The hydrodynamic operation of the ‘Forest Flyer’ type of explosive launching system for shock physics projectiles was investigated in detail using one- and two-dimensional continuum dynamics simulations. The simulations were numerically converged and insensitive to uncertainties in the material properties; they reproduced the speed of the projectile and the shape of its rear surface. The most commonly-used variant, with an Al alloy case, was predicted to produce a slightly curved projectile, subjected to some shock heating, and likely exhibiting some porosity from tensile damage. The curvature is caused by a shock reflected from the case; tensile damage is caused by the interaction of the Taylor wave pressure profile from the detonation wave with the free surface of the projectile. The simulations gave only an indication of tensile damage in the projectile, as damage is not understood well enough for predictions in this loading regime. The flatness can be improved by using a case of lower shock impedance, such as polymethyl methacrylate. High-impedance cases, including Al alloys but with denser materials improving the launching efficiency, can be used if designed according to the physics of oblique shock reflection, which indicates an appropriate case taper for any combination of explosive and case material. The tensile stress induced in the projectile depends on the relative thickness of the explosive, expansion gap, and projectile. The thinner the projectile with respect to the explosive, the smaller the tensile stress. Thus if the explosive is initiated with a plane wave lens, the tensile stress is lower than for initiation with multiple detonators over a plane. The previous plane wave lens designs did however induce a tensile stress close to the spall strength of the projectile. The tensile stress can be reduced by changes in the component thicknesses. Experiments to verify the operation of explosively-launched projectiles should attempt to measure porosity induced in the projectile: arrival time measurements are likely to be insensitive to porous regions caused by damaged or recollected material.

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I. INTRODUCTION

The impact of a disk-shaped projectile against a flat target induces shock waves in the target and the projectile, by which high pressures can be generated and investigated [1]. The projectile may be accelerated in various ways, including by the expansion of compressed gas or hot products of a chemical reaction, electromagnetic forces from a pulsed electrical discharge, or the expansion of material heated by a laser. With experiments involving the impact of a projectile with a target, a frequently-encountered problem is the synchronization of measurements with the short-lived shocked state. The duration of the shocked state is very short compared with the time required to accelerate the projectile, so any uncertainty in triggering time, projectile speed, or acceleration distance makes measurements disproportionately difficult.

Chemical reaction products are most commonly used in a powder gun, where the chemical species react by deflagration, and acceleration takes place over a few meters as the projectile is accelerated along a barrel. The acceleration distance can be reduced greatly if the chemical
species react by detonation instead \[1,2\], i.e. by the use of explosives to accelerate the projectile. Explosives can also make it easier to reach higher speeds and therefore higher impact pressures.

Explosively-launched projectiles have been used to induce shock states with relatively easy synchronization with the novel technique of neutron resonance spectroscopy (NRS), where a pulse of neutrons generated from a spallation target was used to measure the temperature of the target material while it was in the shocked state \[3\]. These experiments gave unexpected temperatures when performed on Mo as a reference material, which can be explained largely by the sensitivity of the NRS technique to subtleties of the loading conditions induced by the projectile \[4\]. The purpose of this paper is to review the physics of a class of explosively-launched projectiles in more detail, identifying aspects of the design which may cause the impact-induced loading to deviate from a one-dimensional shock, and demonstrating palliative measures for improved designs.

II. ‘FOREST FLYER’ DESIGN

The explosively-launched projectiles used in the NRS experiments followed the ‘Forest Flyer’ design \[2\]. In this design, the explosive charge was initiated across a planar face and the detonation products expanded across a gap before accelerating the projectile. If the gap were omitted, the detonation wave would drive a strong shock into the projectile, inducing shock heating and strong tensile stresses after interacting with the free surface, which could cause damage and spallation. The explosive charge was tapered down to the diameter of the projectile. (Fig. 1)

The Forest Flyer design was originally developed to improve on older designs which used a cylindrical explosive charge, initiated by a plane wave lens, to launch a disk-shaped projectile (Fig. 2). The projectile had a smaller diameter than the charge, so a significant part of the explosive energy did not contribute to the acceleration of the projectile. This is particularly inefficient if it is desired to perform a shock wave experiment inside a containment vessel – for example, for experiments on hazardous materials – as the mass of explosive should be minimized. Another disadvantage is that reaction products of the explosive blow past the projectile, and may interfere with the experiment or diagnostics. The Forest Flyer design improved over the older design by removing explosive which did not contribute to the acceleration of the projectile, and adding a case which confined the remaining explosive, increasing the efficiency of the projectile launch and protecting the impact experiment from interference by reaction products.

The Forest Flyer design was documented as a conference proceedings paper \[2\] of a poster presentation. Unfortunately, this reference contains some errors which are corrected and clarified here. The explosive charge and case were tapered down to the diameter of the projectile at an angle intended to avoid the case affecting the shape of the detonation wave in the charge \[5\]. If the case is made of a material of higher shock impedance than the explosive, it will reflect a shock wave which may make the detonation run faster close to the case; if the material has a lower shock impedance, it will reflect a rarefaction which may make the detonation wave run slower. The taper angle can be chosen to minimize the perturbation of a given case material on the detonation wave. The previously-published analysis \[2\] applies to cases of lower impedance, though variants of the Forest Flyer have been used with cases of higher impedance, such as Al alloys. In fact, the Forest Flyer has been used generally with the high explosive PBX-9501, comprising mainly cyclotetramethylene tetranitramine (HMX), whose detonation wave is relatively insensitive to the case \[6\]. A more serious concern is the potential for deformation of the projectile caused by any shock reflected into the detonation products by the taper, for a high-impedance case.

Variants of the Forest Flyer design have been used for a range of shock physics experiments. Forest Flyer projectiles have been used to induce shock waves in Mo and overdriven detonation waves in PBX-9501, to test the use of neutron resonance spectrometry as an internal temperature diagnostic for opaque materials \[3\]. These experiments were performed in a restrictive containment vessel, so a multipoint detonator was used in preference to a plane wave lens to initiate the explosive charge, minimizing the mass of explosive. Forest Flyer projectiles have been used to induce surface ejection from Sn samples, to study the effect of surface finish \[7\]. In these experiments, the projectile and case were Al alloy.

III. DESIGN CONSIDERATIONS

Starting with the basic concepts of the Forest Flyer design, we discuss deficiencies and refinements to improve the key performance aspects of projectile flatness (radial symmetry), projectile uniformity (axial symmetry), and efficiency. It is always desirable to know the condition of the projectile on impact as accurately as possible. For many shock physics experiments, it is desirable to induce a shock which is as planar as possible over some region, which is achieved by having the projectile as flat as possible, i.e. with minimum deformation by the acceleration system. High explosive launching systems must be designed with care, because the pressures induced by detonation can easily exceed the flow stress of materials, distorting the projectile if the flow of the detonation products is not designed properly. Similarly, it is usually desirable to generate a shock with a pressure which is sustained at a constant value for a finite time. This is achieved by preserving the projectile’s mass density through its thickness. With the high launching pressures possible using explosives, it is possible to induce large amplitude reverberating compression waves and also re-
FIG. 1: Schematic of ‘Forest Flyer’ explosive launching system for shock physics projectiles.

FIG. 2: Schematic of boosted plane wave lens launching system for shock physics projectiles.
flected tensile waves which may open voids, reducing the mean density of the projectile. In contrast, projectiles launched conventionally by gas and powder guns are subjected to accelerating pressures well below the flow stress of most solids, so projectiles generally remain flat and at their initial mass density.

A. Choice of taper angle

If the angle of tapering of the case is chosen incorrectly, it could reflect a strong shock or rarefaction wave which could introduce radial variations in loading, distorting the projectile radially. For instance, a reflected shock could drive the outside of the projectile harder than the region near the axis, resulting in a dish-shaped projectile on impact.

The choice of the tapering angle depends on the explosive and the case materials. Ideally, the case would introduce no radial perturbation to the load on the projectile. This is generally not possible to arbitrarily high accuracy, as it would require that no wave be reflected from the detonation wave or the subsequent release history. Perturbations are likely to be greatest at the highest pressures, so the most important requirement for a radially uniform drive is to ensure that no wave is reflected by the peak of the detonation wave.

The interaction of detonation waves with inert materials adjacent to the explosive has been investigated in the context of detonation shock dynamics [6]. The effect of the case depends qualitatively on whether it has a lower or higher shock impedance than the explosive.

1. Low-impedance case

If the adjacent material has a lower shock impedance than the explosive, it always reflects a rarefaction wave. The effect of the case on the detonation wave can be eliminated by choosing a taper angle such that no wave be reflected from the detonation wave or the subsequent release history. Perturbations are likely to be greatest at the highest pressures, so the most important requirement for a radially uniform drive is to ensure that no wave is reflected by the peak of the detonation wave.

The principal shock Hugoniot of both materials and the explosive and inert. They have their own specific relations above are sufficient to determine \( \phi_a \).

An observer sitting on a detonation wave sees unshocked material coming in at a speed \( s \) and shocked material going out at \( s - u \). Signals emitted by a passing particle at a speed \( c \) relative to the particle move at a lower speed \( c_w \) along the shock wave:

\[
c_w = \sqrt{c^2 - (D - u_p)^2},
\]

where \( D \) is the speed of the detonation wave and \( u_p \) the particle speed at the shock front. If the angle between the detonation wave and the edge of the explosive is \( \phi \), then the edge sweeps across the detonation wave at a speed

\[
c_s = \frac{D}{\tan \phi}.
\]

The causal angle of incidence \( \phi_c \) is the value when boundary effects propagate just fast enough to influence other parts of the wave, i.e. when \( c_s = c_w \), so

\[
\tan \phi_c = \frac{D}{\sqrt{c^2 - (D - u_p)^2}}.
\]

A perfectly sonic shock would have \( \phi_c = 90^\circ \), requiring a taper angle of zero.

2. High-impedance case

If the adjacent material has a higher shock impedance than the explosive, it reflects a rarefaction wave for some range of angles including the case of zero taper angle, and a shock at higher angles. [20] The effect of the case can be eliminated by choosing the taper angle such that no wave is reflected by the detonation – this is referred to below as the ‘asymptotic angle’ \( \phi_a \) as this is the angle at which a steady detonation will make with the case beside a long charge.

Denoting quantities in the explosive and inert by a subscript ‘X’ and ‘I’ respectively, and states before and behind the shock with ‘0’ and ‘1’, then the following relations can be used to determine \( \phi_a \):

- Continuity of the shock intersections with the boundary (the ‘fundamental law of shock wave refraction’ [8]):
  \[
  \frac{s_X}{\sin \phi_X} = \frac{s_I}{\sin \phi_I},
  \]

  where the \( s \) are the speeds of the shock in each material \( (s_X \equiv D) \).

- Flow deflection through a shock moving obliquely to a frame of reference:
  \[
  \tan (\phi - \chi) = \frac{v_1}{v_0} \tan \phi,
  \]

  derived from mass conservation (the ratio of particle speeds relative to the shock normal is equal to the ratio of specific volumes \( v_i \) and the requirement that the shock does not alter the flow rate parallel to it. This equation applies to both the explosive and the inert. They have their own specific volumes and angles of incidence \( \phi \), but the same angle of deflection \( \chi \).

The principal shock Hugoniot of both materials and the relations above are sufficient to determine \( \phi_a \). A perfectly rigid case would have \( \phi_a = 90^\circ \), requiring a taper angle of zero.

3. Application to explosively-launched projectiles

Previous Forest Flyer variants have used a range of case materials including ceramics, polymethyl methacrylate
FIG. 3: Signals contributing to the causal angle $\phi_c$.

FIG. 4: States in the computation of the asymptotic angle $\phi_a$. 
(PMMA), and Al alloy. PMMA has a much lower shock impedance than the PBX-9501 charge, and Al alloy has a higher impedance. The taper angle used was 45°.

In calculating the asymptotic angle, the choice of the shocked state in the explosive is ambiguous. Taking the laminar Zel’dovich-von Neumann-Doering (ZND) model of the detonation process, detonation commences with an unreacted shock – the von Neumann (vN) spike – followed by reaction as the explosive expands down the Rayleigh line to the fully-reacted Chapman-Jouguet (CJ) state [4]. Physically, the effect of the case depends on the reflection from the sequence of states in the axially-propagating detonation. The CJ state is sonic with respect to the flow behind, so it is not relevant for the calculation of the causal angle: the vN state must be used. The vN state is not necessarily an accurate representation of the initial shock in heterogeneous explosives such as PBX-9501, as the detonation wave is not perfectly laminar. It is also extremely difficult to measure the unreacted Hugoniot for explosive materials to pressures approaching the CJ state, let alone higher pressures, because chemical reactions take place promptly. Previous studies [6] have shown variations of a few degrees, depending which state was taken, with the CJ state agreeing more closely with experimental measurements. Here, the CJ state was used.

The properties of PBX-9501 were represented by an equation of state (EOS) of the Jones-Wilkins-Lee type for the unreacted explosive and the reaction products, with parameters derived from cylinder expansion tests [10, 11]. No unreacted parameters were found for PBX-9501, so parameters for the similar HMX-based explosive PBX-9404 were used instead. The vN state had mass density \( \rho = 2.56 \text{g/cm}^3 \), pressure \( p = 39.6 \text{GPa} \), particle speed \( u_p = 2.45 \text{km/s} \), sound speed \( c = 12.17 \text{km/s} \), and shock speed \( D = 8.776 \text{km/s} \). The CJ state had mass density \( \rho = 2.49 \text{g/cm}^3 \), pressure \( p = 37.0 \text{GPa} \), particle speed \( u_p = 2.28 \text{km/s} \), sound speed \( c = 6.51 \text{km/s} \), and detonation speed \( D = 8.776 \text{km/s} \). The causal angle \( \phi_c \) is a property of the explosive, irrespective of the case material so longer as it has a lower shock impedance. For the EOS used, \( \phi_c \approx 40.2^\circ \). The properties of Al alloy were represented by EOS of the Grüneisen type using the principal Hugoniot as the reference curve, with parameters derived from measurements of shock and particle speeds from projectile impact experiments [12]. The asymptotic angle \( \phi_a \) was calculated as above for Al alloy, and also for steel as a plausible alternative material providing greater confinement of the reaction products. The asymptotic angle was 68.1° and 78.7° for Al and steel respectively, implying an ideal taper angle of 21.9° and 11.3° respectively. Choosing these precise angles, the projectile may not be as flat as possible because of other wave interactions and friction with the case as the projectile accelerates, but these predictions should be accurate to within a few degrees.

The predicted causal angle is just less than 45°, so the Forest Flyer variant with a 45° taper and a low impedance case should be effective in reducing edge effects, and should hence give a reasonably flat projectile. The predicted asymptotic angle for an Al alloy case is significantly greater than 45°, so the Forest Flyer design with a 45° taper and an Al alloy case is potentially susceptible to problems from the reflected shock.

Continuum dynamics simulations were performed to evaluate the effect of two dimensional reflections from the tapered case on the flatness of the projectile. The simulations were based on the design used for the neutron resonance spectroscopy measurements [3]: a charge 37 mm long and 89 mm in diameter with a 45° taper to 63.5 mm diameter, a case 6.4 mm thick, a 7 mm gap, and a projectile 6 mm thick by 63.5 mm diameter. The simulations were Eulerian, using operator splitting between a second order Lagrangian phase of the predictor-corrector type and a third order remapping using third order van Leer flux limiters and Youngs interface reconstruction [13]. Artificial viscosity of the von Neumann and Wilkins type was used to stabilize shock waves. Explosive detonation was treated by constant speed programmed burn using the CJ speed appropriate for the PBX-9501 EOS. The materials used in the Forest Flyer are common, and their EOS and strength properties have been investigated and reliable models developed [12]. The numerical methods used for the continuum dynamics simulations have been used widely for explosive loading systems. Hence the simulations should be broadly accurate.

Explosive initiation was simulated as a simultaneous plane over the cylindrical face of the charge. Convergence with respect to spatial resolution was tested, and found to be around 0.1 km/s in projectile velocity for a resolution of 0.25 × 0.5 mm. The effect of material strength was evaluated by performing simulations with an elastic-perfectly plastic strength model. The speed and shape of the projectile were not significantly different. The effects of tensile damage and spall were included through a minimum pressure model [1]. With this model, unless the material is subjected large tensions for long periods, it will recompress itself and ‘heal.’ No spall model could be found which was likely to be valid in the loading history applied to the projectile. The effect of tensile stress is discussed further below.

The shape and speed of the projectile were evaluated at an acceleration distance of 20 mm, where the target was placed in typical impact experiments. The projectile was accelerating and reverberating, so there was some ambiguity in the predicted speed, represented as an uncertainty. With a PMMA case, the projectile was calculated to be flat to within 0.15 mm over 31 mm diameter. With an Al alloy case, the projectile was predicted to travel slightly faster, but to be significantly advanced at larger radii. The speed with an Al alloy case matched the speed of 3.6 ± 0.1 km/s in the experiments (Figs 5 and 6 and Table I).

There is no compelling hydrodynamic reason to have a cylindrical section in the charge. Simulations were performed of design variants with a constant taper over the
full length of the charge. These simulations used the predicted asymptotic angles for Al alloy and steel, adjusted slightly to improve the flatness of the projectile. In both cases, the projectiles were calculated to be flat to better than 0.05 mm over more than 30 mm diameter. With the Al alloy case, the modified design gave the same projectile speed as the original design, for less explosive. With the steel case, the explosive mass was significantly less again, for essentially the same projectile speed. (Figs 5 and 6 and Table I.)

One family of Forest Flyer designs uses an explosive lens to initiate the charge over a plane. The lens, comprising two explosives with different detonation speeds to induce a flat detonation wave from a point detonator, is a potential source of two dimensional perturbations, because the pressure history induced varies radially, even if the initial pressure and arrival time are simultaneous.

Continuum dynamics simulations were used to assess the effect of using a plane wave lens (PWL) on the projectile shape and speed. The effect on the projectile loading history was also assessed; this is discussed later. The PWL was a Los Alamos type P-108, comprising PBX-9501 as the fast component and trinitrotoluene (TNT) as the slow. PWL simulations are an interesting problem for continuum dynamics, as there is potential for the slow explosive and ‘acceptor’ charge to be subjected to unusual conditions including overdriving, which are relatively poorly understood and may not be treated accurately by explosive models generally used. PWL simulations are discussed in more detail elsewhere. Programmed burn with a constant CJ detonation speed was used in each component. The CJ detonation pressure in TNT is around 19 GPa, which should induce full detonation in PBX-9501 within a run distance of around 1 mm. This is short in comparison with the length scales of interest for the Forest Flyers, so programmed burn is likely to be a good approximation here. Overdriving of the TNT charge by the PBX-9501 component in the PWL is a potential concern. This was assessed by looking for any unphysical spike in the pressure history exhibited in the TNT. No significant spike was seen, indicating that constant speed programmed burn was unlikely to cause numerical problems although it does not capture the full range of dynamical effects exhibited by real detonation waves in TNT, specifically changes of speed caused by overdriving and curvature.

Using programmed burn with nominal CJ detonation speeds and JWL products EOS the P-108 lens was predicted to give a detonation arrival which was 0.6 µs later at the edges than on axis. This deviation from perfect planarity was larger than predicted for smaller PWL designs. However, the shape of the Forest Flyer projectile was not significantly different from the plane-initiated variant without the PWL, although the projectile speed was predicted to be appreciably faster with the larger mass of explosive (Table I), consistent with the measured speed of 4.3 ± 0.3 km/s with a similar lens [7].

C. Axial dimensions

The family of explosive launchers considered here can be characterized as a radial configuration chosen to make the acceleration of the projectile uniform in the radial direction, and a set of component thicknesses in the axial direction. The axial thicknesses are the explosive charge, the expansion gap between the explosive and the projectile, the projectile, and the acceleration gap between the projectile and the target. If time-dependent material properties can be neglected, which is often the case to an accuracy of a few percent for explosive systems, then it is the ratio of thicknesses that matters, and the complete system can be scaled.

The two dimensional continuum dynamics simulations of the original Forest Flyer designs and the designs with a modified taper but the original axial thicknesses all exhibited free surface velocity histories which were violent, suggesting the possibility of shock formation in the projectile, and with decelerations, indicating tension (Fig. 9).

The axial design objective is to accelerate the projectile efficiently to a constant speed without inducing shock loading or tensile damage. For a given thickness of explosive, a smaller expansion gap means that the explosive products expand less before reaching the projectile, so a higher pressure is applied and the time from the start of the drive to the peak pressure is shorter — both resulting in a higher pressurization rate \( \dot{p} \) applied to the projectile. The higher the pressurization rate, the shorter the distance within the projectile needed for the compression wave to steepen into a shock wave. The peak tensile stress is induced when the accelerating pressure is reduced, and the resulting rarefaction wave reflects from the front surface of the projectile. The faster the pressure is reduced, the stronger the tensile stress. For a given projectile thickness, the expansion rate in the rarefaction wave is

### Table I: Projectile acceleration performance for different cases and tapers.

| Case | Taper | Initiation | Charge mass (kg) | Speed (km/s) |
|------|-------|------------|-----------------|--------------|
| PMMA | 45    | multipoint | 0.387 ± 3.5     | 3.5 ± 0.1    |
| Al alloy | 45 | multipoint | 0.387 ± 3.5     | 3.5 ± 0.1    |
| Steel | 20    | multipoint | 0.308 ± 3.5     | 3.5 ± 0.1    |
| PMMA | 45    | plane wave lens | 0.996 ± 3.8 | 3.8 ± 0.1    |
| Al alloy | 45 | plane wave lens | 0.996 ± 3.8 | 4.1 ± 0.1    |

For the plane wave lens initiated charges, 0.367 kg of the explosive mass is TNT rather than PBX-9501.
FIG. 5: Comparison of projectile flatness predicted from continuum dynamics simulations with different case materials and taper angles. 45° tapers used the original Forest Flyer design with a cylindrical section in the explosive charge; the other tapers were constant over the full length of the charge. The Al case with 20° taper gave much the same result as the steel.

FIG. 6: Example free surface velocity histories from two dimensional continuum dynamics simulations of explosively launched projectiles, suggesting shock formation and tension. High frequency noise is from the use of numerical differentiation of the reconstructed interfaces to calculate the velocity in the Eulerian simulation. The time in each simulation was offset so that acceleration occurred at similar times in all cases.
can be reduced by increasing the thickness of the explosive or the expansion gap. It is possible to express these sensitivities algebraically, but this is of limited value as the material properties and wave interactions are fairly complicated. Instead, one dimensional, axial, continuum dynamics simulations were made of the acceleration process and the loading history in the projectile. One dimensional simulations allowed a finer spatial resolution, and meant that a Lagrangian representation of the components could be used, which is much more convenient when following the load and response of individual elements of the material as opposed to particular locations in space. Again, a second order accurate time integration scheme of the predictor-corrector type was used, with artificial viscosity of the von Neumann and Wilkins type to stabilize shock waves \([12]\). The spatial resolution used was 0.2 mm in the explosive and 0.1 mm in the projectile.

Simulations were performed representing multipoint and PWL initiation. For PWL, an additional thickness of 67 mm of TNT was used to represent the PWL. The one dimensional representative thickness should be less than the actual thickness to account for radial expansion and the lower pressure imparted by the TNT component. The free surface velocity history was consistent with the two dimensional simulations and experiments. The drive pressure applied to the projectile rose to over 20 GPa in the original Forest Flyer designs, and as intended was shockless (Fig. 7). The loading history was investigated at the center of the projectile. With PWL initiation, the simulations predicted that the tensile stress would just reach the spall strength of Al alloy inferred from projectile impact experiments \([12]\); with multipoint initiation, the faster decrease of pressure gave a significantly higher tensile stress (Fig. 8). The damage and spall response of materials depends on the strain rate, with generally higher strength being exhibited at higher strain rates. The strain rates experienced by the projectile in these experiments was considerably slower than in typical projectile impact experiments or in loading by an explosive in direct contact, so it would be reasonable to expect more damage than implied by the published spall model, though it is difficult to predict the precise amount without a more sophisticated understanding of dynamic damage than exists at present. Thus, with the component thicknesses used, the Forest Flyer variants should be considered as unsafe in respect of tensile damage to the projectile, and it would be surprising if the multipoint design did not induce a large amount of tensile damage. The accelerating pressure from the expanding reaction products is sustained for several cycles of compression and tension, so some recompaction is likely to occur.

Given the pressurization rate \(\dot{p}(t)\) applied to the projectile, the distance required for the resulting compression wave to steepen into a shock is the distance at which adjacent characteristics intersect. If at some instant \(t\) the interface has been compressed to a displacement \(x\), and the particle speed and longitudinal sound speed are \(u\) and \(c\) respectively, adjacent characteristics \(u + c\) intersect at a distance

\[
x_{int} = x + \frac{c(c + u)}{d(c + u)/dt}, \tag{6}
\]

where

\[
x = \int u \, dt, \tag{7}
\]

c and \(u\) are calculated as a function of \(p\) along the isentrope of the projectile material, and the derivative is calculated from \(\dot{p}(t)\) applied along the isentrope. This analysis assumes no release from the front of the projectile, so it is suitable for finding the thickest projectile that can be driven shocklessly with a given loading history. Analysis using the intersection of characteristics is more appropriate than the continuum dynamics simulations because the use of artificial viscosity to stabilize shock waves makes it difficult to distinguish them from steep but shockless compression waves.

With the 7 mm expansion gap, the load applied to the projectile rose to over 20 GPa. Considering the intersection of characteristics, the compression wave steepened into a shock for pressures from 10 to 20 GPa in around 1.5 mm, so the projectile was substantially shock-loaded. A single shock to 20 GPa and release to zero pressure in Al produces a residual temperature of around 400 K taking plastic flow into account, and a 1% reduction in mass density. The shock formation distance was slightly shorter at intermediate pressures using a plane wave lens instead of multipoint initiation. With a 15 mm expansion gap, the maximum load was around 15 GPa and the pressurization rate was significantly lower, with the shortest shock formation distance around 4 mm for pressures around 7.5 GPa and a shock forming between 6 and 10 GPa for a projectile 6 mm thick; this would lead to much less residual heating. (Fig. 9)

Simulations were used to quantify the effect of changing the thickness of the expansion gap and the projectile, with respect to the explosive. The magnitude of the tensile stress was relatively insensitive to the gap thickness, though it could be reduced quite easily by reducing the projectile thickness, also giving a higher projectile speed. (Fig. 10)

The acceleration rate increases rapidly at first to a maximum when the peak pressure is applied, then falls steadily as the explosive products expand. Lateral expansion, i.e. two dimensional effects, reduce the acceleration at late times. The greater the thickness and mass density of the case, the less the energy used to accelerate it, and the greater the efficiency of projectile launch. If the projectile is accelerating, it has a gradient of pressure and mass density through its thickness. To induce a shock on impact which is as constant as possible in time, the axial gradients should be as small as possible. For a given thickness of explosive, expansion gap, and projectile, the projectile speed is higher and closer to constant for a larger acceleration gap. However, the larger the gap the greater the effect of radial variations in pressure
FIG. 7: Drive pressure histories predicted by one dimensional continuum dynamics simulations, for plane wave lens and multipoint initiation schemes, using the component thicknesses from the original Forest Flyer design and also for a thicker gap.

FIG. 8: Pressure histories predicted at the midplane of the projectile by one dimensional continuum dynamics simulations, for plane wave lens and multipoint initiation schemes, using the component thicknesses from the original Forest Flyer design, and also for a thicker gap.
FIG. 9: Shock formation distances predicted as a function of drive pressure as predicted from one dimensional continuum dynamics simulations with multipoint initiation, using the component thicknesses from the original Forest Flyer design (7 mm gap) and also for a thicker gap (15 mm). The high frequency noise is from the use of a tabulated numerical calculation of the isentrope.

FIG. 10: Sensitivity of loading history at midplane of projectile to projectile thickness. Explosive 37 mm thick, 7 mm gap, multipoint initiation.
which may deform the projectile. It may be useful to include a radial escape gap for the reaction products just before the target, to reduce the axial gradients in the projectile (Fig. [11]). If the acceleration gap is too small, the higher density reaction products may scour the rear of the projectile as they expand laterally, deforming it.

IV. EXPERIMENTAL OBSERVATIONS OF FLATNESS AND DAMAGE

A conclusion from the hydrodynamic analysis and simulations is that, with an Al alloy case, the original Forest Flyer design would be expected to give a dish-shaped projectile, and this can be avoided by a more careful choice of case taper angle. The experiments performed to investigate the original designs measured the projectile’s flatness from its impact with a flat glass block, with Ar-filled grooves which produce a light flash when compressed [2, 16]. These experiments suggested that impact was more planar than predicted by the simulations, though they did indicate that the edges of the projectile arrived earlier than the axis.

The Ar-flash technique indicates when a substantial amount of material has arrived, but it does not guarantee that the projectile is solid. Since the simulations also predicted that the projectile was subjected to a strong axial tension, a plausible explanation is that the projectile was damaged by the opening of internal voids, for multipoint initiation with an Al alloy case.

Explosive launching of projectiles does not present particular problems for continuum dynamics simulations. The states induced in the materials are not notably different from states induced in other explosively-driven systems. The materials used in the Forest Flyer designs are not unusual or poorly-understood. One would expect continuum dynamics simulations to be accurate, certainly for the broad deformation and motion of the components. Indeed, the simulations reproduced the measured projectile speeds to within their uncertainty. Damage and spall depend more sensitively on the precise composition and manufacturing history of a component, and the loading history applied. A discrepancy related to tensile damage is quite possible, and could well explain why the arrival-time measurements suggested that the projectile was flat. It would be valuable to perform projectile acceleration and impact trials with a more detailed diagnostic such as imaging Doppler velocimetry or radiography, to measure or infer a density distribution through the projectile.

Fortuitously, proton radiographs were obtained of a Forest Flyer projectile just before impact in experiments to study surface ejecta from Sn [7]. In these experiments, the charge was initiated by a PWL, so the tensile stress in the projectile was predicted to be less than with multipoint initiation. The case was Al alloy, so the simulations predicted a reflected shock from the tapered section and dishing of the projectile. The radiographs were not optimized for reconstruction of the mass density in the projectile, but they clearly showed curvature of the rear surface of the projectile. Simulations of the operation of this variant of the Forest Flyer were in good agreement with the measured shape of the projectile, except at the outside edge (Fig. [12]), indicating that two dimensional flow was predicted accurately and hence that the predicted deformation was likely to be accurate. It would be preferable to compare an unfolded density map from the radiograph or a simulated radiograph from the simulation, but this is not worthwhile without optimizing the radiography for the range of areal mass in the projectile. The front of the projectile is less likely to be accurate as this is the region most affected by tensile damage.

Doppler velocimetry measurements were made of the surface of a Mo target impacted by a Forest Flyer driven Al alloy projectile, using multipoint initiation [17]. In different experiments, measurements were made of the free surface and of the surface in contact with a LiF window. If the projectile had a constant mass density through its thickness, the peak surface velocity induced by the shock should be constant. The measured velocity histories showed acceleration during the peak, which is a clear indication of density variations in the projectile; these could be caused partly by the continued acceleration of the projectile in impact, but are likely to be caused mostly by damage-related porosity in the projectile. (Fig. [13])

Another variant of the Forest Flyer design has been used to study interface friction [18]. The case was Al alloy, the charge was initiated with a PWL, and the projectile was 15 mm thick. The axial analysis above predicted tensile stresses exceeding the spall strength of Al-6061. Two dimensional simulations predicted less curvature than the 6 mm thick projectiles. A proton radiograph was obtained just after impact with the target assembly, before the shock wave had reached the rear part of the projectile. The radiograph clearly showed cracking of the projectile. This observation correlates well with the simulations: damage is likely to occur to the projectile when the tensile stress exceeds the published spall strength, and quite possibly not for smaller tensile stresses.

V. DISCUSSION

This study has shown that there are some subtleties in the hydrodynamic design of explosive launching systems for projectiles. Because the pressures induced by detonation waves and the expanding fluid of reaction products can easily exceed the compressive and tensile strength of solids, care is needed to ensure that projectiles remain flat and solid.

There are compelling indications that the projectiles used in the neutron resonance temperature experiments on Mo were somewhat curved and damaged. This deformation is of concern in experiments where the region to
be studied in the target is close to the impact face and when the state of interest is the impact-induced shock, as in the case of the Mo shock temperature experiments. The deformation is less important further through the target and when studying states later in time, as in release temperature and surface ejecta experiments. The projectiles can be made flatter by adjusting the shape of the case around the explosive. Case improvements can also improve the efficiency of the drive, reducing the amount of explosive needed or increasing the maximum possible projectile speed. There seems no reason not to use the case modifications for future experiments based on the Forest Flyer design.

All Forest Flyer variants used so far are likely to sub-
FIG. 13: Comparison between Doppler velocimetry records at the surface of a Mo target with continuum dynamics simulations with and without strength (SG: Steinberg-Guinan [12]), assuming a solid projectile. The low initial speed in the experimental records may indicate a region of low density near the front of the projectile, as may the smoother onset of elastic release from the peak velocity which shows up clearly in the LiF release record.

ject the projectile to tensile stresses around or in excess of its spall strength. The expansion time scale of the detonation products, and hence the time over which the projectile accelerates, is longer than the reverberation time in the projectile, so material ejected from the surface of the projectile by the initial strong tension is likely to be recollected, and material affected by tension-induced porosity may be recompressed, but the projectile should not be assumed to comprise pristine material at its initial density. If the explosive charge is initiated with a plane wave lens, the explosive in the lens reduces the expansion rate of the reaction products, reducing the tensile stress compared with multipoint initiation, but the tensile stress is still large enough to potentially cause damage. The peak tensile stress can be controlled by adjusting the relative thickness of the explosive, expansion gap, and projectile.

The use of arrival time images as a measure of projectile flatness is limited, as it does not indicate how solid the projectile is behind the leading material. It is preferable to follow the acceleration history of the projectile using Doppler velocimetry imaged along a line or even over an area [19], complemented with lateral radiography if the possibility of tensile damage is suspected. The glass ‘witness block’ technique could be used in conjunction with Doppler velocimetry to measure the velocity history of the impact interface instead of merely the arrival time; this velocity history would provide a fairly direct indication of tension-induced porosity in the projectile.

The work reported here provides a deeper understanding of the physics of projectile acceleration by explosives. Using the Forest Flyer design as a basis, the radial and axial modifications discussed, and the hydrodynamic details elucidated, should lead to a family of projectiles giving loading conditions closer to the one-dimensional ideal desirable for experiments in shock physics.

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[20] For zero taper angle – the detonation running parallel to the interface – it can be seen intuitively that a rarefaction is reflected by considering that, for one dimensional flow, the particle speed behind the detonation is parallel with the boundary, whereas in the normal case where the shock speed in the case is lower than the detonation speed, the particle speed in the case must have a radial component, so a rarefaction wave must be reflected from the case in order to impart a radial component to the reaction products and hence preserve continuity of radial velocity at the interface.