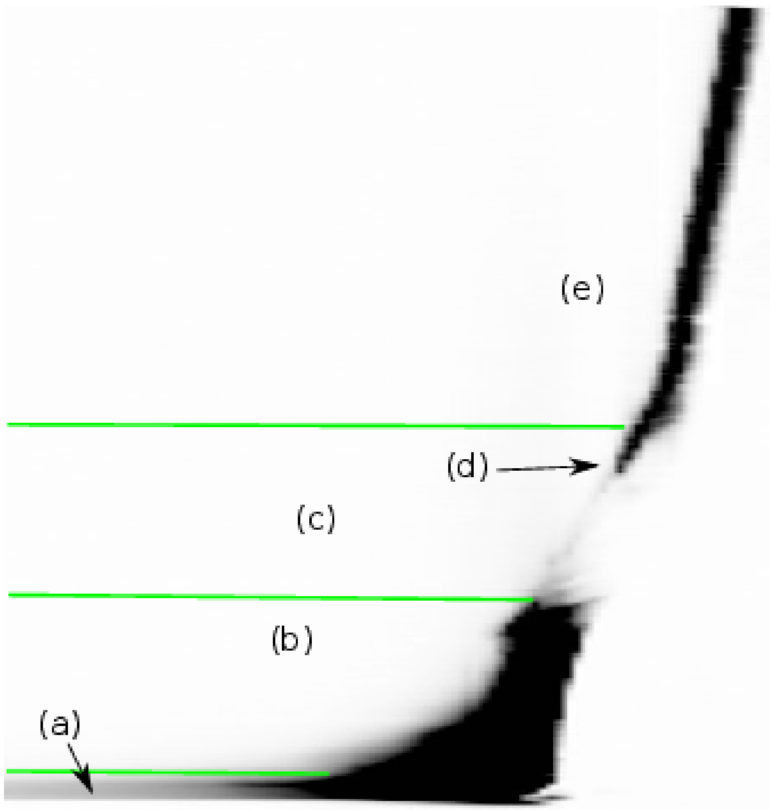


Figure 2: Overview of a streak image illustrating the steps of the DDT process. (a) Surface burning of explosive. (b) The convective burn. (c) Formation of the high-density compact. (d) The compressive burn. (e) Detonation.

umn of PBX 9501 there were placed 1 to 6 mm thick tungsten disks positioned where they will affect the building compact of high-density explosive before the transition to detonation. The barriers are placed such that the compact of high-density explosive has built up a significant amount of energy, typically about 10-12 mm before the transition to detonation would occur in a DDT test with no barriers present. Several tests where also performed were the explosive behind the tungsten barrier is replaced with a hardened steel rod, to determine the effect of a hard stop versus a compaction wave moving through the barrier. There were also several test performed with both thermally damaged PBX 9501 and HMX powder in sapphire tubes with tungsten barriers in an attempt to observe gross motion of the barriers and particle bed.

Both the tests with the barriers in the column of PBX and the hardened steel rod suggested the reflection off of the high-impedance barriers can lead to the initiation of detonation. While a significant decrease in run length was not determined, the results are enough to warrant further study.

2 Experimental Setup

The standard LANL 1-D steel DDT tubes were used in these experiments. Please see Gary Parker's report [2] for a full description. Figure 3 give an overview of the DDT tubes. The custom Kapton heaters were used for these experiments, where the temperature was controlled by in house LabView Software. The explosive was ignited using a diesel engine glow plug. The glass slide was imaged with the Phantom 2512 high-speed camera at 9.8x10^5 FPS to produce streak images for analysis.

Pressed 1/4"x1/4" pellets of PBX 9501 at normal density were used to load the DDT tube with explosive. To place the tungsten barriers 1, 3 or 6 mm barriers were slide down between the PBX 9501 pellets after the correct height of pellets were added. For example, to place the barrier at 64 mm, 10 pellets were loaded into the tube, then the tungsten barrier was added. The tube would then be filled to the top with PBX 9501 pellets. When a steel rod was used, a hardened steel rod replaced the pellets behind the tungsten barriers. This prevented significant motion of the barrier after impact of the building DDT wave.

3 Results

A total of eight tests were performed in the steel 1-D DDT tubes with tungsten barriers. All tests, except for tests 5 and 8 were heated at 5°C/min to 185°C where they were held at temperature for one hour. The glow plug igniter failed during tests 6 and 8, so the temperature was ramped from 185°C after the

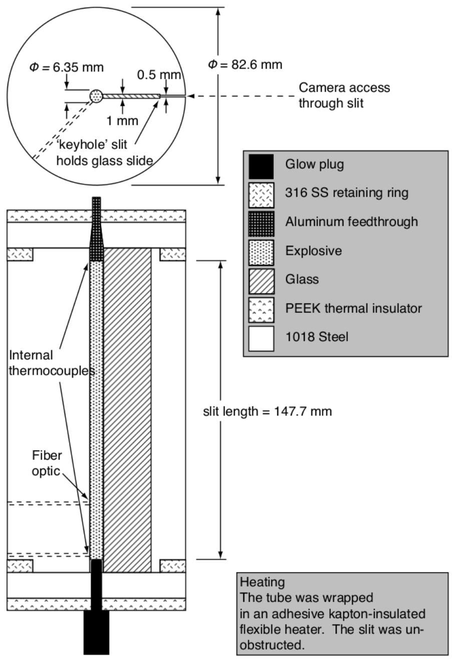


Figure 3: Schematic of the 1-D DDT test.

Test	Barrier, x(mm)	Barrier thickness (mm)	Rod	DDT
1	32	1	No	Yes
2	64	1	No	Yes
3	64	3	No	Yes
4	64	6	No	Yes
5	64	5	Yes	No
6	70.4	6	Yes	Yes
7	70.4	6	Yes	Yes
8	64,92,129	3,3,1	No	Yes

Table 1: Summary of the barrier position and thickness, presence of a rod and if the test underwent DDT.

hour soak to 250°C and held at temperature until the PBX 9501 under went ignition. Test 6 underwent DDT approximately 40 mm from the tungsten barriers and propagated towards the glow plug, therefore this was not useful for this experiment. Table 1 summarizes the location and thickness of the tungsten barriers for the eight tests, as well as the presence of the steel rod and if DDT occurred.

The porosity of the explosive is an important experimental variable in DDT experiments. The porosity of each of the tests was estimated using Zerkle's PBX 9501 porosity model [4], where the Arrhenius decomposition kinetics of PBX 9501's components, HMX, BDNPA and estane, are modeled to give mass loss of each of the components. Zerkle's original work assumed that the sample was small enough to be estimated as zero dimensional but for this work Dickson's PBX 9501 model was used to generate a temperature field and the decomposition kinetics of the components was modeled for the full system. This technique was used to estimate the mass fraction of each of the components, as well as the thermal expansion of the components and the beta to delta phase change in HMX, which, given the size of the DDT tube can be used to estimate the average porosity and give an estimate of the detonation velocity. This model was implemented in the COMSOL Multiphysics Modeling Software.

Table 2 summarizes the calculated porosity, the measured run length to detonation, measured detonation velocity and estimated detonation velocity from the porosity model. Tests 1 - 5 have an estimated porosity of zero, which is obviously incorrect. The beta to delta phase change is responsible for a large change in density for HMX based explosives at temperature, however, it is unlikely that this would be enough to press all porosity out of the explosive and if it had it would be unlikely to undergo DDT. This estimate of porosity is the most accurate when the PBX 9501 is slightly constrained, it is unclear what is happening in these fully constrained cases - is the beta to delta phase change being suppressed? Is there extra space in the tube or is the estane being ex-

Test	Porosity,%	Run length, mm	Det vel $\frac{mm}{\mu s}$	Est. Det vel
1	0	73	8.5	8.6
2	0	92	8.7	8.6
3	0	82	8.8	8.6
4	0	125	8.5	8.6
5	0	NA	NA	8.6
6	NA	NA	NA	NA
7	1	64	NA	8.5
8	3	89	7.6	8.3

Table 2: Summary of the estimated porosity, run length to detonation, measured detonation velocity and the estimated detonation velocity.

truded into cracks in the tube? However, this estimate of porosity is useful to compare the relative porosities.

Tests 1-4 all under went DDT behind the tungsten barriers, indicating that the reflected pressure wave off of the barriers did not immediately initiate detonation for these cases. It was possible for tests 1,3 and 4 to break apart the steel DDT tubes and use the tubes as a witness plate. These tubes gave several key insights into the effect of the tungsten barriers, such as the dent depth, which gives an integrated measure of the pressure. Also, the transition to detonation gives a characteristic blackening on the inside of the tubes (see Figure), which gives a clear indication where the transition to detonation occurs. The tubes also show the final position of the tungsten barriers, which move around during the heating process and their position relative to the transition to detonation. The dent depth measurements are summarized in Tables 3 and 4.

The results of tests 1 - 4 are as expected if the tungsten barriers did not initiate detonation. Comparison of the dent depth measurements indicate that the tungsten barriers reduce the pressure on the back side of the barrier and delay the onset of detonation. As seen in Figure 4 the 1 mm barrier in Test 1 is located at 32 mm. As the pressure wave runs over the barrier, the pressure is reduced and the dent depth of Test 1 lags behind the dent depth of Test 3 until the 3 mm barrier of Test 3 is hit. As expected, the 3 mm barrier reduces the pressure more than the 1 mm barrier and the run length to detonation is increased. The barriers in Test 3 and 4 are placed in approximately the same place and as can be seen in Figure 5 the 6 mm barrier of Test 4 reduces the pressure further than the 3 mm barrier and increases the run length to detonation.

One aspect of the dent measurements which is not captured clearly in the dent depth plots is depth of the dent immediately before the barriers. The dent depths were measured on a mill table with a dial displacement gauge, which

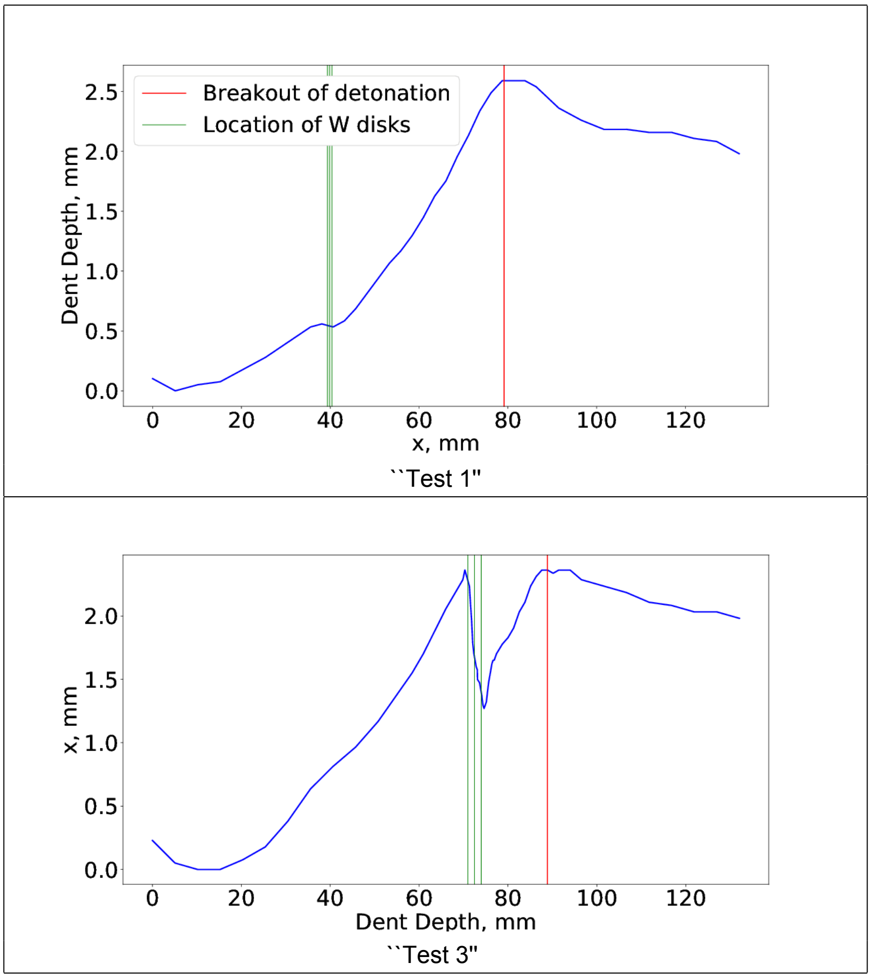
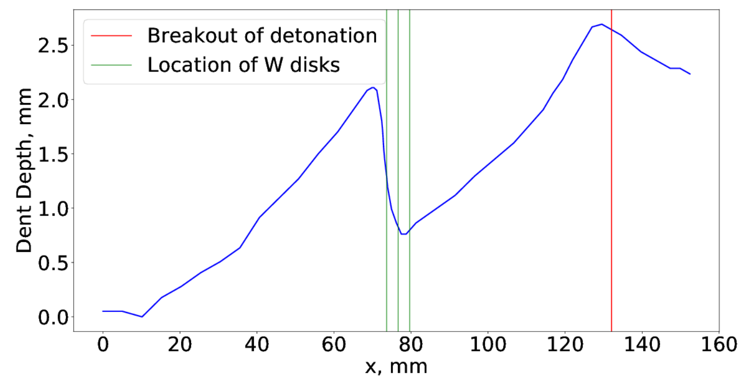
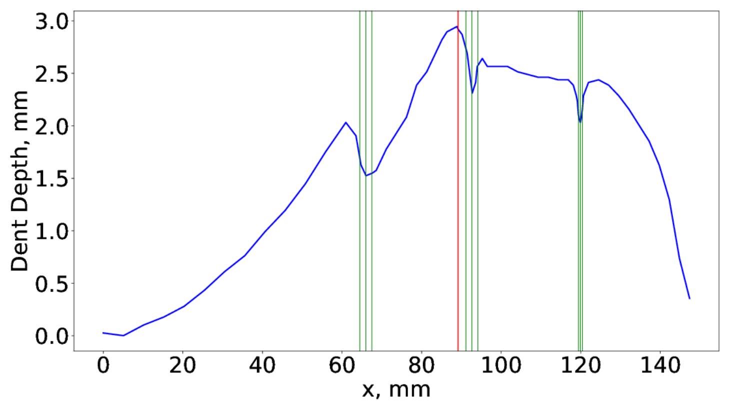


Table 3: Dent depth measurement for Tests 1 and 3. Shows dent depth (blue), location of the barrier (green), with the front and back edge and where detonation occurred (red).



``Test 4"



``Test 8"

Table 4: Dent depth measurement for Tests 1 and 3. Shows dent depth (blue), location of the barrier (green), with the front and back edge and where detonation occurred (red).

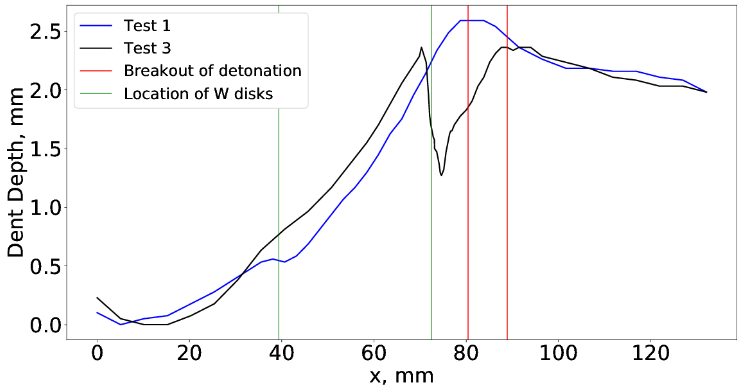


Figure 4: Comparison of dent depth between Tests 1 and 3. The 1 mm barrier in Test 1 reduces the dent depth, which trails the dent depth of Test 3 until the 3 mm barrier in Test 3 is reached. The 3 mm barrier reduces the pressure more than the 1 mm barrier which results in a longer run length to detonation.

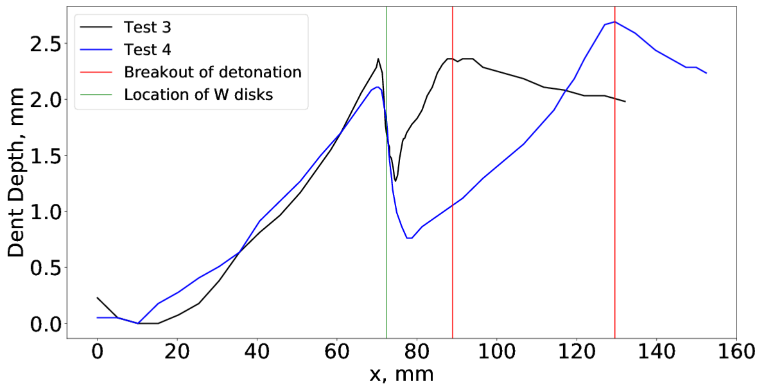


Figure 5: Comparison of dent depth between Tests 3 and 4. The barriers are in approximately in the same place for both tests. The 6 mm barrier in Test 4 reduces the pressure more the 3 mm barrier in Test 3, which results in a longer run length to detonation.

uses an 1/8" ball to measure along the surface. This ball is large enough that the sharp dent in front of the barrier is not fully resolved. Upon visual inspection it appears that the dents in front of the barrier in both Test 3 and 4 are deeper than the dent caused by the detonation in these tests.

Tests 5 through 7 used a steel rod behind the barriers rather than a continuing column of explosive. Test 5 with the barriers at 64 mm did not undergo DDT. The glow plug igniter for Test 6 failed and the experiment was heated to 250°C until ignition occurred. Unfortunately, the ignition occurred near the barrier and propagated towards the glow plug and not the barriers, which means these results were not useful for this experimental series.

Test 7 underwent DDT approximately 5-6 mm before the barriers at 70.4 mm. Test 7 was the first test which had a positive estimated porosity and it also had the shortest run length to detonation of tests in this series. The detonation region for Test 7 was so short it was not captured on the high-speed video but the characteristic blackening of detonation was observed near the barrier. It is a distinct possibility that the reflection off the barrier initiated detonation in this case. However, it is also possible that the run length would have remained the same without the barriers. Due to the limited amount of explosive in Test 5 - 7 it was not possible to break these tubes in half to measure the dent depth of these tubes which would be particularly useful for Test 7. As Test 3 and with 4, a sharp dent was observed immediately proceeding the barrier indicating an increase in pressure.

Test 8 was the only test performed with multiple barriers. The ignition glow plug failed for this test and as with Test 6 it was heated to 250°C until ignition occurred. In this case, the ignition occurred on the opposite end of the tube to the glow plug igniter, however, unlike Test 6 all the barriers were in path of the building DDT process and the test was still useful. As can be seen in Table 3 Test 8 transitions to detonation approximately 5 mm before the second 3 mm barrier. This, together with Test 7, is suggestive that the reflection off the barrier initiated the detonation, however, it is not conclusive. Due to the high temperature this was the most porous of the tests, which as with Test 7, the extra porosity could give rise to the extra sensitivity need to have the reflection off the barriers lead to detonation.

Two tests were performed in sapphire tubes. The first test used PBX 9501 heated to 185°C and held at temperature for one hour. Unfortunately, the pressures need for DDT with thermally damaged PBX 9501 are too high to be contained by sapphire and the tube failed before DDT occurred. The second test in sapphire used HMX powder at pour density and had 3 mm tungsten barriers placed at 22.6 mm and 47.6 mm. The transition to detonation occurred somewhere between the first and second barriers, however, the camera were over exposed and the exact point of transition was impossible to observe. It was possible to observe the tungsten barriers during the build up to detonation and no movement was noticeable. This is expected due to the short time the barriers are observed. In order to move the barriers in the measured time frame would require forces far beyond the yield strength of the sapphire.

4 Discussion

For all the test performed, the detonation proceeded away from the ignition source and did not propagate in both directions from where the transition to detonation occurred. Backwards travelling detonation is often referred to as a retonation. Retonations are very rarely observed in 1-D DDT experiments, and would be a detonation travelling down the high-density compact. As it is currently understood for DDT, a compressive burn starts at the end of the compact and the pressure from the burn builds up to the point where a shock is formed which initiates the detonation. Since this occurs close to the interface between the high-density plug and the yet uncompacted porous explosive the pressure builds to the point where it initiates the more sensitive porous explosive but not high enough to initiates the high-density compact. In fact, it is quite likely that the compact is not of uniform density, where the leading edge of the compact is likely at a lower density than the material further back in the compact. Since it appears the compressive burn occurs slightly behind from the leading edge of the compact, the transition to detonation starts in a higher density material than it subsequently moves into. This results in a decreasing pressure as the detonation propagates, which can be seen in the dent depth profiles, where the dent from the detonation grows smaller as it runs away from the transition point.

Tests 7 and 8 were the only two tests performed were the transition to detonation occurred immediately ahead of the tungsten barriers. In both cases the transition occurred within 5-6 mm of the barriers. They were also the only two tests performed with a positive estimated porosity. These two tests are candidates for the reflective pressure wave off of high impedance barriers initiating detonation. This could be due to the compacts for these two tests having a higher porosity than the previous tests, which means more work is done, which leads to more heat being produced, as the porosity is crushed out against the barrier. However, it also possible that the transition to detonation would have occurred in the same place without the presence of the barriers. This seems less likely since they both transitioned approximately the same distance from the the barrier. Also, it has been observed in previous DDT tests that PBX 9501 at close to full density has a significantly shorter run length than PBX 9501 in the 1 to 3% porosity region. Since Test 7 had a porosity of 1%, the run length would expected to be longer than the run lengths for Test 1 - 4, instead it had the shortest run length of the performed tests. Test 8 had a porosity of 3%, with the same barrier configuration in the build up to detonation as Test 3 but had approximately the same run length as Test 3, rather than the expected 15

- 20 mm increase in run length.

Neither Test 7 nor 8 showed conclusively that the reflection off high-impedance barriers lead to a reduction in run length to detonation in DDT, however, they did hint at it being a viable mechanism for transition from the compressive burn to detonation. Of more importance to weapons safety is the mechanism for DDT in three dimensions. The vast amount of work done has been on one dimensional or pseudo-one dimensional systems (weak confinement). Will the mechanism for DDT remain the same as for the one dimensional case or will it introduce some previously unknown mechanism? The presence of Rayleigh-Taylor instabilities in a 3-D geometry could make the driven compact mechanism too unstable to lead to DDT with the same mechanisms seen in 1-D. Without the presence of the compact would the dangers of a reflected pressure wave even be an issue in high dimensional system? However, the presence of a concave reflective surface, as is almost always present in most explosive systems, may make the presence of a compact immaterial and lead to DDT anyway. In any event, more experimental work must take place, especially in higher dimensions.

5 Conclusions

A total of eight test were performed in 1-D steel DDT tubes with high-impedance barriers. The tests which transitioned to detonation behind the high-impedance barriers all had the expected effect from the barriers. As in Test1 - 4, the barriers reduced the pressure behind the barrier and led to a longer run length to detonation with increasing thickness of the barriers. This effect is illustrated quite clearly in Figures 4 and 5. While the dent depth plots act as an integrated pressure measure, they do not capture any sharper dents present in the tube. For example, the dent immediately before the barrier in Test 3 and 4 is deeper than the dent caused by the detonation. This indicates that the pressure reflection off the barrier was higher than the detonation, but did not cause detonation, possibly due to the low porosity of the compact. This effect was not clearly captured by the dent depth measurement due to the coarseness of the measurement technique.

The two tests of most interest in this test series were Tests 7 and 8. These tests had the highest porosity of all the test performed and both transitioned to detonation approximately 5-6 mm before the barrier. While the transition to detonation may have still occurred at that location without the presence of the barriers, the fact that both these tests transitioned to detonation approximately the same distance from barriers suggest that the barriers had some effect. Also, in previous DDT tests the tests with close to zero porosities had the shortest run length to detonation, which would suggest that Test 7 and 8 would have the longest run lengths, which was not observed. While neither test conclusively proved that pressure amplification off high impedance barriers significantly shorten the run length to detonation, they do suggest that the barriers have some effect and certainly warrant further study. In fact, further analysis on this whole data set will lead to valuable insights into the 1-D DDT process, regardless of the pressure amplification issue and will be a rich source of data for further papers.

6 Further Research

While the 1-D DDT model is an illustrative and important model for studying DDT, and deserves further study, it is not clear at this point if it applies to higher dimension systems. There has been very little work done studying DDT in 2 and 3 dimensions and it is currently unknown if the formation of high-density compacts which lead to a compressive burn are the primary mechanism for DDT in more complex geometries. Not only are the two and three dimensional systems divergent, the presence of Rayleigh-Taylor instabilities, which do not exist in one dimensional system, would suggest that the compact could not be driven hard enough to ignite the compressive burn and this would not be a viable mechanism in three dimensional systems. Therefore, a study of DDT in two and three dimensions seems to be the logical next step.

A two dimensional DDT study would possibly be the easiest to implement and understand. A useful 2-D study would be to use a pie shaped wedge of 1/4" thick explosive with a curved wide end. The explosive would be sandwiched between two heavy steel plates to provide heavy confinement and give a witness plate to help diagnose the mechanism. This would allow the experiment to be thermal damaged as well as the possibility of a slit to optically access the building DDT process. The experiment would then be ignited on the narrow end of the wedge and the DDT process would build up the wedge in a two dimensional divergent manner. The presence of the curved back edge would allow for the study of the reflection of the building DDT wave off a concave geometry as seen in many explosive systems.

A three dimensional study would be the most applicable to existing weapon systems but it is the most difficult to accurately diagnose. A suggested three dimensional study would be to use a 3-D cone of explosive, where the cone is ignited on the narrow and the building DDT process is allowed to expand into the widening cone. While it currently not possible to gather pressure or optical data for such a system, the insertion of very fine coaxial cables or a chirped fiber Bragg grating into the cone of explosive could be use to diagnose the point at which the detonation occurs and the detonation velocity or, if the pressures are high enough, the building of high-density compact if it exist. Since the pressures in the 1-D tests are higher than the yield strength of steel during the compact phase of the mechanism, they will likely be high enough to crush the coaxial cable or chirped fiber. It should be possible differentiate between the detonation and compaction by the velocity, especially when in conduction with an X-ray diagnostic.

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