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Strength-Stabilized Rayleigh-Taylor Growth Experiment Design Calculations

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Strength-Stabilized Rayleigh-Taylor Growth Experiment Design Calculations

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1 Introduction

The purpose of the calculations presented here is to inform decisions on experimental design for a Strength-Stabilized Rayleigh-Taylor (RT) growth experiment of molybdenum samples at a proton radiography facility. The radiogrpahs will provide snapshots of an an accelerating Mo target seeded with a sinusoidal perturbation. The growth of these perturbations will be used to tune a PTW constitutive model of Mo. The target is accelerated using a P56 plane wave lens, Figure 1. A first stage plane wave lens is detonated which drives a steel flyer plate into a PBX-9501 secondary charge. This produces an overdriven detonation. The expansion gases of the secondary charge accelerate the Mo target and proton radiographs image the target in flight. PDV probes are situated behind the target to measure drive. The following discussion focuses on modeling of this experiment and the design of targets to extract the most relevant data.

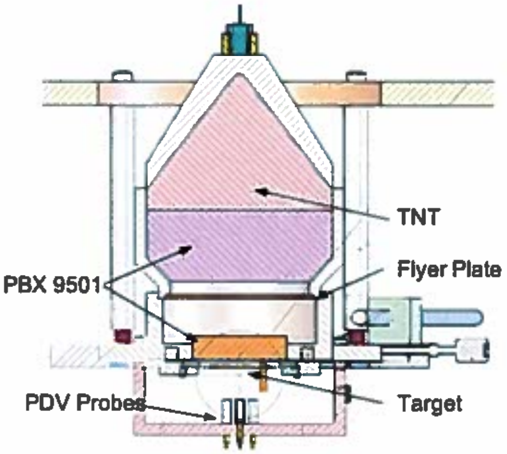


Figure 1: The P56 plane wave lens.

2 Model Details

The entirety of the P56 lens is not modeled. Previous measurements have been performed to determine the velocity of the flyer plate leaving the plane wave lens: $0.401\,\mathrm{cm\,\mu s^{-1}}$. The calculation starts with the flyer impacting the second PBX-9501 causing detonation. The calculation ends after $7.8\,\mu\mathrm{s}$, in this time the target has moved a little more than $1.5\,\mathrm{cm}$. To reduce calculation time, only a single wavelength of the target perturbation is modeled with reflecting boundary conditions (Figure 2). This is assumed to be a good approximation of target behavior far from the edges.

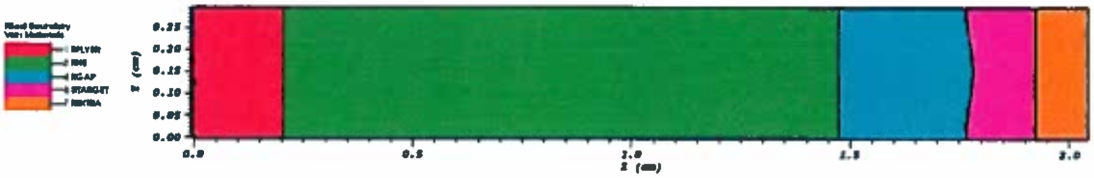


Figure 2: Calculation setup

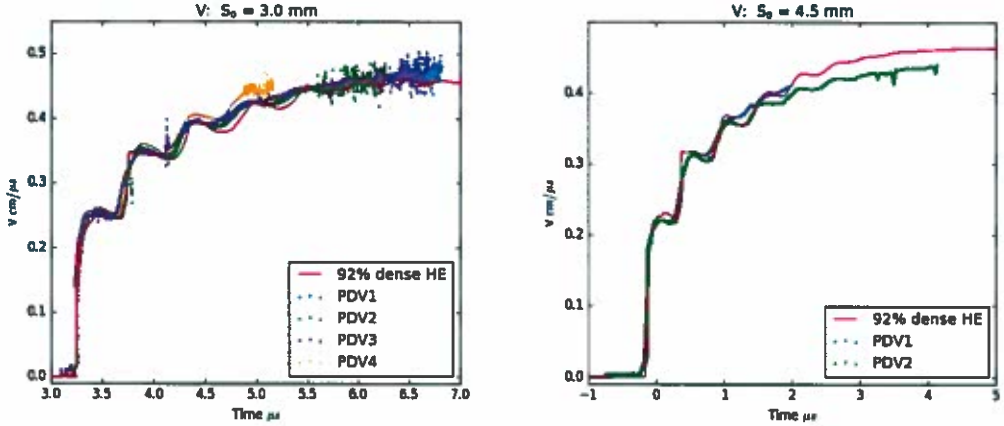


Figure 3: Vanadium sample HE drive data with model drive (red). The model drive was changed by adjusting the HE density.

2.1 HE Drive

Data are available from previous RT experiments performed at the pRad facility with vanadium samples. Velocimetry data is available for HE target standoff distances of 3 mm and 4.5 mm from PDV probes behind the target. The first task is to adjust model HE properties to match the drive given by data. The method for adjusting the drive that proved best was to decrease the HE density. The optimal density was chosen such that it matched drive data at 3.0 mm and 4.5 mm qualitatively well. Results are shown in Figure 3. After the appropriate drive was determined the target material was simply switched to molybdenum without any other changes.

2.2 PTW Strength Model

There is plenty of ambiguity as to which PTW parameters are appropriate for a molybdenum strength model, this is the point of the experiment. The parameters used in these calculations are given in Table 1. These are taken from the initial publication with a few modifications. Not least of which, the melting temperature of molybdenum is 2896 K. In the PTW formalization, $T_{melt}(\rho)$ is used as a scaling factor for dimensionless temperature. As implemented in the hydrocode, T_{melt} is a constant and needs to be selected to reflect proper dynamic behavior. The value of $T_{melt} = 3660\,\mathrm{K}$ is that of "expert" consensus, increasing it will make the material stronger. The LLNL implementation of the PTW strength model

Table 1: PTW parameters

ρ_{Mo}	θ	p	s_0	s_∞	κ	γ	y_0
$10.228\,\mathrm{g\,cm^{-3}}$	1.4e-2	0	9.45e-3	3.8e-3	0.41	8e-6	7.95e-3

y_∞	y_1	y_2	β	G_0	α	T_{melt}	$s_{0,drag}$
2.3e-3	9.45e-3	0.36	0.23	1.303 Mbar	0.41	3660 K	9.45e-3

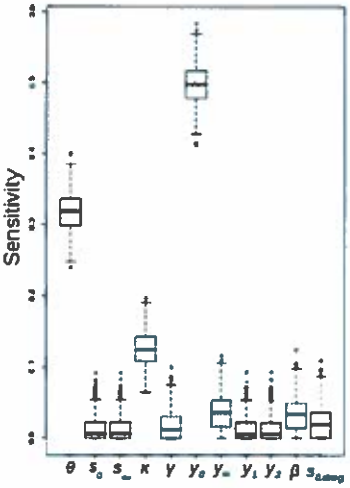


Figure 4: Sensitivity indices of PTW parameters to an RT experiment.

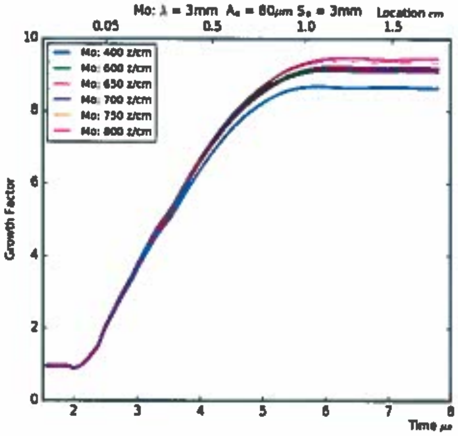


Figure 5: Growth factor convergence with increasing zone density.

decouples high strain-rate scaling in the phonon drag regime by introducing the variable $s_{0,drag}$.

Numerical simulations of the proposed RT growth experiment have been previously performed. The results verify the applicability of data obtained from an RT experiment to the PTW constitutive model. A sensitivity analysis of over 100 ensemble calculations was performed studying the change in perturbation growth while allowing each PTW parameter to vary ±20%. The sensitivity analysis considered a design with target parameters: $S_0 = 3\,\mathrm{mm}$, $\lambda = 3\,\mathrm{mm}$, and $A_0 = 60\,\mathrm{\mu m}$. The sensitivities determined are summarized in Figure 4. Among the sensitive parameters, y_0 is well constrained by low strain-rate Hopkinson-bar experiments. The parameter κ is less strongly constrained by the current low rate data. However, θ, which accounts for strain hardening, is poorly constrained by current data. The RT experiment is particularly well suited to study this parameter.

2.3 Model Convergence

A quick convergence study was performed to determine the appropriate zoning for the simulation. The suggested zoning for accurately model the HE detonation with a JWL++ equation of state is 400 zones/cm, but the important variable for RT growth in the target is the growth factor.

$$GF = \frac{x_{peak} - x_{trough}}{A_0}$$

where the x-positions are calculated following tracer particles at the peak and trough of the seed perturbation.

Results from the convergence study are shown in Figure 5. Although the calculated GF continues to change, at resolutions of 600 zones/cm and above, differences in GF are due only to drifts in the position of tracer particles located at the peak and troughs as the mesh relaxes. A resolution of 650 zones/cm is chosen since the GF does not increase when increasing the resolution to 700 zones/cm suggesting any changes henceforth are due to tracer particle drift.

3 Target Design

Target design selection was based on the following criteria regarding experimental limitations and attempts to maximize the quality of collected data.

- There are a total of three shots expected in one week at pRad. A fourth shot is possible but a luxury.
- Two shots will be of the same target and experiment design with molybdenum from different vendors.
- There will be two adjacent seed perturbations on the same target.
- Growth factor (strain) should be maximized, in the linear RT growth regime, without destroying the target.
- A variety of drives and wavelengths should be used.
- Larger strain rates are desired (10^5–$10^6\,s^{-1}$).
- Peak pressures approximately 500 kbar.

A suite of calculations was performed consisting of a combination of different wave amplitudes A_0 from 60–95 µm; wavelengths, $\lambda = 2, 3, 4$ mm; and HE standoff distances; $S_0 = 3, 4, 5$ mm. The growth factors determined from these calculations are summarized in Figure 6. In many configurations the RT growth eventually stops as the material strain-hardens. If, and when, this happens is dependent on the initial perturbation amplitude and how hard the target is driven. It would be interesting to watch this strain-hardening and cessation of growth in pRad radiographs. The data would provide an excellent constraint to θ, the strain-hardening parameter of the PTW formulation.

3.1 Target Perturbation

Since only three shots are expected, two of which will be identical with different molybdenum suppliers, two target designs are initially selected. It was found that at GF above about 15 the target is destroyed, so these designs were excluded. The two perturbations that will accompany each other on a target are chosen such that the growth is not drastically different to minimize asymmetrically deforming the target which may cause it to wobble or bend. To this end, for a given S_0 the same A_0 was selected which still allows a range of strain and strain-rates to develop, see Table 2 and Figure 7.

Two options are considered for the fourth shot's target design. The first is to use a single feature target which is not discussed here. The other option is to increase the target drive further. Since moving the target closer to the HE will likely result in shock, the target mass is reduced. The thickness is reduced from 1.5 mm to 1.4 mm; any thinner and the target is easily destroyed. Results of calculations are shown in Figure 8. The suggested target design is given in Table 3.

3.2 Shot Order

The driving consideration for shot order is to hedge to avoid destroying a target and gathering poor data. With this in mind, the first shot should not drive the target too hard. Shot 1 will be Design 1 at a standoff of 4 mm. This will be the basis for choosing the following two shots. Shot 2 will be Design 2; with a possible adjustment to $A_0 \pm 5\,\mu m$ if Mo measured to be stronger or weaker than calculations. Shot 3 will be a duplicate of either Shot 1 or Shot 2, whichever performed better, using the second supplier of molybdenum. If a fourth

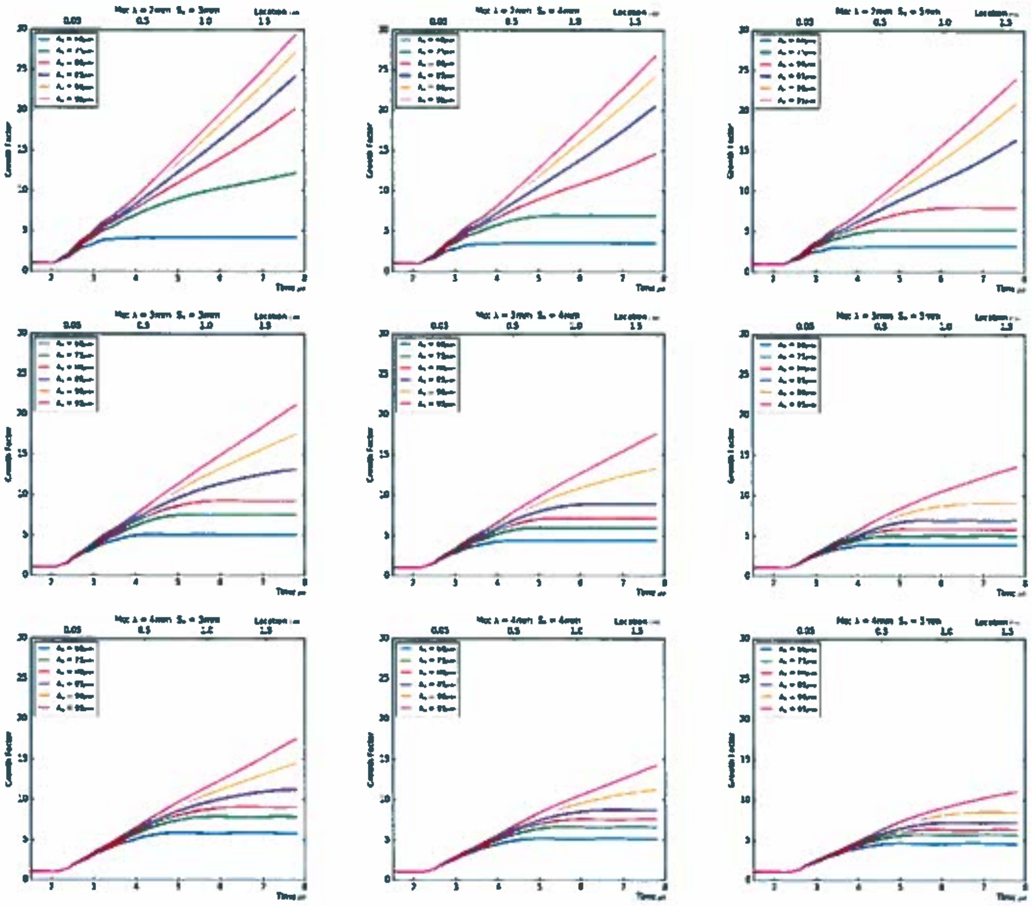


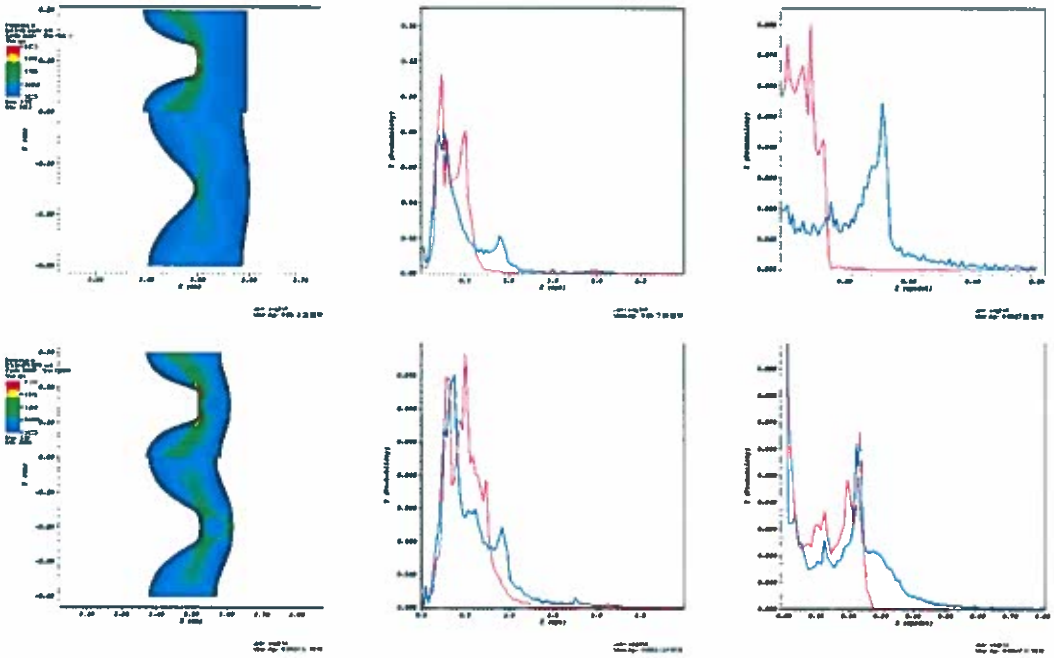
Figure 6: Growth factor calculation results.

Table 2: Designs for the first three shots.

	Standoff	Thickness	Wavelength	Amplitude
Design 1	4 mm	1.5 mm	2 mm	75 µm
			3 mm	75 µm
Design 2	3 mm	1.5 mm	3 mm	80 µm
			4 mm	80 µm

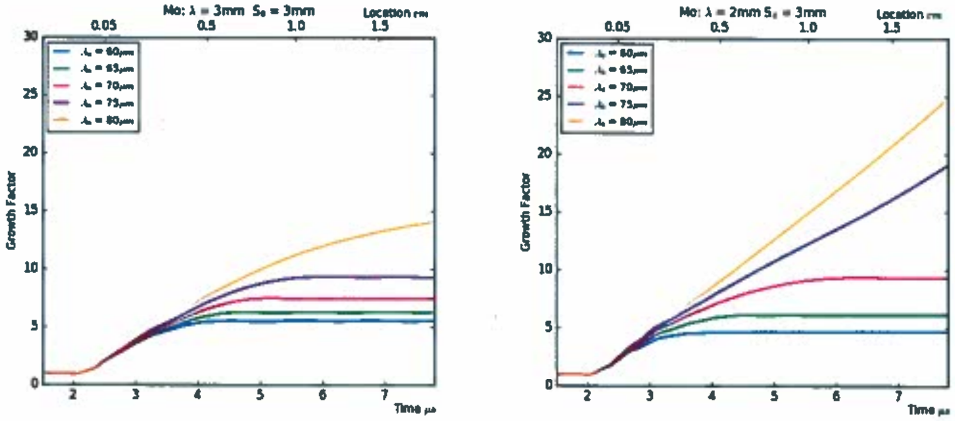
Table 3: Possible designs for a fourth shot.

	Standoff	Thickness	Wavelength	Amplitude
Design 3	3 mm	1.4 mm	2 mm	70 µm
			3 mm	75 µm
Design 4	Single Feature Design			

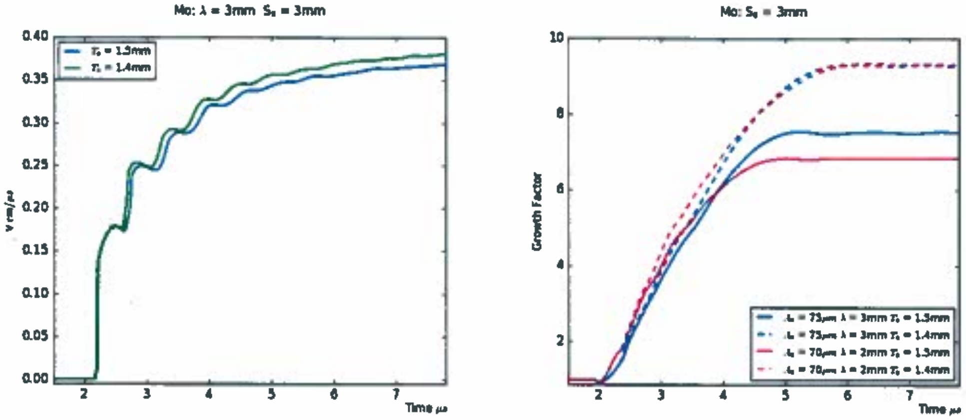


(a) Target shape (b) Equivalent plastic strain (c) Strain rate

Figure 7: (top) Design 1. (bottom) Design 2. Target shape and equivalent plastic strain are at 7.5 µs after HE detonation, about 1.5 cm of target movement. Strain rate is taken at a peak after initial pressure wave. All plots only consider target zones. Blue curves correspond to the top perturbation, red curves, the bottom.



(a) $\lambda = 3\,\mathrm{mm}$ (b) $\lambda = 2\,\mathrm{mm}$



(c) Drive (d) Growth factor changes with T_0

Figure 8: Calculations for a thin target, $T_0 = 1.4\,\mathrm{mm}$

Table 4: Shot order and targets needed.

Shot No.	Design	Mat. Supplier	No. Targets
1	1	DeltaMetal	1
2	2	DeltaMetal	3
3	1 or 2	Plansee	4
4	3 or 4	DeltaMetal	6

shot is granted either Design 3 or 4 will be chosen with appropriate adjustment to A_0. In all, fourteen targets will need to be fabricated: one of each Mo supplier of Design 1, three of each supplier of Design 2 with $A_0 \pm 5\,\mu\text{m}$. The remaining six will be fabricated from the first supplier of molybdenum with Designs 3 and 4 (Table 4).

3.3 Other Considerations

To maintain Rayleigh-Taylor growth, the target should be accelerated shocklessly. A shock in the target will be evident by a sharp jump in entropy. The calculated entropy was extracted at the center of the target, averaged over the length of one perturbation. Figure 9 shows the results from drives at $S_0 = 3, 4, 5\,\text{mm}$.

A jump in entropy can be seen for each standoff position coinciding with the initial pressure wave, at the first velocity jump. This is evidence of some shock, but it is relatively weak at $S_0 = 3\,\text{mm}$ and further, especially compared to the vanadium calculation, which was shot in an experiment. A shot at 2 mm probably shocks too much. If a stronger drive is required a thinner target can be used. This will increase the acceleration, care should be taken as the target can be more easily destroyed.

It is also of interest to know the pressure of the expanding HE gas driving the target. Figure 10 follows the pressure at a zone on the problem axis just inside the HE. This zone moves across the gap and ends up on the surface of the target. The spike at early time the detonation wave passing. The second spike near peak pressure is caused by distortion of the reflected pressure wave arising from the seeded perturbation on the target.

4 Full Target Simulations

To be completed.

- Edge bevel
- Asymmetric target bend.

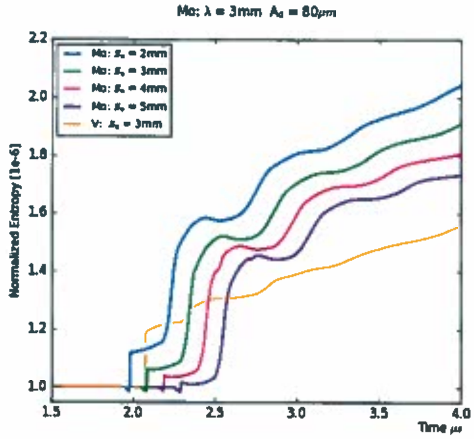


Figure 9: Mo and V entropy.

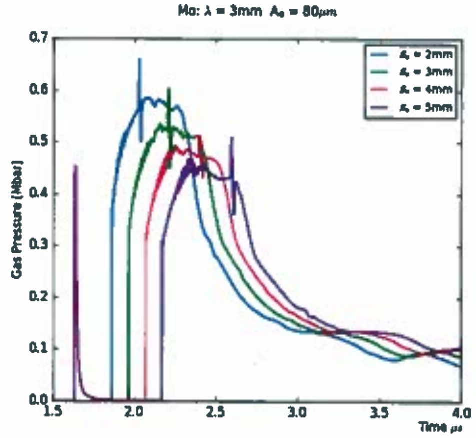


Figure 10: Drive pressure.