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“Chunk” Projectile Launch Using The Sandia Hypervelocity Launcher Facility

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Abstract

An experimental technique is described to launch an intact “chunk”, *i.e.* a 0.3 cm thick by 0.6 cm diameter cylindrical titanium alloy (Ti-6Al-4V) flyer, to 10.2 km/s. The ability to launch fragments having such an aspect ratio is important for hypervelocity impact phenomenology studies. The experimental techniques used to accomplish this launch were similar but not identical to techniques developed for the Sandia HyperVelocity Launcher (HVL). A confined barrel impact is crucial in preventing the two-dimensional effects from dominating the loading response of the projectile chunk. The length to diameter ratio of the metallic chunk that is launched to 10.2 km/s is 0.5 and is an order of magnitude larger than those accomplished using the conventional hypervelocity launcher. The multi-dimensional, finite-difference (finite-volume), hydrodynamic code **CTH** was used to evaluate and assess the acceleration characteristics *i.e.*, the in-bore ballistics of the chunky projectile launch. A critical analysis of the **CTH** calculational results led to the final design and the experimental conditions that were used in this study. However, the predicted velocity of the projectile chunk based on **CTH** calculations was ~ 6% lower than the measured velocity of ~10.2 km/s.

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Acknowledgment

The interest and the partial funding support provided by Dr. Thomas N. Tsai and John Connell from Defense Nuclear Agency is gratefully acknowledged. We also thank James Peery and David Crawford for critically reviewing the manuscript.

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Executive Summary

It is the purpose of this report to describe a technique that has been developed to launch an intact "chunk", *i.e.* a 0.3 cm thick by 0.6 cm diameter cylindrical titanium alloy (Ti-6Al-4V) flyer, to approximately 10.2 km/s. Fragments having this and similar aspect ratios are important for hypervelocity impact phenomenology studies, for example, in studying the consequences of the impact of space debris upon satellites. The experimental techniques used to accomplish this launch were similar to but not identical to techniques developed for the Sandia HyperVelocity Launcher (HVL).

The HyperVelocity Launcher, HVL, has the capability to launch gram-size plates to velocities not previously achievable on guns such as the two-stage light-gas gun. The technique is primarily an impact technique (Chhabildas, *et al.*, 1992a, 1993) in which a time-dependent structured pressure pulse is generated (upon impact) to launch 0.5-mm to 1.0-mm thick flier plates to velocities up to 12.2 km/s. A graded-density impactor assembly is used to produce the nearly shockless and uniform loading that is necessary (upon impact) during the acceleration process. Since the loading on the flier plate is shockless, excessive heating is minimized to prevent melting of the flier plate (Chhabildas, *et al.*, 1990; Chhabildas and Asay, 1992). The technique inherently necessitates that the flier plate thickness be *thin* to prevent shock up and hence melting. Therefore, the current aspect ratio *i.e.*, the length to diameter ratio, of the thin flier plates launched on the Sandia HVL is approximately 0.05 to 0.1, as opposed to the chunk aspect ratio of 0.5.

An important component of our study was the use of the multi-dimensional, finite-difference (finite-volume, to be precise) hydrodynamic code CTH (McGlaun, *et al.*, 1990) to evaluate these issues and assess the acceleration characteristics *i.e.*, the in-bore ballistics of the chunky projectile launch. A critical analysis of the CTH calculational results led to the final design and the experimental conditions that were used in this study. It should, however, be emphasized that the predicted velocity of the projectile chunk based on CTH calculations was ~ 6% lower than the measured velocity of ~10.2 km/s. Additional refinement of the modeling is required for a full understanding of this complex experimental technique.

It is not merely sufficient that the graded-density impactor and the flier-plate thickness be scaled to obtain an intact chunk launch. The following technical issues are crucial for producing a successful launch of an intact chunk:

- Two-dimensional effects due to edge effects/release waves, if not addressed, will dominate the loading response of the scaled projectile chunk, resulting in a substantially lower terminal velocity of the chunk.
- A confined barrel impact is crucial in preventing two-dimensional effects from dominating the loading response of the projectile chunk.
- A high-impedance, low sound-speed material for the barrel is necessary to

prevent stress waves in the barrel (due to impact) from outrunning the chunky projectile.

The confined barrel impact design suggested in this study operates as an acceleration reservoir *i.e.*, a velocity enhancement of the projectile chunk. An experiment was performed in which the length to diameter ratio of the metallic chunk launched to 10.2 km/s is 0.5. This aspect ratio is an order of magnitude larger than those accomplished using the conventional hypervelocity launcher, confirming our understanding and control of these technical issues.

1. Introduction

Sandia has recently developed a HyperVelocity Launcher, HVL, that has the capability to launch gram-size plates to velocities not previously achievable on guns such as the two-stage light-gas gun. The interest in increased velocity launch capabilities was motivated in part by Strategic Defense Initiative research, and concern regarding impact of orbital debris particles on space vehicles. This has led to the development of an impact technique (Chhabildas, *et al.*, 1992, 1993) in which a time-dependent structured pressure pulse is generated via impact and then used to launch 0.5-mm to 1.0 mm thick flyer plates to velocities of up to 12.2 km/s.

There are two main requirements to launch thin flier plates to hypervelocities. First, very high pressures are needed to launch the flier plate, and second, this loading must be nearly *shockless* and *uniform* over the entire surface. To achieve both of these criteria, a graded-density material referred to as a "pillow" (Barker, 1984) or a "multi-ply" (Chhabildas and Barker, 1988, Chhabildas, *et al.*, 1988) is used to impact the thin flier plate. When this graded-density material contacts a flier plate at high velocities on a two-stage light-gas gun, nearly shockless 100 GPa pressure pulses (Chhabildas, *et al.*, 1990a, Chhabildas and Asay, 1992) are generated in the flier plate. Since the loading is shockless, heating of the flier plate is minimized, and melting is prevented (Chhabildas, *et al.*, 1990, Chhabildas and Asay, 1992). The generated high pressures are controlled through the use of a sacrificial "barrel extension" which is carefully designed to help maintain the integrity of the flier plate. The barrel extension does not survive the experiment, and must be replaced after each shot. The method has been used (Chhabildas *et al.*, 1991, 1992) for intact launch of a 2 mm thick titanium alloy (Ti-6Al-4V) plate to a velocity of 8.1 km/s, 1-mm thick aluminum, magnesium, and titanium alloy plates to velocities in excess of 10 km/s, and 0.5 mm thick titanium and aluminum alloy plates to 12.2 km/s. With further improvements to this technique, launch velocities approaching 16 km/s have been achieved (Chhabildas *et al.*, 1994).

As indicated above, the loading that is necessary to launch flier plates must be nearly *shockless* (i.e., a pressure ramp-up in time) and spatially *uniform* during the acceleration process. When a material is subjected to ramp loading, material non-linearity causes the compressive ramp wave to steepen as it traverses the material. This effectively increases the loading rate within the sample until the compression wave achieves a steady "high-pressure shock" profile resulting in temperature increases that can lead to melting. This requires that the flier plate thickness be *thin* to prevent shock up and hence melting. The current aspect ratio i.e., the length to diameter ratio, of the thin flier plates launched on the Sandia HVL is approximately 0.05 to 0.1. It is the purpose of this report to describe a technique

that has been developed to launch an intact "chunk", *i.e.* a 0.3 cm thick by 0.6 cm diameter cylindrical titanium alloy (Ti-6Al-4V) flyer, to approximately 10.2 km/s. The experimental techniques used to accomplish this launch were similar but not identical to techniques developed for the Sandia HyperVelocity Launcher (HVL).

The key to the success of this experiment is in part due to the pretest design work that was performed utilizing the **CTH** hydrodynamic code (McGlaun, *et al.*, 1990). Although many pretest calculations were necessary to achieve the final design, only a subset of these will be reported here to highlight the technical issues associated with the launch of a projectile chunk. In particular, the calculations represented in this paper have been tailored to indicate the path that led to the experimental conditions that were finally selected. The **CTH** calculations that were performed to address these technical issues are highlighted in the next section, while further details of the experimental and computational results are discussed in subsequent sections.

2. Technical Issues

In this section, a variety of technical issues that are relevant for launching a thick metallic projectile "chunk" are addressed. As indicated earlier, a high-pressure quasi-isentropic loading wave is necessary to prevent the flier plate from melting during hypervelocity launch. To achieve this condition, a graded-density "multi-ply" material (Chhabildas and Barker, 1988, Chhabildas, *et al.*, 1988) is used to impact the thin flier plate. At impact velocities near to, or exceeding, the 6 km/s achievable on a two-stage light gas gun, this graded-density material produces nearly shockless 100 GPa pressure pulses (Chhabildas, *et al.*, 1990, Chhabildas and Asay, 1992) in the flier plate. If one wants to launch a thicker flier, then momentum conservation demands that the graded-density impactor be scaled proportionately to allow the loading of the thick chunk by a similarly scaled time-dependent high-pressure pulse. This, however, cannot be arbitrarily accomplished for the following two reasons.

First, thickening the graded-density impactor will add considerable mass to the two-stage light-gas gun projectile. The increased mass restricts the velocity capabilities of the gun system to velocities well below the desired impact velocity which exceeds 6 km/s. This reduces the driving pulse pressures to values below those that are necessary to launch the heavier mass. Second, the loading pressure pulse resulting from a thicker impactor will scale proportionately and thus will be of a *longer* duration. As a result of the longer stress pulse duration, two-dimensional effects emanating from the edges of the thick chunk can become important and cause a severe velocity gradient over a large radius of the plate and thus dominate the experiment. This will cause the flier plate to bend and possibly fragment. A series of **CTH** calculations, performed to evaluate these technical issues, are summarized in Table 1.

Table 1: CTH Calculation Summary Highlighting the Technical Issues

Calc No.	Geometry	Impact Velocity (km/s)	COMMENTS
1	1-D No edge effects	5.8	Graded-density impactor and the chunk has an infinite diameter; no edge effects
2	2-D axisymmetric	5.8	Graded-density impactor and the chunk has the same diameter as the barrel diameter
3	2-D axisymmetric	5.8	No barrel stepdown, otherwise configured the same as the basic experiment.
4	2-D axisymmetric	5.8	Basic simulation of experiment.

Calculation 1. One-Dimensional Simulation

We performed a 1-D calculation (see Table 1) to investigate if the graded-density impactor assembly (specified in Table 2) will launch a flier plate without melting or fracture during the acceleration phase, and also to determine the magnitude of the final velocity obtained. As seen in Figure 1, the terminal velocity of the approximately 3 mm thick titanium flier plate is calculated to be 8.8 km/s, based on a graded-density impact velocity of 5.8 km/s. It should be pointed out, however, that this experiment cannot be performed because the required two-stage gun projectile would be too heavy to achieve the required impact velocity of 5.8 km/s. This is one of the advantages of having computational tools available with which to explore experimental design issues.

Figure 1. Schematic (not to scale) and axial velocity history of calculation #1, the “1-D” configuration. The velocity of the entire impactor configuration is 5.8 km/s.

Table 2: Graded-density impactor dimensions.

Material Layer	Thickness (mm)	Diameter (mm)
TPX	3.00	12.7
Magnesium	1.803	12.7
Aluminum	1.499	12.7
Titanium	1.194	12.7
Copper	6.375	12.7
Titanium Alloy	0.792	26.97

Calculation 2. Two-Dimensional Simulation Using Full-Bore Diameter Geometry

The calculational geometry of this two-dimensional simulation is shown in Figure 2. The layered impactor and the chunk projectile now have the same diameter as the tungsten barrel (~ 29 mm) that is generally used in Sandia HVL experiments. The major difference between this calculation and calculation #1 is that the tungsten barrel is now present in the calculation, rather than an idealized reflective boundary condition. The impact velocity is still 5.8 km/s in the calculation. This is not achievable in a real experiment because the layered impactor is still too massive in this case. Even if such an experiment were feasible, the calculations show that two-dimensional effects emanating from the edges of the thick chunk will cause a severe velocity gradient over a large radius of the plate due to the loading times, which are three times longer. This can cause the chunk flyer to bend considerably, resulting in fracture. This is observed in the calculation and illustrated in Section 4, where we analyze the calculations in greater detail. Notice, however, that the peak axial velocity at the center of the chunk, as plotted in Figure 2, is only 8 km/s. This shows that two-dimensional effects, also referred to in this report as edge effects, can reduce the maximum flyer-plate velocity considerably from what is expected from ideal one-dimensional impact conditions. We can view the maximum flyer velocity as a measure of the efficiency of energy conversion from the impactor to the flyer in these experiments. If we then compare the one-dimensional calculational result shown in Figure 1, which yielded a chunk velocity of 8.8 km/s, with the configuration of calculation #2, this efficiency is smaller by 9% for calculation #2.

Figure 2. Schematic (not to scale) and axial velocity history of calculation #2, a 2-D configuration with finite barrel thickness.

Calculation 3. Two-Dimensional Simulation Using a Reduced-Diameter Layered-Impact Geometry

In this calculation, the layered impactor diameter is reduced to 12.7 mm and embedded in the lexan sabot. This reduces the overall mass of the layered material. This makes it possible to achieve an impact velocity of 5.8 km/s in a realistic experiment. The calculational geometry is shown in Figure 3. The chunk flyer is indicated as the center of a guard ring arrangement similar to that used in normal HVL experiments. The guard ring provides some protection from edge effects originating at the barrel/titanium interface during peak acceleration. In this calculation, the loading time to accelerate the flier-plate chunk resulting from the impact of the graded-density impactor is the same as in calculation 2. However, edge effects emanate from the lexan/layered impactor boundary. This results in (i) substantial deformation of the chunk flyer when compared to the results of calculation #2 and (ii) reduction of the flyer velocity even further to less than 6 km/s (note that the impact velocity is 5.8 km/s). The efficiency in this configuration is thus approximately 32% less than in the "ideal" 1-D case.

This calculation clearly demonstrates why thin plates can be launched much more effectively than thicker plates. The thicker the flyer is in relation to its diameter, the less velocity augmentation is to be expected from the layered impactor technique described in earlier reports. This also implies that an important condition to successfully launch plates to hypervelocities is that the loading time be small, increasing the resulting acceleration. Since loading times *must* be relatively larger for chunk flyers, a method must be developed to avoid the dominance of edge effects during the acceleration process. This method is discussed in #4.

Figure 3. Schematic (not to scale) and axial velocity history of calculation #3, a 2-D configuration with finite barrel thickness and reduced layered impactor diameter.

Calculation 4. Two-Dimensional Simulations Using a Step-Down Barrel and a Reduced Bore-diameter Geometry

One reason two-dimensional effects have the net effect of reducing the chunk velocity in calculation #3 is because edge effects emanating from the layered impactor and the flyer boundary are *release waves*. The stresses are not sustained sufficiently, thereby lowering the acceleration and resulting in reduced velocity of the chunk. As the loading time increases, or as the diameter of the graded density impactor becomes smaller, then the effects due to edge release waves will become increasingly significant. One way of mitigating the detrimental influence of two-dimensional edge effects is to ensure that these edge effects are *compressive waves* and not *rarefaction waves*. This can be achieved by using a step-down barrel as indicated in Figure 4. The smaller diameter sample chunk (10 mm) is inserted in the barrel and is shown in Figure 4, while the diameter of the layered impactor (12.7 mm) is greater than the chunk diameter (10 mm). Tungsten is chosen as a barrel material because of its high-impedance and relatively low sound speed.

Figure 4. Schematic (not to scale) and axial velocity history of calculation #4, a 2-D configuration with a reduced layered impactor diameter and a tungsten barrel “step-down”. Detailed dimensions are given in Figure 6.

Upon impact, the stress states at the tungsten/flyer boundary are higher than those in the sample itself. This prevents the release of pressure and instead establishes higher stress *i.e.*, *reshock* states within the flyer. This compression prevents significant bending of the flyer chunk and, perhaps more significantly, increases the peak acceleration of the flyer over a longer duration. As indicated in Figure 4, this results in a maximum flyer velocity of approximately 9.6 km/s. This is even

higher than the velocity of 8.8 km/s expected based on the ideal one-dimensional calculation #1. The efficiency of this configuration is actually predicted to be 9% higher when compared to the 1-D configuration. Thus, we have the dramatic reversal that 2-D effects are actually *improving* the performance of the system in this case. Notice that a potential trade-off that must enter this design is that now the chunk flier might be overly "squeezed" by the lateral compression waves. We must optimize this effect in order to increase the final velocity of the chunk as part of the process of refining the final experimental design.

To summarize, it is not strictly sufficient to scale the graded-density impactor and flier-plate dimensions from normal HVL designs to launch a thick flier-plate chunk. Two-dimensional release waves emanating upon impact at the flier-plate/layered impactor boundary will dominate both the integrity and the maximum velocity of the chunk. However, by choosing a step-down barrel geometry as indicated in calculation #4, these effects can be minimized and controlled to launch a flier-plate chunk to velocities higher than those even achieved for thin flyers.

3. Experimental Summary

A graded-density impactor approximately 3 times the thickness used in a normal HVL experiment and 12.7 mm in diameter was used to impact a 10 mm diameter by 3 mm thick titanium plate. Details of the graded-density impactor and the flier plate configuration used in these studies are shown in Figure 5. The detailed dimensions of the graded density impactor are given in Table 2. As indicated in Figure 5, a guard ring is located at approximately a 6 mm diameter location to separate the center chunk from the material that remains in close contact with the barrel wall. The graded-density material impacts the undersized titanium chunk and the barrel walls at ~ 5.8 km/s. The detailed experimental schematic is shown in Figure 6. The estimated impact velocity, although not directly measured in the experiment, is expected to be accurate to within 2%. The impact velocity is based on the gun performance data for this two-stage light-gas gun. Radiographic measurements of the chunky fragments and the guard ring are taken along its flight path after exit from the tungsten barrel and up to a flight distance of over 1.4 meters after impact. These measurements are documented in Table 3, while the radiographs of the flier are shown in Figures 7 and 8.

Figure 5. Details of the (A) flier plate configuration and (B) graded-density layered impactor.

Table 3: Time-distance measurements for the projectile chunk.

Measurement Identification Number	Time μ s	Distance (mm)
1T	11.8	100
2T	15.8	140.2
3S	32.3	309.1
4S	76.1	756.9
5T	77.5	759.1
6T	93.1	963.6
7S	143.1	1434.5

Figure 6. Schematic of the experimental configuration.

The four radiographs shown in Figure 7 represent the image taken from the top of the range tank (top view), while the three radiographs shown in Figure 8 are views

imaged from the side of the tank. A linear least squares fit to the distance time measurements indicated in Table 3 is shown in Figure 9 and yields an average velocity of 10.2 km/s for the chunky fragment. The chunky projectile appears to be tumbling as it traverses, and has rotated approximately half a turn over this flight distance. The mass of the chunky fragment is 0.33 g, while the mass of the guard ring is 0.7 g. It should be noted that only a third of the entire projectile mass is that of the chunky fragment. Note that many of the fragments from the guard ring are in the same plane as the chunky fragment, and is traversing at the same velocity. This suggests that a larger center chunk *i.e.*, with a smaller guard ring would have survived the extreme loading conditions. This concept needs to be pursued further in future experiments.

Figure 7. Radiographs of the projectile chunk in flight indicating the top view. These corresponds to measurements 1, 2, 5, 6 in Table 3.

In a conventional HVL experiment, the graded-density material impacts only the flier plate. As indicated in the previous section, it is crucial that the barrel wall also be impacted in this experiment; otherwise two-dimensional effects *due to longer loading times dominates* the launch characteristics of the chunk resulting in lower velocities. The interior ballistics for a chunk projectile launch reported in this report are sufficiently different than for a more typical HVL experiment (Chhabildas, *et al.*, 1993) in which a thin flyer is launched intact. In the next section, calculations performed in order to understand the interior ballistic performance of this experiment is discussed in detail. A brief description of these calculational results have been already highlighted in the section on technical issues (see section 2). Generally speaking, calculations are important and are being used not only for experimental design but also for interpretation of the acceleration history in lieu of any *in situ* measurements during the peak acceleration phase of the flyer. These calculations provide a means of understanding the behavior of the launch system as the chunk projectile accelerates from zero to terminal velocity over a few microseconds.

Figure 8. Radiographs of the projectile chunk in flight indicating the side view. These corresponds to measurements 3, 4, 7 in Table 3.

Figure 9. Time distance measurements of the chunky projectile in flight.

4. Discussion of the Calculations

In this section we discuss the results of the calculations in greater detail. The calculations that we discuss are listed in Table 4. The *computational* geometries that are the focus of this discussion are shown in Figures 6 and 10. They represent various modifications of the experimental geometry at the time of impact. The flyer plate configuration was modeled similarly to the geometry in Figure 5. It is an exact representation of the experiment as related to the design of the layered impactor and the chunk flyer. In particular, the barrel extension is assumed to be completely tungsten, as opposed to the experimental case where the extension is partly steel, followed by a tungsten fixture. Since the impact of the layered projectile upon the chunk occurs in the region of the tungsten barrel extension, our present simplification is entirely appropriate. No attempt was made, however, to simulate the precise thickness of the tungsten barrel extension. In all cases, this barrel extension is assumed to be thick enough to provide inertial confinement as the layered impactor strikes the chunk projectile. The dimensions indicated in Figure 6 are those used in the **CTH** calculations. As in the experiment the impact velocity of the graded-density impactor was assumed to be 5.8 km/s.

Table 4: CTH Calculation Summary

CALC NO.	GEOMETRY	Impact Velocity (km/s)	COMMENTS
#1	1-D	5.8	1-D CTH calculation. No barrel, no 2-D geometry variations, no wave propagation edge effects.
#2	2-D axisymmetric	5.8	No barrel stepdown, no 2-D variation in the impactor.
#3	2-D axisymmetric	5.8	No barrel stepdown, otherwise configured the same as the basic experiment.
#4	2-D axisymmetric	5.8	Basic simulation of experiment.
#5	2-D axisymmetric	5.8	TPX buffer removed.
#6	2-D axisymmetric	6.0	Velocity increase of impactor to within experimental bounds. Estimated expt. velocity error is ~ 0.2 km/s.

For the 2-D calculations in Table 4, we used a fine zoning of $\Delta x = 0.01$ cm, $\Delta y = 0.01$ cm. This resolves the diameter of the flier with approximately 60 zones, the flier thickness with approximately 30 zones. The computational problem that results has approximately 105,000 zones. For the 1-D calculation #1, we used the same resolution of $\Delta x = 0.01$ cm, resulting in a problem having 497 zones. All of the calculations were performed on the Sandia Cray YMP/864.

Figure 10. Schematics for calculations #1 through #5. (Not to scale.)

In these calculations, nine materials were modeled using the ANEOS Mie-Grüneisen equation of state option (Thompson, 1989). For these simulations, the validity of this equation of state for the TPX plastic is a serious concern, primarily

because we expect this material to dissociate under the intense loading conditions of the experiment. We will discuss this issue later. The appropriate material parameters are listed in Table 5.

Table 5: ANEOS Mie-Grüneisen parameters.

MATERIAL	Density (g/cc)	Bulk Sound Speed (km/s)	Hugoniot s	Grüneisen Parameter	Yield Strength (kb)
Titanium Alloy (Ti-V6-AL)	4.42	4.99	1.05	1.09	12.0
TPX Plastic (CH)	0.835	2.20	1.513	0.97	0.1
Magnesium	1.74	4.492	1.263	1.425	5.0
Aluminum	2.7	5.328	1.338	2.06	3.0
Copper	8.94	2.74	1.489	1.99	1.0
Plexiglass	1.185	2.74	1.36	0.856	1.0
Tungsten Alloy	17.25	4.03	1.237	1.54	40.0
TPX Plastic	0.835	2.20	1.513	0.97	0.1
Titanium Alloy	4.42	4.99	1.05	1.09	12.0

Two calculations that were not discussed in Section 2 are listed in Table 4. Calculation #6 simulates the baseline experiment, but with an impactor velocity of 6 km/s. This calculation was performed to estimate the influence of impactor velocity uncertainties. Calculation #5 is a simulation in which the TPX buffer is removed. As in thin flyer launches on the HVL, the presence of the TPX buffer is intended to cushion the chunk projectile launch, lowering the temperature and magnitude of the tensile states observed in the chunk. This calculation was intended to explore this phenomena for the more complex impact geometry used in the present experiment.

Performance results of all the calculations are summarized in Table 6. The table includes estimates for peak driving pressures, the maximum tensile states, the residual temperature, and the terminal velocity for the flier. Only the measured flier velocity, however, can be directly compared with the experimental measurements. The velocity achieved by the chunk in the experiment was 10.2 km/s.

The first question we should ask about these calculations is how significant is the 6% underestimate of the chunk flyer velocity in calculation #4. This is a slightly greater error in the CTH flyer velocity prediction than we typically have observed in simulating thin flyer launches on the HVL. Because the impactor velocity is not measured in the experiment, there is an implicit uncertainty in the estimated impact

velocity of 5.8 km/s of approximately ± 0.1 km/s. Therefore, in calculation #6 we used an impact velocity of 6.0 km/s, a conservative overestimate of the experimental impact velocity. The resulting computed velocity of the chunk is closer to the experimental velocity, but the error is still 4%. Therefore, underprediction of the flyer velocity by the code can not be explained by a faster impactor velocity.

Table 6: Performance data from **CTH** calculations.

CALC NO.	CHUNK VELOCITY (km/s)	PREDICTED VELOCITY ERROR (%)	Maximum Driving Pressure (Mbars)	Maximum Tensile Pressure (Mbars)	Residual Temperature (K)
#1	8.8	15	0.65	< 0.005	850
#2	8.0	23	0.65	0.021	725
#3	6.0	41	0.70	> 0.047	850
#4	9.6	6	0.75	0.048	900
#5	10.0	3	1.05	> 0.05	> 2000
#6	9.9	4	0.80	0.043	800

Although a 4% error in a **CTH** prediction is within the expected accuracy of the code at its best performance for any given problem, we still believe that the underprediction of the experimental velocity is important. It may point to subtle effects in chunk launch phenomena that are not modeled accurately in our calculations.

One of the effects that may be inaccurately modeled is the cyclic loading of the graded-density layered impactor materials during peak acceleration of the chunk. Acceleration of the chunk takes considerably longer than the acceleration of the thin flyer. In Figure 11 we have plotted the axial velocity of the flyer vs time for calculations #2, #3, and #4. We have also contrasted these curves with a typical velocity history from a calculation simulating a thin flyer HVL experiment. (We emphasize that there is no corresponding experimental data with which to compare these results.) Each chunk calculation shows a longer period of acceleration than the thin flyer, with the longest acceleration occurring for the most complete simulation of the experiment, #4.

Figure 12 illustrates the radial variability of the axial velocity of the chunk flyer for calculation #4. The curve correspond to selected Lagrangian tracers representing different radial positions on the impact side of the chunk projectile. The radius of 0.25-0.3 demarcates the chunk from the surrounding guard ring. The velocity uniformity through the main body of the flyer is predicted to be exceptionally uniform. This is, of course, a critical and a necessary condition for intact launch.

Figure 11. Illustrative particle velocities from a sample thin flyer CTH calculation.

Figure 12. Particle velocities of the chunk launch simulation #4.

The longer duration of the acceleration of the chunk is not simply a scaling result due to the increased thickness of the impactor and the flyer. We have demonstrated that with the velocity comparison in Figure 13, where the strictly 1-D calculation (but with the proper thicknesses!) is contrasted with the experiment

simulation. For the experiment, acceleration continues for an additional three microseconds beyond that of the 1-D idealization, resulting in an additional velocity increment of 0.8 km/s. These longer acceleration times are a unique feature of the chunk projectile launch design, when compared to a thin flier launch or less effective chunk flyer designs.

Figure 13. Comparison of velocity histories in the chunk for the 2-D and 1-D simulations #4 and #1. The radial location of the Lagrangian tracers where these velocities were acquired is near the axis of symmetry.

Thin flyer launch is dominated by wave reverberations and the influence of material impedance upon these. Second-order corrections arise from the possibility of additional energy release in the TPX buffer material. In experiments up to this date, however, very accurate predictions of the flyer velocity have been achieved (to less than 5%) without modeling possible energetic decomposition of the TPX buffers. This leads us to conclude that these experiments are primarily impedance dominated and effects due to possible energetic buffer decomposition are not as significant.

In contrast, multi-dimensional effects in the chunk launch play a significant role in addition to impedance effects. Our simulations of the experimental configuration suggest that the early acceleration is influenced by wave reverberations and impedance considerations similar to the case of thin flyer launch. It is the late time acceleration of the chunk which is dominated by multi-dimensional effects. These effects are primarily (1) the flow of the impactor material down the barrel, which

maintains long time acceleration of the flyer, and (2) the coupling of the barrel extension to the system. In fact, the design of the successful experiment fundamentally includes the knowledge of 2-D effects that we gained through computational simulations in order to achieve the final velocity of the flyer. This is visible in Figure 13, where we have compared the velocity histories of calculation #4 near the axis of symmetry with those from calculation #1. The 1-D calculation #1 significantly underpredicts the final velocity of the projectile, as shown in Table 5. This is because the acceleration of the chunk occurs for an additional 3 μ s longer in the 2-D calculation than in the 1-D calculation, yielding an additional 0.8 km/s to the final velocity of the chunk.

In addition, the comparison of calculation #4 with #2 in Figure 11 supports our argument that multi-dimensional effects are important. Calculation #2 produced a flyer velocity that was even less than that predicted by #1. As shown in Figure 11, #2 is less efficient than #1 because multi-dimensional edge effects are present. By allowing premature reduction of the driving pressure, they lower the peak acceleration of the flyer. The degradation caused by the edge effects induced release waves is even more dramatic in calculation #3, where the experimental configuration is simulated without the barrel step. In this case, release waves arrive even earlier due to the smaller layered impactor diameter, and reduce the final velocity of the chunk to 6.0 km/s, although the chunk is still predicted to remain intact. This conclusively demonstrates that the additional acceleration that we observe in calculation #4 results from using the step-down barrel design.

The layered impactor functions as a working fluid in this experiment, as in other HVL experiments. This is due to the use of the barrel stepdown, which is designed to maintain high pressures in the region of the impactor. The impactor must achieve two goals. First, it must be designed so that catastrophic fragmentation or melting of the chunk does not occur. In other words, the impactor must act as a cushion. This is achieved by controlling the thicknesses and shock impedances of the constituents of the layered impactor. Melting of the chunk flyer is prevented through proper grading of the impactor impedance. Fracture is controlled by the risetime and the faltime of the loading pressure (an impactor design issue) and the thickness of the flyer. Overall design of the experiment is intended to minimize both chunk fracture and chunk melt by controlling these variables.

Second, it is also important, however, to tune the impactor design so as to maximize forward momentum and kinetic energy transfer from the impactor to the chunk. In these experiments, the impactor behaves like a "jet" for the following reasons. The "step down" barrel design and dimensional details of the impactor produce continued acceleration of the impactor materials *following* the impact. The length of time that acceleration occurs in the experiment shows how effective our current design is at achieving this effect. We caution the reader that the equation of state descriptions of the impactor materials under cyclic loading (especially the TPX) become more important as the accuracy requirements for modeling this jetting are refined. For this reason, TPX is one material in particular that we are

Figure 14. (a) Axial velocity as a function of axial position at $2.0 \mu\text{s}$ and (b) corresponding system configuration from the CTH calculation #4. Note that the flyer velocity is equal to the initial graded-density impactor velocity at this time.

concerned about using the Mie-Grüneisen equation of state to describe. As the intensity of the loading of the TPX increases, it will tend to decompose, possibly accompanied by energy release. This phenomenon can not be modeled using a simple material description like the Mie-Grüneisen equation of state. Decomposition may indeed be occurring in the present experiment and our failure to adequately model this process could be one reason that the CTH velocity predictions are smaller than the experimental velocities. However, even if

decomposition takes place its effects are (apparently) small in the present experiment. In experiments involving different geometric configurations, the influence of decomposition might be greater.

Figure 15. (a) Axial velocity as a function of axial position at $3.0 \mu\text{s}$ and (b) corresponding system configuration from the CTH calculation #4. Note that part of the flyer is now traveling at velocities greater than the initial impact velocity.

In Figures 14 and 15, axial material velocity in the drive system is plotted as a function of axial distance, for calculation #4, at the times of 2.0 and $3.0 \mu\text{s}$. In addition, we have shown the calculated configuration of the experiment "in

progress" at those same times of 2.0 and 3.0 μs . Between these two times, the mean axial velocity of the chunk changes from 5.5 km/s (which is below the impact velocity of 5.8 km/s) to 8.6 km/s (which is well above the impact velocity). This is because materials in the layered portion of the impactor have begun to accelerate within the narrowed barrel of the experiment, resulting in continuous acceleration of the chunk. At later times (not shown), we see further increase of the velocity of these materials, with some portions of the impactor achieving on-axis velocities of over 10 km/s, so that they are moving faster than the chunk in the calculation. The result of this is to maintain an efficient drive on the chunk. The continued drive contributes to the late time flyer acceleration as seen in Figures 11 and 12.

It is very important to properly design the barrel extension. There are three different factors that play a role. The barrel must be stepped down to enhance impactor momentum and kinetic energy transfer to the chunk. This introduces the downstream barrel diameter as an important parameter. The barrel extension must "inertially confine" the impact point so that severe deformation of the chunk, with subsequent fracture, does not occur. This introduces a combination of factors related to barrel equation of state and the impactor configuration. Finally, high pressure waves in the barrel resulting from the impact should not outrun the motion of the chunk. Otherwise, the barrel will squeeze the chunk substantially, reducing its velocity and, more significantly, fracturing it. This last consideration also introduces barrel EOS as a parameter of concern. It may not be possible to satisfy all of these goals, and it is not yet clear what the optimal design that best accounts for these goals may be. There are trade-offs. For example, while we simultaneously seek high impedance barrels for inertial confinement, we also need to minimize the sound speed of the barrel. An optimal, although difficult to implement material, would be depleted uranium, which has a higher density than the tungsten alloy we currently use, but a lower sound speed. This limits the choice of barrel materials. One advantage of the titanium alloy that we have used in the flyer is that it has high ductility, along with a large fracture strength (approximately 55 kbars - Chhabildas, *et al.*, 1990a). Thus, our flyer is fairly forgiving as to the region of barrel design parameter space that we focus on. As the technology is pushed to the limit, however, we would expect that every parameter will become important.

Peak acceleration occurs approximately 2.0 μs after impact in the experiment. Figure 16 shows 2-D plots of the calculated configuration of the system at 3.0 and 4.0 μs after impact. Contours of constant pressure are drawn in these plots. Successful inertial confinement of the impact is perhaps the most important of the above goals. This guarantees that the chunk is accelerated through the high deformation/high pressure impact region intact, with minimal degradation from 2-D edge effects. The barrel step down was successful in both appropriately confining the flyer and in allowing late-time impactor jetting to sustain flyer acceleration. At 3.0 μs the impact generated pressure waves are downstream of the flyer in the barrel. Prior to the experiment we could not be certain as to how sensitive the accelerator process was to the compressive waves being downstream near peak

acceleration. The success of the experiment suggests that early time loading of the chunk by these waves in the barrel is not detrimental to chunk integrity; this is our first experimental confirmation of this hypothesis. By $4.0 \mu\text{s}$, as seen in the figure, the chunk has drawn even with these barrel waves, and eventually will outrun them. Exactly the opposite of this effect occurred when the TPX buffer was removed in calculation #5. Very strong pressure waves in the barrel lead the chunk, resulting in strong pinching and ultimate break-up of the chunk during acceleration (not shown).

Figure 16. Pressure contours in calculation #4 at 3.0 and 4.0 μs .

While pressure confinement of the chunk is desirable, this may also contribute to the fracture of the chunk if it either lasts too long or if the magnitude is too large. The impedance of the impactor is designed to prevent the type of loading that would cause the chunk to spall - *i. e.* fracture due to impact generated wave propagation effects. Just the right balance of parameters must be achieved in order to keep the flyer intact while it is accelerated to high velocity. As indicated by the experimental radiographs in Figures 7 and 8, both of these goals seem to have been accomplished in this experiment, resulting in the launch of an intact chunk.

Table 6 shows that we may have been quite close to fracturing the chunk in the experiment. Calculation #4 predicted approximately 50 kbars of tension in the middle of the chunk, which is comparable to the approximately 55 kbar spall strength of Ti6 alloy. Note that the chunk in the experiment could have undergone an internal fracture that would not be visible to the experimental diagnostics. Since spall strength tends to increase with isentropic loading pressure (Chhabildas, *et al.*, 1988, Chhabildas and Asay, 1992 - not modeled in our calculations), it is conceivable that under a structured time-dependent loading condition the material can sustain higher spall stresses than the nominal 55 kbars.

It is very interesting that the increased impact velocity in calculation #6 *lowered* the flyer residual temperature and the observed tensile pressure, while increasing the velocity of the chunk. This fact demonstrates further the role of the impactor as a working fluid. The higher impact velocity produced greater heating, hence more vaporization, in the TPX. In the ANEOS Mie-Grüneisen model for the TPX, an ad hoc method is used to represent expanded states. This model does not include the decomposition behavior mentioned earlier and is not guaranteed to provide an accurate vapor equation of state for this material. However, this equation of state is adequate for noting trends due to vaporization. Vaporization changes the compressibility, and hence the cushioning effect, of the impactor and buffer, and lowered the amplitude of the pressure in the flyer. At the same time, higher sound speeds of the compressed TPX produced higher expansion velocities, which were more successful at accelerating the flyer. One should not expect this trend to continue at ever higher velocities. At some point, the timing of the wave propagation will change sufficiently that a strong shock will enter the chunk, producing higher heating and spall formation.

5. Conclusion

In this report we have presented a detailed analysis of the successful launch of a chunk (thick flyer) on the Sandia Laboratories Hypervelocity Launcher (HVL). This analysis gives some insight into how complex this type of experiment really is. Successful launch of an intact chunk flyer requires:

- An experimental design that incorporates 2-D effects in the impact region, while minimizing 2-D effects in the body of the chunk.
- An impactor design that allows the impactor to function as a working fluid. This both cushions the chunk, and maximizes momentum and kinetic energy transfer from the impactor to the chunk.
- A barrel extension design that is different than the barrel extensions previously used for thin flyers. The barrel design acts like an acceleration reservoir and contributes to the momentum and kinetic energy transfer efficiency while helping to minimize destructive 2-D effects in the chunk.

It is interesting to examine the results in Figure 17. There, we have plotted the total kinetic energy and forward axial momentum of the impactor and of the chunk, minus the guard ring, as functions of time. This plot shows that the efficiency of this system is really quite low. Note that the forward axial momentum of the impactor *increases* because of backward moving debris caused by the initial impact. Since total axial momentum must be conserved, forward momentum must increase to compensate for the creation of rearward momentum. We have also shown the limiting kinetic energy and chunk momentum that are possible to attain in impact driven systems when the impact velocity is 5.8 km/s. These values correspond to the kinetic energy and momentum of the central chunk moving at the velocity of 11.6 km/s (the limiting value of double the impact velocity for an infinite mass impactor). In the case of kinetic energy, the chunk is within 33% of its limiting value, while forward momentum is within 18%. These results show that achieving chunk velocities of 14.0 km/s exceeds the limit possible with non-complex impact techniques. This goal will require greater impactor velocities and more precisely designed experimental configurations. These configurations may possibly utilize energetic materials in the impactor and the buffer. We stress, however, that a very small increase in the present momentum and energy conversion efficiency between the impactor and the chunk could result in a significant increase in the terminal velocity of the chunk, provided that the additional energy is not expended in heating the flyer. We have contrasted the chunk momentum of the flier with that of the projectile to show the relatively small amounts of momentum which are being transferred during the experiment.

Figure 17. (a) Kinetic energy of the chunk and (b) forward momentum of the impactor and chunk as functions of time in CTH calculation #4.

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Appendix A. Sample CTH INput Listing

```

*eor* cgenin
*
*****
*
*
***** 11/92 *****
*
* TITLE RECORD
*
P41 - Chhabildas Experiment Simulation, Corrected TI backing
*
***** control block *****

control
  EP
  MMP
endcontrol

*
* START OF GEOMETRY BLOCK 1
*
MESH
  BLOCK 1 GEOM=2DC TYPE=E

    X0 0.
    X1 N=150 DXF=.010 W=1.5
    X2 DXF=.010 DXL=.05 W=1.5
    ENDX

    Y0 -0.05
    Y1 N=100 DYF=.020 W=2.00
    Y2 DYF=.020 DYL=.01 W=0.4
    Y3 N=200 DYF=.010 W=2.00
    Y4 DYF=.010 DYL=.02 W=0.6
    Y5 N=250 DYF=.020 W=5.00
  ENDY

  XACT = 0,1.5
  YACT = -0.05,2.5

  ENDB
*
ENDMESH * END GEOMETRY BLOCKS
*
*****
* MATERIAL INSERTION INPUTS
  INSERTION OF MATERIAL
    BLOCK 1
    PACKAGE 'TITANIUM FLYER PLATE INSERT'
    MATERIAL 1
    NUMSUB 100
    DEN = 4.42
    VELOCITIES YVEL 0.0
    INSERT UDS
      POINT1 = 0.0,2.865864
      POINT2 = 0.2593,2.865864
      POINT3 = 0.29845,3.165584
      POINT4 = 0.0,3.165584
    ENDINSERT
  ENDPACKAGE
    PACKAGE 'TITANIUM GUARD RING INSERT'
    MATERIAL 9
    NUMSUB 100
    DEN = 4.42
    VELOCITIES YVEL 0.0
    INSERT UDS
      POINT1 = 0.2593,2.865864
      POINT2 = 0.49784,2.865864
      POINT1 = 0.49784,3.165584
      POINT1 = 0.29845,3.165584
    ENDINSERT
  ENDPACKAGE
    PACKAGE 'TPX FLYER PLATE INSERT'

```

```

MATERIAL 8
NUMSUB 100
DEN = 0.835
VELOCITIES YVEL 0.0
INSERT BOX
  X1 0.0 X2 1.48209
  Y1 2.426464 Y2 2.865864
ENDINSERT
ENDPACKAGE
PACKAGE 'PLYWOOD LAYER #1 - TPX'
MATERIAL 2
NUMSUB 100
DEN = 0.835
VELOCITIES YVEL 5.8E5
INSERT BOX
  X1 0.0 X2 0.635
  Y1 2.126744 Y2 2.426464
ENDINSERT
ENDPACKAGE
PACKAGE 'PLYWOOD LAYER #2 - MAGNESIUM'
MATERIAL 3
NUMSUB 100
DEN = 1.740
VELOCITIES YVEL 5.8E5
INSERT BOX
  X1 0.0 X2 0.635
  Y1 1.946404 Y2 2.126744
ENDINSERT
ENDPACKAGE
PACKAGE 'PLYWOOD LAYER #3 - ALUMINUM'
MATERIAL 4
NUMSUB 100
DEN = 2.7
VELOCITIES YVEL 5.8E5
INSERT BOX
  X1 0.0 X2 0.635
  Y1 1.796544 Y2 1.946404
ENDINSERT
ENDPACKAGE
PACKAGE 'PLYWOOD LAYER #4 - TITANIUM'
MATERIAL 10
NUMSUB 100
DEN = 4.42
VELOCITIES YVEL 5.8E5
INSERT BOX
  X1 0.0 X2 0.635
  Y1 1.677164 Y2 1.796544
ENDINSERT
ENDPACKAGE
PACKAGE 'PLYWOOD LAYER #5 - COPPER'
MATERIAL 5
NUMSUB 100
DEN = 8.94
VELOCITIES YVEL 5.8E5
INSERT BOX
  X1 0.0 X2 0.635
  Y1 1.588264 Y2 1.677164
ENDINSERT
ENDPACKAGE
PACKAGE 'PLYWOOD LAYER #6 - COPPER'
MATERIAL 5
NUMSUB 100
DEN = 8.94
VELOCITIES YVEL 5.8E5
INSERT BOX
  X1 0.0 X2 0.635
  Y1 1.039624 Y2 1.588264
ENDINSERT
ENDPACKAGE
PACKAGE 'PLYWOOD LAYER #7 - TITANIUM'
MATERIAL 10
NUMSUB 100
DEN = 4.42
VELOCITIES YVEL 5.8E5
INSERT BOX
  X1 0.0 X2 1.34874
  Y1 0.960376 Y2 1.039624
ENDINSERT
ENDPACKAGE
PACKAGE 'LEXAN PROJECTILE BODY INSERT'
MATERIAL 6

```



```

NUMSUB 100
DEN = 1.185
VELOCITIES YVEL 5.8E5
INSERT BOX
  X1 0.0 X2 1.4859
  Y1 0.0 Y2 2.426464
ENDINSERT
ENDPACKAGE
PACKAGE 'TUNGSTEN ALLOY FIXTURE INSERT'
MATERIAL 7
NUMSUB 25
DEN = 17.25
INSERT BOX
  X1 1.4859 X2 3.0
  Y1 0.0 Y2 9.90
ENDINSERT
ENDPACKAGE
PACKAGE 'TUNGSTEN ALLOY FIXTURE INSERT'
MATERIAL 7
NUMSUB 25
DEN = 17.25
INSERT BOX
  X1 0.5 X2 3.0
  Y1 2.865864 Y2 9.90
ENDINSERT
ENDPACKAGE
ENDBLOCK
ENDINSERTION
*
*****
* TEST OF EDIT
EDIT
BLOCK 1
EXPANDED
ENDBLOCK
ENDEDIT
*****
*
* tracers
TRACER
*
*PLYWOOD LAYER #7 (TITANIUM) INSERT - MIDDLE
*
ADD = 0.05 1.02
ADD = 0.1 1.02
ADD = 0.3 1.02
ADD = 0.50 1.02
ADD = 0.60 1.02
*
*PLYWOOD LAYER #6 (COPPER) INSERT - MIDDLE
*
ADD = 0.05 1.314
ADD = 0.1 1.314
ADD = 0.3 1.314
ADD = 0.50 1.314
ADD = 0.60 1.314
*
*PLYWOOD LAYER #5 (COPPER) INSERT - MIDDLE
*
ADD = 0.05 1.633
ADD = 0.1 1.633
ADD = 0.3 1.633
ADD = 0.50 1.633
ADD = 0.60 1.633
*
*PLYWOOD LAYER #4 (TITANIUM) INSERT - MIDDLE
*
ADD = 0.05 1.737
ADD = 0.1 1.737
ADD = 0.3 1.737
ADD = 0.50 1.737
ADD = 0.60 1.737
*
*PLYWOOD LAYER #3 (ALUMINUM) INSERT - MIDDLE
*
ADD = 0.05 1.871
ADD = 0.1 1.871
ADD = 0.3 1.871
ADD = 0.50 1.871
ADD = 0.60 1.871
*

```

*PLYWOOD LAYER #2 (MAGNESIUM) INSERT - MIDDLE

*

ADD = 0.05 2.036

ADD = 0.1 2.036

ADD = 0.3 2.036

ADD = 0.50 2.036

ADD = 0.60 2.036

*

*PLYWOOD LAYER #1 (TPX) INSERT - MIDDLE

*

ADD = 0.05 2.276

ADD = 0.1 2.276

ADD = 0.3 2.276

ADD = 0.50 2.276

ADD = 0.60 2.276

*

*TPX BUFFER - REAR

*

ADD = 0.05 2.46

ADD = 0.1 2.46

ADD = 0.3 2.46

ADD = 0.5 2.46

ADD = 0.60 2.46

*

*TPX BUFFER - FRONT

*

ADD = 0.05 2.84

ADD = 0.1 2.84

ADD = 0.3 2.84

ADD = 0.5 2.84

ADD = 0.60 2.84

*

*TITANIUM FLYER - REAR

*

ADD = 0.05 2.88

ADD = 0.1 2.88

ADD = 0.15 2.88

ADD = 0.20 2.88

ADD = 0.25 2.88

ADD = 0.30 2.88

ADD = 0.35 2.88

ADD = 0.40 2.88

ADD = 0.45 2.88

*

*TITANIUM FLYER - MIDDLE

*

ADD = 0.05 3.01

ADD = 0.1 3.01

ADD = 0.15 3.01

ADD = 0.20 3.01

ADD = 0.25 3.01

ADD = 0.30 3.01

ADD = 0.35 3.01

ADD = 0.40 3.01

ADD = 0.45 3.01

*

*TITANIUM FLYER - FRONT

*

ADD = 0.05 3.14

ADD = 0.1 3.14

ADD = 0.15 3.14

ADD = 0.20 3.14

ADD = 0.25 3.14

ADD = 0.30 3.14

ADD = 0.35 3.14

ADD = 0.40 3.14

ADD = 0.45 3.14

* 72 TRACERS

ENDTRACER

EOS NUM=10 * no ANEOS on the vax

MAT1 = -1

MAT2 = -2

MAT3 = -3

MAT4 = -4

MAT5 = -5

MAT6 = -6

MAT7 = -7

MAT8 = -8

MAT9 = -9

MAT10 = -10

```

*****
* TITANIUM ALLOY ANEOS DATA
*
* slt 5/6
* DEFINE ANEOS TITANIUM - NO. 4: TI-6AL-4V ALLOY WITH SOLID/SOLID
* NO ELECTRONIC TERMS
*
* * * * * W A R N I N G * * * * *
*
* DON'T USE MELT TRANSITION WITH SOLID/SOLID TRANSITION
*
* IF YOU NEED MELT, USE TI2 EOS
*
* SHOCK HUGONIOT DATA USED
*
* US = C0 + S*UP
*
* C0 = 4.99E5 ] CHHABILDAS - APRIL, 1989
* S = 1.05 ] CHHABILDAS - APRIL, 1989
*
* Y0 = 12 KBARS ] CHHABILDAS - APRIL, 1989
*
* SPALL = 41 KBARS ] CHHABILDAS - APRIL, 1989
*
* POISSON RATIO = .322 ] CHHABILDAS - APRIL, 1989
*
* SOLID/SOLID PHASE TRANSITION - BEGINS AROUND 175 KBAR
* ENDS NEAR 185 KBAR
*
* 0.6 % VOLUME CHANGE
* * * * *
*
* MARTINYUK'S CRITICAL TEMPERATURE FOR TITANIUM IS:
*
* TC = 7030 K = 0.598 EV
* -----
*
* NEOS TITLE LIB TYPE RHUG THUG
* ANEOS1 -1 'TI4S' RHUG=-1 THUG=-1
* V1 V2 V3 V4 V5 V6 V7 V8
* ANEOS2 3. -1. 4.42 0. 0. 4.99E5 1.09 0.0
* V9 V10 V11 V12 V13 V14 V15 V16
* ANEOS3 1.05 0. 0.0 1.E6 0.0 0.0 0.0 0.0
* V17 V18 V19 V20 V21 V22 V23 V24
* ANEOS4 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0
* Z(I) F(I)
* ANEOS5 22. .90
* ANEOS5 13. .06
* ANEOS5 23. .04
* ***** END OF DATA *****
* *****
* -----
* TPX
* -----
*
* ANEOS1 -2 'TPX' THUG=-1 RHUG=-1
* ANEOS2 2. -1. 0.835 0.0 0.0 2.20E5 0.970 0.0
* ANEOS3 1.513 0. 0.0 1.E6 0.0 0.0 0.0 0.0
* ANEOS4 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
* ANEOS5 1. 0.5
* ANEOS5 6. 0.5
* *****
* *****
*
* -----
* MAGNESIUM
* -----
*
* ANEOS1 -3 'MAGNESIUM' THUG=-1 RHUG=-1
* ANEOS2 1. -1. 1.740 0.0 0.0 4.492E5 1.425 0.0
* ANEOS3 1.263 0. 0.0 1.E6 0.0 0.0 0.0 0.0
* ANEOS4 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
* ANEOS5 12. 1.0
* *****
* *****
*
* -----
*
* NEOS TITLE LIB TYPE RHUG THUG

```

```

ANEOS1 -4 'ALUMINUM-1' RHUG=-1 THUG=-1
* V1 V2 V3 V4 V5 V6 V7 V8
ANEOS2 1. -1. 2.7 0. 0. 5.328E5 2.06 0.0
* V9 V10 V11 V12 V13 V14 V15 V16
ANEOS3 1.338 0. 0.0 1.E6 0.0 0.0 0. 0.
* V17 V18 V19 V20 V21 V22 V23 V24
ANEOS4 0.0 0 0 0 0 0 0.0 0.0
* Z(I) F(I)
ANEOS5 13. 1.
***** END OF DATA *****
*
* -----
* COPPER
* -----
ANEOS1 -5 'COPPER' RHUG=-1 THUG=-1
* V1 V2 V3 V4 V5 V6 V7 V8
ANEOS2 1. -1. 8.94 0. 0. 3.94E5 1.99 0.0
* V9 V10 V11 V12 V13 V14 V15 V16
ANEOS3 1.489 0. 0.0 1.E6 0.0 0.0 0.0 0.
* V17 V18 V19 V20 V21 V22 V23 V24
ANEOS4 0.0 0 0 0 0 0 0.0 0.0
* Z(I) F(I)
ANEOS5 29. 1.
*
* -----
* PLEXIGLASS
* -----
ANEOS1 -6 'PLEXIGLASS' THUG=-1 RHUG=-1
ANEOS2 2. -1. 1.185 0.0 0.0 2.74E5 0.856 0.0
ANEOS3 1.360 0. 0.0 1.E6 0.0 0.0 0.0 0.0
ANEOS4 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
ANEOS5 1. 0.5
ANEOS6 6. 0.5
*****
* DEFINE ANEOS TUNGSTEN ALLOY - 1
* -----
* NEOS TITLE LIB TYPE RHUG THUG
ANEOS1 -7 'TUNGSTEN ALLOY-1' RHUG=-1 THUG=-1
* V1 V2 V3 V4 V5 V6 V7 V8
ANEOS2 1. -1. 17.25 0. 0. 4.03E5 1.54 0.0
* V9 V10 V11 V12 V13 V14 V15 V16
ANEOS3 1.237 0. 0.0 1.E6 0.0 0.0 0.0 0.
* V17 V18 V19 V20 V21 V22 V23 V24
ANEOS4 0.0 0 0 0 0 0 0.0 0.0
* Z(I) F(I)
ANEOS5 74. 1.
***** END OF DATA *****
*
* -----
* TPX
* -----
ANEOS1 -8 'TPX' THUG=-1 RHUG=-1
ANEOS2 2. -1. 0.835 0.0 0.0 2.20E5 0.970 0.0
ANEOS3 1.513 0. 0.0 1.E6 0.0 0.0 0.0 0.0
ANEOS4 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
ANEOS5 1. 0.5
ANEOS6 6. 0.5
*****
* TITANIUM ALLOY ANEOS DATA
*
* slt 5/6
* DEFINE ANEOS TITANIUM - NO. 4: TI-6AL-4V ALLOY WITH SOLID/SOLID
* NO ELECTRONIC TERMS
*
* * * * * W A R N I N G * * * * *
*
* DON'T USE MELT TRANSITION WITH SOLID/SOLID TRANSITION
*
* IF YOU NEED MELT, USE TI2 EOS
*
* SHOCK HUGONIOT DATA USED

```

```

* US = C0 + S*UP
*
* C0 = 4.99E5 ] CHHABILDAS - APRIL, 1989
* S = 1.05 ] CHHABILDAS - APRIL, 1989
*
* Y0 = 12 KBARS ] CHHABILDAS - APRIL, 1989
*
* SPALL = 41 KBARS ] CHHABILDAS - APRIL, 1989
*
* POISSON RATIO = .322 ] CHHABILDAS - APRIL, 1989
*
* SOLID/SOLID PHASE TRANSITION - BEGINS AROUND 175 KBAR
* ENDS NEAR 185 KBAR
*
* 0.6 % VOLUME CHANGE
* * * * *
*
* MARTYNYUK'S CRITICAL TEMPERATURE FOR TITANIUM IS:
*
* TC = 7030 K = 0.598 EV
* -----
*
* NEOS TITLE LIB TYPE RHUG THUG
ANEOS1 -9 'TI4S' RHUG=-1 THUG=-1
* V1 V2 V3 V4 V5 V6 V7 V8
ANEOS2 3. -1. 4.42 0. 0. 4.99E5 1.09 0.0
* V9 V10 V11 V12 V13 V14 V15 V16
ANEOS3 1.05 0. 0.0 1.E6 0.0 0.0 0.0 0.0
* V17 V18 V19 V20 V21 V22 V23 V24
ANEOS4 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0
* Z(I) F(I)
ANEOS5 22. .90
ANEOS5 13. .06
ANEOS5 23. .04
***** END OF DATA *****
*****
* TITANIUM ALLOY ANEOS DATA
*
* slt 5/6
* DEFINE ANEOS TITANIUM - NO. 4: TI-6AL-4V ALLOY WITH SOLID/SOLID
* NO ELECTRONIC TERMS
*
* * * * * W A R N I N G * * * * *
*
* DON'T USE MELT TRANSITION WITH SOLID/SOLID TRANSITION
*
* IF YOU NEED MELT, USE TI2 EOS
*
* SHOCK HUGONOT DATA USED
*
* US = C0 + S*UP
*
* C0 = 4.99E5 ] CHHABILDAS - APRIL, 1989
* S = 1.05 ] CHHABILDAS - APRIL, 1989
*
* Y0 = 12 KBARS ] CHHABILDAS - APRIL, 1989
*
* SPALL = 41 KBARS ] CHHABILDAS - APRIL, 1989
*
* POISSON RATIO = .322 ] CHHABILDAS - APRIL, 1989
*
* SOLID/SOLID PHASE TRANSITION - BEGINS AROUND 175 KBAR
* ENDS NEAR 185 KBAR
*
* 0.6 % VOLUME CHANGE
* * * * *
*
* MARTYNYUK'S CRITICAL TEMPERATURE FOR TITANIUM IS:
*
* TC = 7030 K = 0.598 EV
* -----
*
* NEOS TITLE LIB TYPE RHUG THUG
ANEOS1 -10 'TI4S' RHUG=-1 THUG=-1
* V1 V2 V3 V4 V5 V6 V7 V8
ANEOS2 3. -1. 4.42 0. 0. 4.99E5 1.09 0.0
* V9 V10 V11 V12 V13 V14 V15 V16
ANEOS3 1.05 0. 0.0 1.E6 0.0 0.0 0.0 0.0
* V17 V18 V19 V20 V21 V22 V23 V24
ANEOS4 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0

```

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* Z(I) F(I)
ANEOS5 22. .90
ANEOS5 13. .06
ANEOS5 23. .04
***** END OF DATA *****
*****
*
*eor* cthin
*
* TITLE RECORD
*
P41 - Chhabildas Experiment Simulation; Corrected TI backing
*
* START OF GEOMETRY BLOCK 1
*
RESTART
  NU=1
ENDR
CONTROL
  TSTOP = 8.0E-6
  NSCYCLE = 55000
  RDUMPF = 991800.
  CPSHIFT = 600.
  ntbad = 100000
ENDC
CONVCT
  CONVECTION = 1
  INTERFACE = HIG
  NOFRAGMENT = 1
  NOFRAGMENT = 2
  NOFRAGMENT = 3
  NOFRAGMENT = 4
  NOFRAGMENT = 5
  NOFRAGMENT = 6
  NOFRAGMENT = 7
  NOFRAGMENT = 8
  NOFRAGMENT = 9
  NOFRAGMENT = 0
ENDC

EDIT
  SHORTC
  CY = 00 , DC = 5000000
ENDS

LONGT
TIM = 00. , DT = 1.E10
EXTENDED
ENDL

HISTT
TIM = 00. , DT = 1.0E-8
HTRACER1
HTRACER2
HTRACER3
HTRACER4
HTRACER5
HTRACER6
HTRACER7
HTRACER8
HTRACER9
HTRACER10
HTRACER11
HTRACER12
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HTRACER67
HTRACER68
HTRACER69
HTRACER70
HTRACER71
HTRACER72

ENDH

RESTT

TIM = 00. , DT = 0.2E-6

TIM = 2.0E-6, DT = 0.25E-6

ENDR

PLOTT

TIM = 0.0, DT = 2.0E-8

ENDP

PLOTDATA

VOLUME

MASS

PRESSURE

NEWFILE = 100

ENDP

ENDE

EPDATA

MATEP=1 , YIELD=12.0E9 , POISSON=.332

MATEP=2 , YIELD=0.1E9 , POISSON=.296

MATEP=3 , YIELD=5.0E9 , POISSON=.29

MATEP=4 , YIELD=3.0E9 , POISSON=.33

MATEP=5 , YIELD=1.0E9 , POISSON=.355

MATEP=6 , YIELD=1.0E9 , POISSON=.33

MATEP=7 , YIELD=40.E9 , POISSON=.33

MATEP=8 , YIELD=0.1E9 , POISSON=.296

MATEP=9 , YIELD=12.0E9 , POISSON=.332

MATEP=10 , YIELD=12.0E9 , POISSON=.332

SLIDE = 1,7

SLIDE = 1,8

SLIDE = 1,9

SLIDE = 2,7

SLIDE = 3,7

```

        SLIDE = 4,7
        SLIDE = 5,7
        SLIDE = 7,8
        SLIDE = 9,8
MIX=1
ENDE
* SPALL PARAMETERS
FRACTS
PRESSURE
PFRAC1 -1.0E12
PFRAC2 -1.0E12
PFRAC3 -1.0E12
PFRAC4 -1.0E12
PFRAC5 -1.0E12
PFRAC6 -1.0E12
PFRAC7 -1.0E12
PFRAC8 -1.0E12
PFRAC9 -1.0E12
PFRAC10 -1.0E12
PFMIX -1.0E20
PFVOID -1.0E20
ENDF

BOUNDARY
BHY
BL 1
BXB = 0 , BXT = 2
BYB = 2 , BYT = 2
ENDB
ENDH
ENDB

MINDT
TIME = 0. DT = 1.E-12
ENDN

MAXDT
TIME = 0. DT = .01
ENDX

```


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