

LA-UR-16-20679

Approved for public release; distribution is unlimited.

Title: A Report on the Validation of Beryllium Strength Models

Author(s): Armstrong, Derek Elswick

Intended for: Report

Issued: 2016-02-05

Disclaimer:

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

A Report on the Validation of Beryllium Strength Models

Derek E. Armstrong, XCP-8

Los Alamos National Laboratory, Los Alamos, NM

Abstract

This report discusses work on validating beryllium strength models with flyer plate and Taylor rod experimental data. Strength models are calibrated with Hopkinson bar and quasi-static data. The Hopkinson bar data for beryllium provides strain rates up to about 4000 per second. A limitation of the Hopkinson bar data for beryllium is that it only provides information on strain up to about 0.15. The lack of high strain data at high strain rates makes it difficult to distinguish between various strength model settings. The PTW model has been calibrated many different times over the last 12 years. The lack of high strain data for high strain rates has resulted in these calibrated PTW models for beryllium exhibiting significantly different behavior when extrapolated to high strain.

For beryllium, the α parameter of PTW has recently been calibrated to high precision shear modulus data. In the past the α value for beryllium was set based on expert judgment. The new α value for beryllium was used in a calibration of the beryllium PTW model by Sky Sjue. The calibration by Sjue used EOS table information to model the temperature dependence of the heat capacity. Also, the calibration by Sjue used EOS table information to model the density changes of the beryllium sample during the Hopkinson bar and quasi-static experiments.

In this paper, the calibrated PTW model by Sjue is compared against experimental data and other strength models. The other strength models being considered are a PTW model calibrated by Shuh-Rong Chen and a Steinberg-Guinan type model by John Pedicini. The three strength models are used in a comparison against flyer plate and Taylor rod data. The results show that the Chen PTW model provides better agreement to this data. The Chen PTW model settings have been previously adjusted to provide a better fit to flyer plate data, whereas the Sjue PTW model has not been changed based on flyer plate data. However, the Sjue model provides a reasonable fit to flyer plate and Taylor rod data, and also gives a better match to recently analyzed Z-machine data which has a strain of about 0.35 and a strain rate of $3e5\text{ s}^{-1}$.

1 Introduction

In this report, simulation results from different beryllium strength models are compared and analyzed. The strength models considered are the PTW model with settings determined by Shuh-Rong Chen, the PTW model with settings calibrated by Sky Sjue, and a Steinberg-Guinan (SG) type model used by John Pedicini. The PTW model settings from Sky Sjue use an updated and data calibrated value for the PTW α parameter. The α parameter of PTW is used to help model the temperature dependence of the shear modulus. High precision shear modulus data from Boris Maiorov and Albert Migliori has recently been used by Sky Sjue to calibrate the α parameter of PTW. The new PTW calibration by Sjue used EOS table information to model the temperature and density changes of the beryllium sample during Hopkinson bar and quasi-static experiments. Previous calibrations assumed a constant heat capacity and density for the beryllium sample. The previous calibration attempts did model the change in temperature of the beryllium sample during the experiments, but did so with a constant heat capacity.

Over the last 12 years, there have been several attempts to calibrate the beryllium PTW model with Hopkinson bar and quasi-static data. The different calibration attempts have resulted in models with significantly different settings and extrapolation behavior. One of the main reasons for these differences in the calibrated settings is due to the Hopkinson bar data being limited to low strain (< 0.15). The different calibrated PTW settings could be distinguished with the availability of high strain data at high strain rates. The Hopkinson bar and quasi-static data will be discussed in the next section.

The simulation results from the different strength models were compared against flyer plate and Taylor impact experimental data. The simulation results show that the Chen PTW model settings provide the best agreement to the flyer plate and Taylor rod experimental data. The Sjue PTW model settings provide a generally acceptable agreement to the experimental data. The Sjue PTW model settings have not been adjusted based on a calibration to flyer plate data. The Chen PTW settings

Table I: Beryllium Calibration and Validation Data for Strength Models

Experiment	Density (g/cc)	Temperature (K)	Strain	Strain Rate (s^{-1})
quasi-static	≈ 1.85	473 - 873	up to 0.9	0.001 - 1
Hopkinson bar	≈ 1.85	77 - 773	up to 0.15	3000 - 4300
flyer plate	up to 2.1	up to 950	up to 0.15	up to 8e6
Taylor rod	up to 1.9	up to 600	up to 0.08	up to 4e5

have been previously adjusted based on a comparison of simulation results to flyer plate data. Also, the Sjure PTW model settings give a computed flow stress that is closer to recently analyzed Z-machine data [1] as compared to the Chen PTW model or Pedicini SG model. In the future, the Sjure PTW model settings could be investigated to determine if they can be modified to provide a better match to flyer plate and Taylor rod experimental data. The Pedicini SG model provides a reasonable fit to flyer plate data, but it does not come close to matching experimental Taylor rod profiles.

The results demonstrate that the current available data for beryllium is insufficient for calibration and validation. The current data is lacking information on the strength of beryllium at high strain for high strain rates. Table I provides information on the density, temperature, strain, and strain rate regimes for the data used to calibrate and validate beryllium strength models. The information in the table for flyer plate and Taylor rod experiments are obtained from simulations. The strain ranges provided for flyer plates and Taylor rods are for the strain experienced by a large part of the beryllium sample. For these experiments and according to the simulations, there are very small localized regions in the beryllium sample that experience higher strain (up to about 0.2 for Taylor rods and up to about 0.6 for some flyer plates). In any case, the strain experienced by the beryllium in the higher strain rate experiments (Hopkinson bar, flyer plate, and Taylor rod) is limited. The limited information at higher strain and strain rates has resulted in different calibrated PTW models exhibiting different behavior at high strain (for high strain rates) and making it difficult to then distinguish between PTW models.

2 Hopkinson Bar and Quasi-Static Data

Hopkinson bar and quasi-static experimental data are used to calibrate strength models. Hopkinson bar experiments can provide experimental data with strain rates up to several thousand per second. Quasi-static experiments give experimental data at lower strain rates; at around one per second or much less. Different strength models such as PTW, SG, and MTS [2] have been calibrated against the Hopkinson bar and quasi-static data.

In the case of the PTW model for beryllium, there have been numerous calibrations by different groups of people that have resulted in significantly different parameter settings for PTW. There are several reasons why different calibration attempts have resulted in significantly different parameter settings. The differences in the calibrated parameters settings are due to the Hopkinson bar data of beryllium being limited to low strain (< 0.15), applying different methods for treating the data, and the use of different statistical methods. Of the various reasons for the differences, the most important reason is that the Hopkinson bar data of beryllium is limited to low strain and, thus, this data does not constrain the PTW model for the higher strain rates of around several thousand per second. The different calibration methods treated the data differently in two primary ways: (1) they used different weightings during the calibration for the high strain rate data (Hopkinson bar) relative to the low strain rate data (quasi-static) and (2) they handled the twinning issue differently. Some of the beryllium samples in the Hopkinson bar experiments (especially for low temperature) underwent deformation twinning. Twinning is believed to be a significant contributor to deformation at low strains for beryllium. The calibration by Chen [3] used expert judgment while fitting to the Hopkinson bar data that underwent twinning while other groups did not address the impact of twinning. PTW does not model twinning and there is a possibility that fitting beryllium directly to Hopkinson bar data, without compensating for twinning, could result in the calibration over predicting the strength of beryllium at higher strains. The issue of handling twinning during calibration could be mitigated by having experimental data at higher strains (> 0.15) and strain rates ($> 1000s^{-1}$) to better constrain the PTW model.

The quasi-static data for beryllium ranges in temperature from 473K to 873K and strain rates from 0.001 to 1 per second. The Hopkinson bar data for beryllium ranges in temperature from 77K to 773K and with strain rates from 3000 to 4300 s^{-1} . This experimental data is given in Figure 1. Note that the Hopkinson bar data is limited to low strain. The plot and table of Figure 1 is given so that the curve with the highest stress values corresponds to the first row of the table (Temp. = 77K, Strain Rate = 3000 s^{-1}), the second highest curve corresponds to the second row (Temp. = 223K, Strain Rate = 3500 s^{-1}), and so on. This also holds for Figures 2 and 3.

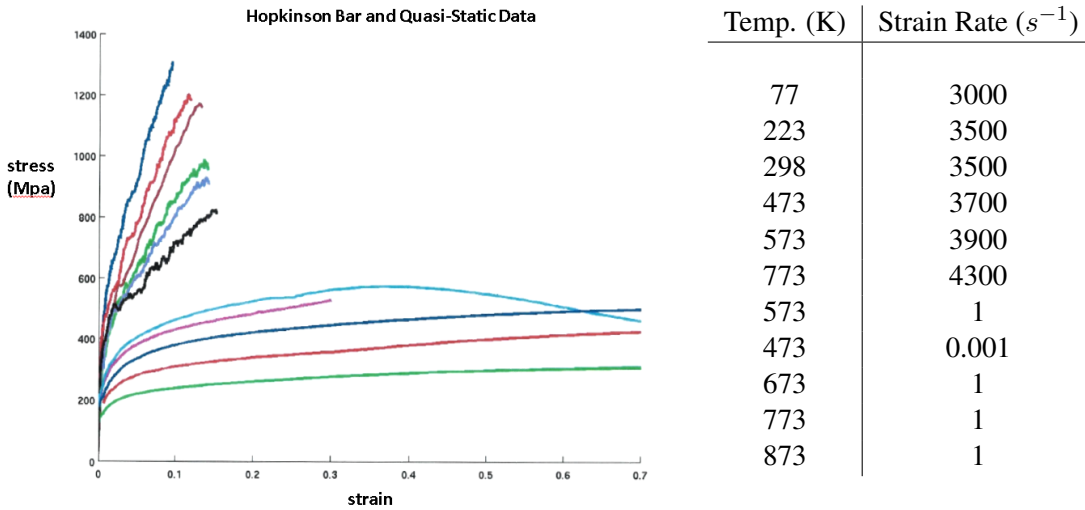


Figure 1: Beryllium Quasi-Static and Hopkinson Bar Data.

In the remainder of this section, several of the different PTW calibrated settings will be discussed. These different PTW models are listed in Table II. The Preston PTW model is the parameter settings originally given in the paper introducing PTW [4]. The CCS PTW model was fit by a group in CCS and this model was obtained without using the quasi-static data during the calibration [5]. The Chen PTW model was fit by Shuh-Rong Chen and it used expert judgment in calibrating to the Hopkinson bar experiments that underwent twinning deformation [3]. The comparison of the Chen PTW model to the data is given in Figure 2. For the Chen PTW beryllium calibration, there was a discrepancy in the melt temperature used in the fit as compared to the melt temperature values used in the FLAG computer simulations. The Chen PTW calibration used a constant pressure melt temperature and the FLAG codes use a constant density melt temperature. For the calibration of the other materials

Table II: PTW Parameter Settings

Parameter	Preston	CCS	Chen	Modified-Chen	Sjue
θ	0.04	0.31	0.0394	0.0394	0.0241
p	1.4	1.76	2	2	1.8
s_0	0.007	0.0166	0.0077	0.0077	0.011498
s_∞	0.0012	0.0038	0.0006	0.0006	0.000935
κ	0.14	0.3526	0.145	0.177	0.1994
γ	1e-05	1.2e-06	1e-06	1e-06	1e-06
y_0	0.0015	0.002	0.0018	0.0018	0.002015
y_∞	0.0005	0.0009	0.0004	0.0004	0.000411
y_1	0.007	NS	0.0077	0.0077	0.01259
y_2	0.25	NS	0.4	0.4	0.259975
β	0.25	NS	0.25	0.25	0.25
α	0.23	0.23	0.23	0.281	0.199

by Chen, there was also a discrepancy between the shear modulus used in the fit and the shear modulus used by FLAG. In the case of beryllium, this discrepancy was quite small. Since the melt temperature is used to normalize the temperature in the PTW model, some of the parameter settings in the Chen beryllium PTW model can be scaled in order to obtain an equivalent and appropriate model to use with the simulation codes of FLAG. A scaled PTW beryllium model was computed by Armstrong that adjusts the Chen PTW model to be consistent with specific shear modulus and melt temperature tables. This model is referred to as the Modified-Chen model in Table II. The items in Table II denoted as "NS" are used to represent values that were not specified in the corresponding report. An issue with all of these models is that the α parameter of PTW used for the calibration was not determined based on data and was set to 0.23 based on expert judgment.

In 2015, Sky Sjue computed an α value of 0.199 by using precision shear modulus data from Boris Maierov and Albert Migliori. Sjue then used this value of α to recalibrate the beryllium PTW model [6]. During the calibration, Sjue used a temperature dependent heat capacity to estimate the temperature increase of the beryllium sample as it undergoes plastic strain in the Hopkinson bar experiments. Also, the Sjue PTW calibration of beryllium used information from EOS tables in order to account for the changes in density experienced by the beryllium sample as the strain increases in the experiment. The Chen PTW calibration used a constant heat capacity and a constant

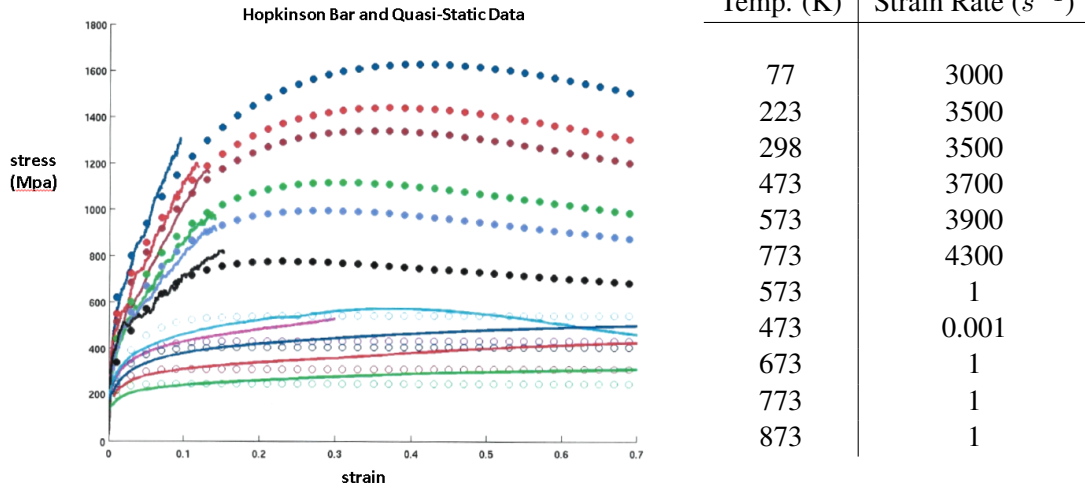


Figure 2: Chen PTW Model Compared to Be Quasi-Static and Hopkinson Bar Data.

density for the beryllium sample. The use of a constant density and heat capacity for the Chen PTW calibration is acceptable, in the case of beryllium, since these values for the beryllium sample only change by a few percent across the experiments. A comparison of the Sjuje PTW model with the data is given in Figure 3.

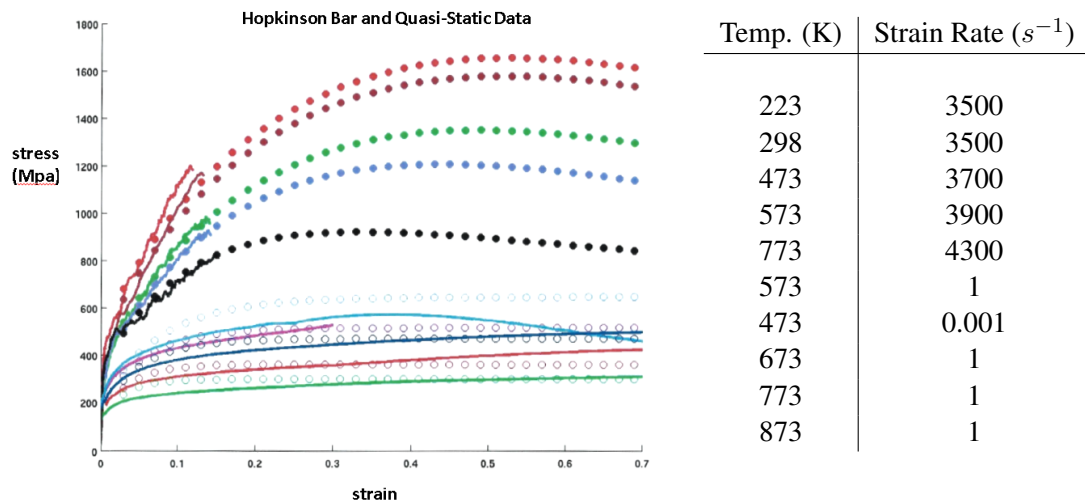


Figure 3: Sjuje PTW Model Compared to Be Quasi-Static and Hopkinson Bar Data.

Due to the Hopkinson bar data being limited to low strain (< 0.15), the different PTW calibration settings can have significantly different computed flow stress values when they are extrapolated to higher strains. To illustrate this, Figure 4 gives a comparison between the Chen PTW model and

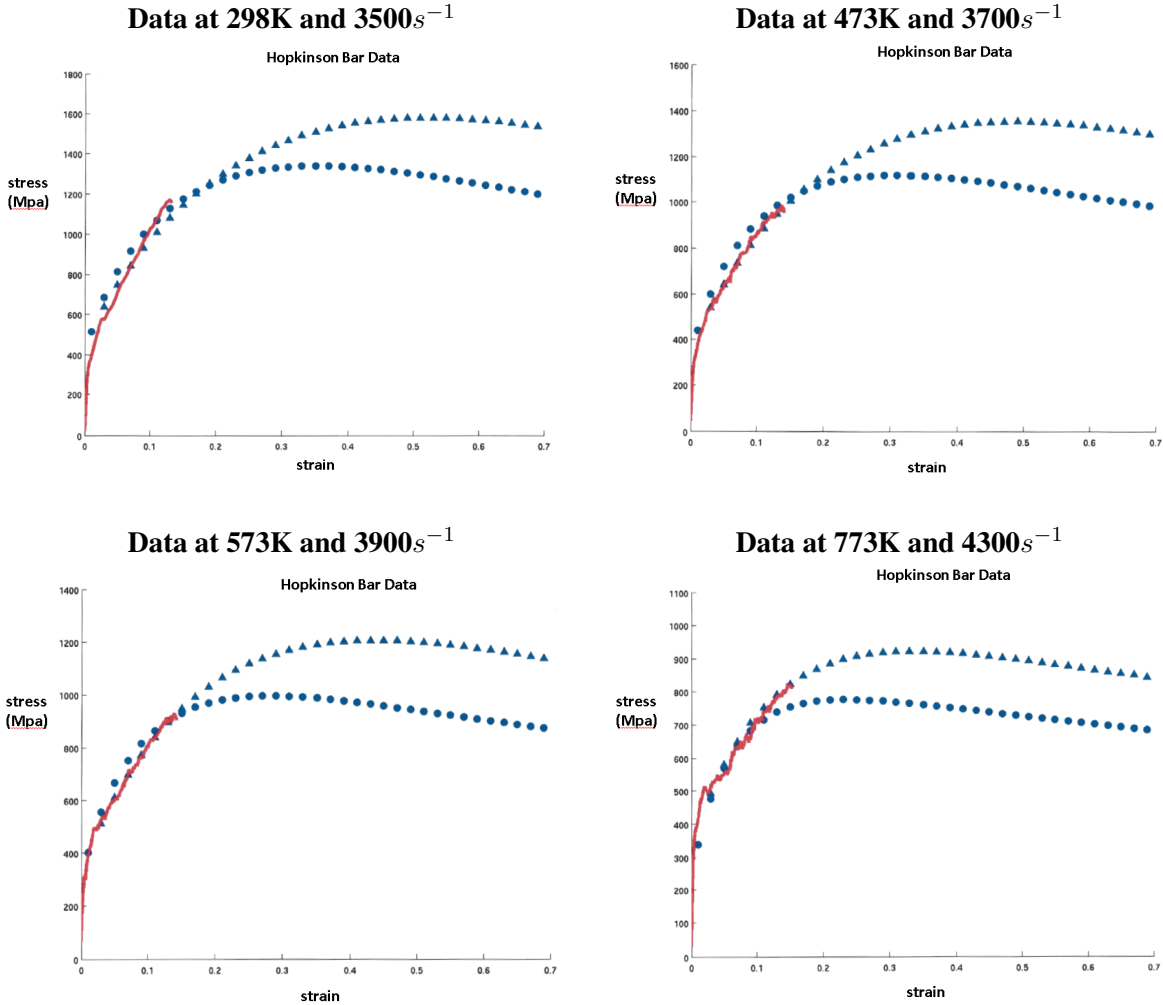


Figure 4: Chen PTW and Sjue PTW models compared to Hopkinson bar data at different temperatures and strain rates. Data is in red. Chen PTW model is blue circles. Sjue PTW model is blue triangles.

the Sjue PTW model at higher strains for some of the Hopkinson bar experiments. As can be seen in the figure, the Sjue PTW model predicts higher flow stress values than the Chen PTW model at higher strains. This is due to the saturation stress parameters of PTW, s_0 and s_∞ , being about 50% higher in the Sjue PTW model (0.011498, 0.000935) as compared to the Chen PTW model (0.0077, 0.0006). The difference between the two models in the figure is about 30% at high strains. The Chen PTW model has a larger work hardening parameter than does the Sjue PTW model (0.0394 versus 0.0241) and this can be seen in the figure with the larger slope for the Chen PTW flow stress at strains near zero.

3 Flyer Plate Experiments

Flyer plate experiments can be used to validate strength models at higher strain rates. The beryllium flyer plate experiments reach strain rates of about 10^6 s^{-1} . These experiments can also be used to calibrate the PTW parameters that are related to higher strain rates. For example, Shuh-Rong Chen and Mike Prime used the beryllium flyer plate experiments to calibrate the PTW parameters β and y_2 [7]. There are six beryllium flyer plate experiments that are used for the calibration and validation of beryllium strength models. Two of these flyer plate experiments use a beryllium flyer as well as a beryllium target and these two experiments are the most sensitive to beryllium strength parameters. All six of the beryllium flyer plate experiments are listed in Table III.

In this section, three strength model settings for beryllium will be compared against the experimental flyer plate data. The flyer plate simulation results of this paper do not include a damage model since the focus is on strength models. This also means that the plots and results of this section ignore the spall signal in the experimental flyer plate data. The three models are the Sjure PTW model, the Chen PTW model, and a SG model from Pedicini. The SG model of Pedicini is given in Table IV. The parameter settings of the SG model of Table IV is very similar to the settings prescribed in a report by Steinberg [8].

Table III: Beryllium Flyer Plate Experiments

Experiment	Flyer (diameter / thickness)	Target (diameter / thickness)	Flyer velocity
55-429	Beryllium (1.125" / 2mm)	Beryllium (1.125" / 4mm)	0.7209 mm/ μ s
55-430	Beryllium (1.125" / 2mm)	Beryllium (1.125" / 4mm)	1.246 mm/ μ s
55-432	Sapphire (1.5" / 3mm)	Beryllium (1.125" / 6mm)	0.6540 mm/ μ s
55-433	Tantalum (1.5" / 1mm)	Beryllium (1.125" / 4mm)	1.418 mm/ μ s
55-436	Quartz (1.5" / 4mm)	Beryllium (1.125" / 4mm)	0.2546 mm/ μ s
55-442	Composite (1.125" / 2mm)	Beryllium (1.25" / 4mm)	1.553 mm/ μ s

First, results from a convergence study will be given. Figure 5 gives the beryllium flyer plate simulation results for 55-429 and 55-430 at 100, 50, 25, and 10 microns for the beryllium target. All of the simulations of this section are two dimensional. As can be seen from Figure 5, there is little

Table IV: Pedicini SG Model Settings

Parameter	Value	Units	Definition
$r0$	1.845	g/cc	reference density
$sm0$	1.51	Mbar	initial shear modulus
au	1.5231788	Mbar ⁻¹	pressure dependence multiplier
bu	2.5827815e-04	Mbar ⁻¹	temperature dependence multiplier
$y0$	0.0033	Mbar	initial flow stress
yx	0.0123	Mbar	maximum flow stress
yb	81.0	N/A	work hardening
xn	0.22	N/A	work hardening exponent
qy	1.0	N/A	extra pressure dependence factor for flow stress
fg	0.001	N/A	melt shaping for shear modulus
fy	0.001	N/A	melt shaping for flow stress
$r0s$	1.845	N/A	crushed-up density

difference between the 10 and 25 micron resolution simulations. Thus, throughout the remainder of this section, results will be given for 10 micron resolution simulations. In the case where the flyer is not beryllium, the flyer mesh was determined by impedance matching with the beryllium target.

Previous work has indicated that the flyer plate experiments 55-429 and 55-430 are the most sensitive to beryllium strength settings. This is not surprising since both the flyer and the target are beryllium in these two experiments. However, even these experiments are not significantly sensitive to strength. In figures 6 and 7, the Chen PTW model is plotted against the data, together with the Chen PTW model at $\pm 25\%$ and $\pm 50\%$, respectively. The Chen PTW models of $\pm 25\%$ and $\pm 50\%$ are obtained by scaling six of the Chen PTW parameter settings so that the computed flow stress is exactly $\pm 25\%$ and $\pm 50\%$ of the computed flow stress of the Chen model. The six parameters that are scaled are y_0 , y_1 , y_∞ , s_0 , s_∞ , and θ .

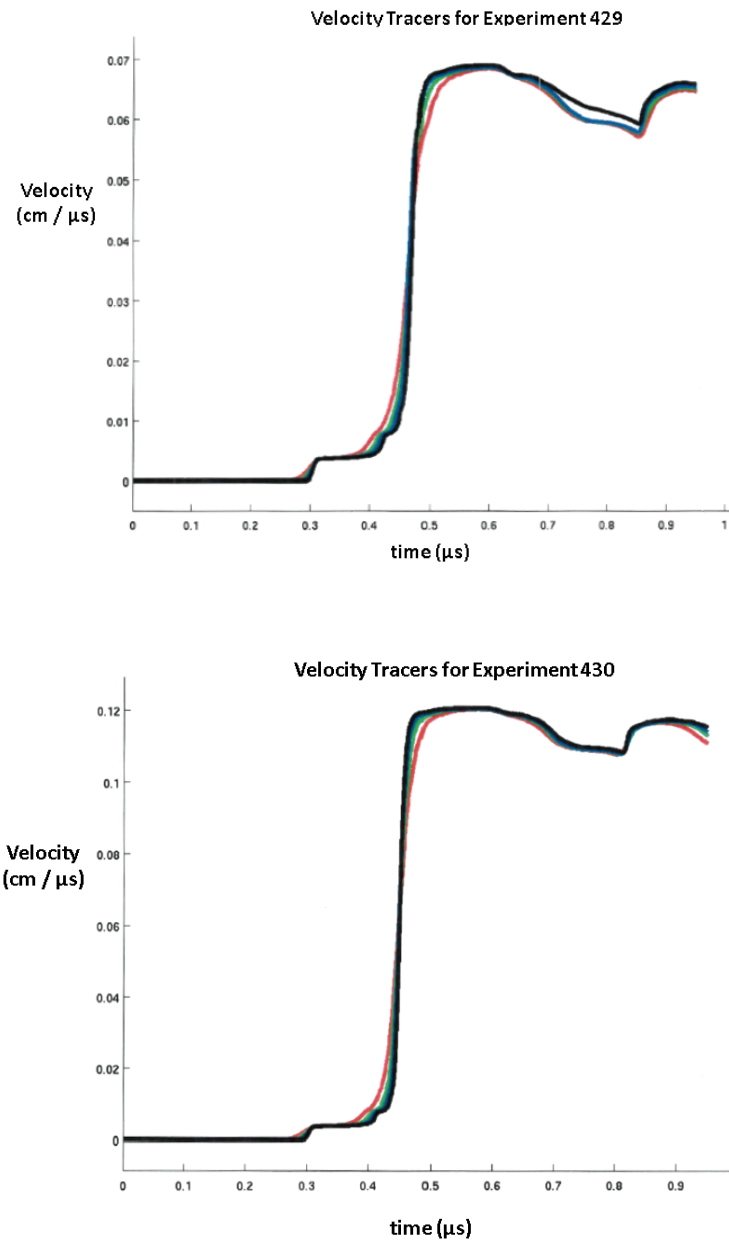


Figure 5: Convergence study results: VISAR simulation results for experiments 55-429 and 55-430. Red is 100 microns, green is 50 microns, blue is 25 microns, and black is 10 microns.

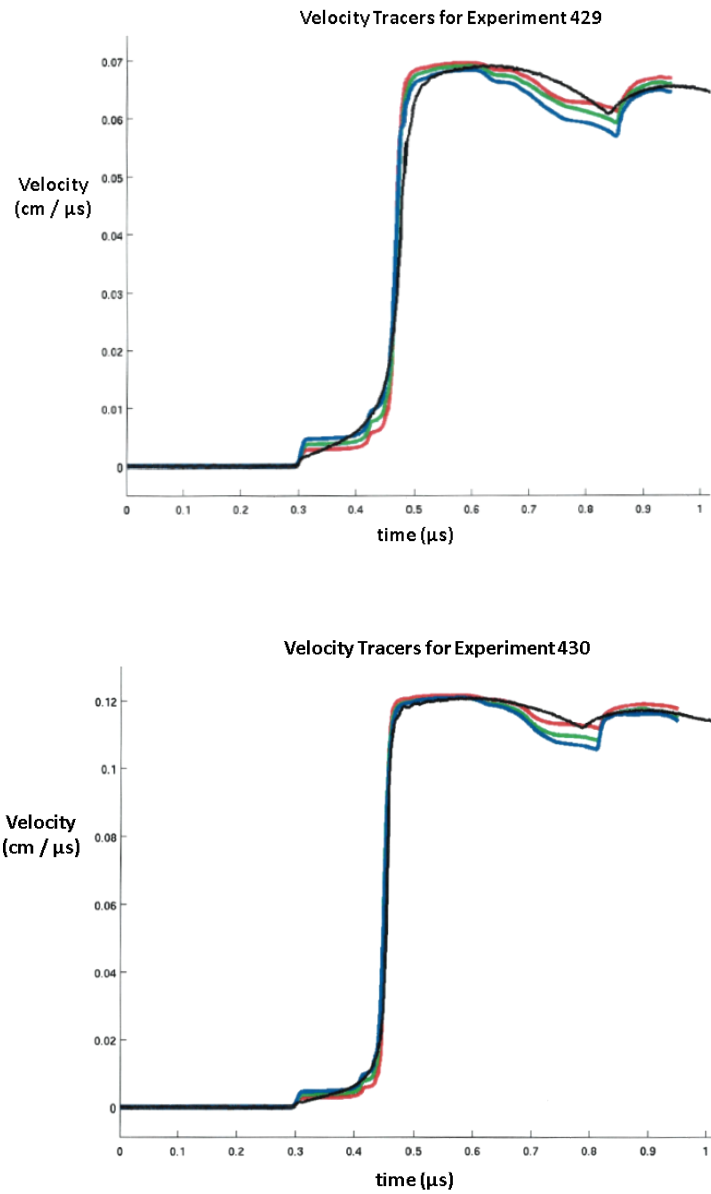


Figure 6: Chen PTW model compared to the data. Also included is the Chen PTW model scaled by $\pm 25\%$. Data is in black. Chen PTW is green. Chen PTW -25% is red and Chen PTW $+25\%$ is blue.

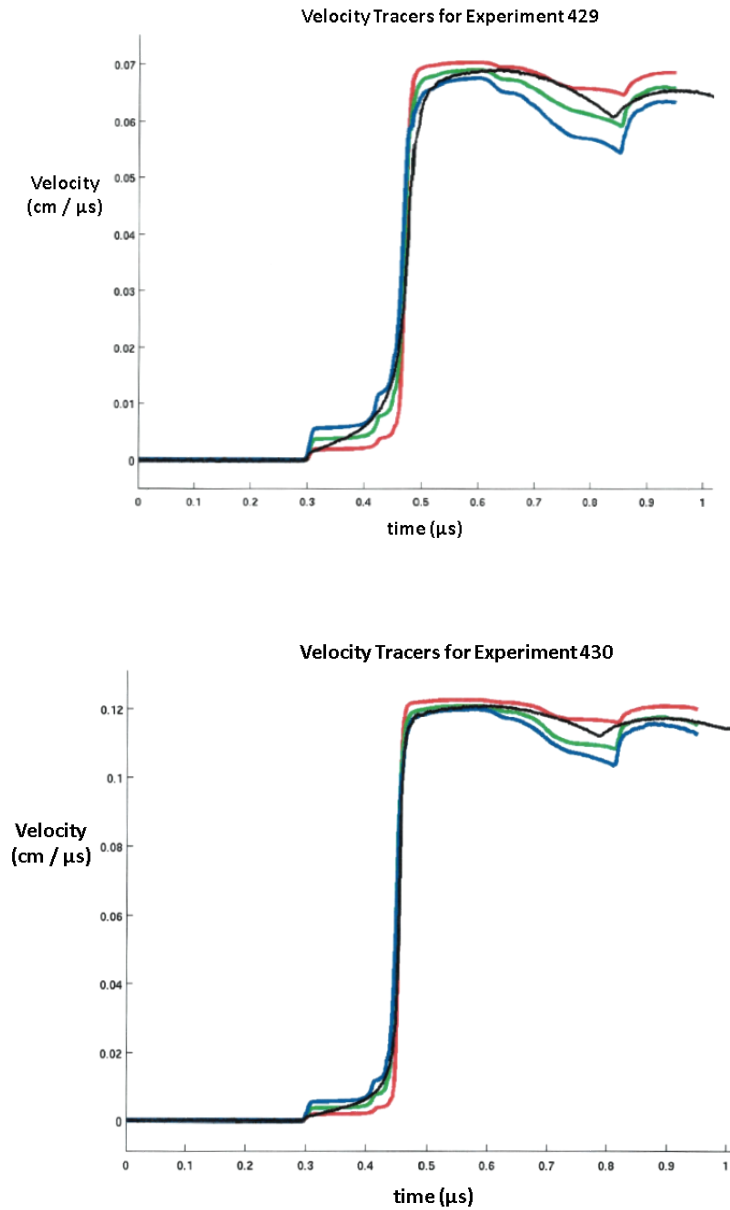


Figure 7: Chen PTW model compared to the data. Also included is the Chen PTW model scaled by $\pm 50\%$. Data is in black. Chen PTW is green. Chen PTW -50% is red and Chen PTW $+50\%$ is blue.

Based on figures 6 and 7, it would be unreasonable to use these flyer plate experiments to discriminate between PTW models that differ in strength by less than about $\pm 25\%$. Flyer experiment 55-430 is also not showing much difference between the Chen PTW model and the Chen PTW models at $\pm 50\%$. Next, the Chen PTW, Sjue PTW, and Pedicini SG models will be compared against each other and against the data. This is given in figures 8 and 9. Based on the results in these figures, the Chen PTW model and the Pedicini SG model provide better agreement to the flyer plate data. As mentioned earlier, the Chen PTW model settings have been adjusted to obtain a better match to the flyer plate data. The Sjue PTW model settings have not yet been calibrated to the flyer plate data. Changing the y_2 parameter of the Sjue PTW Model to equal 0.4 gives a much better fit to the data. The Sjue PTW model results with y_2 equal to 0.4 is given in Figure 10. The fact that the Sjue PTW model provides a better fit to the data when y_2 is equal to 0.4 is not to be taken as a recommendation to use that value for y_2 in simulations. Changing the value of y_2 to 0.4 could result in a model with significantly different fits when compared with other data, including the Z-machine data. Figure 10 is given to demonstrate that it may be possible to obtain a better agreement with the flyer plate data by making modifications to the Sjue PTW model.

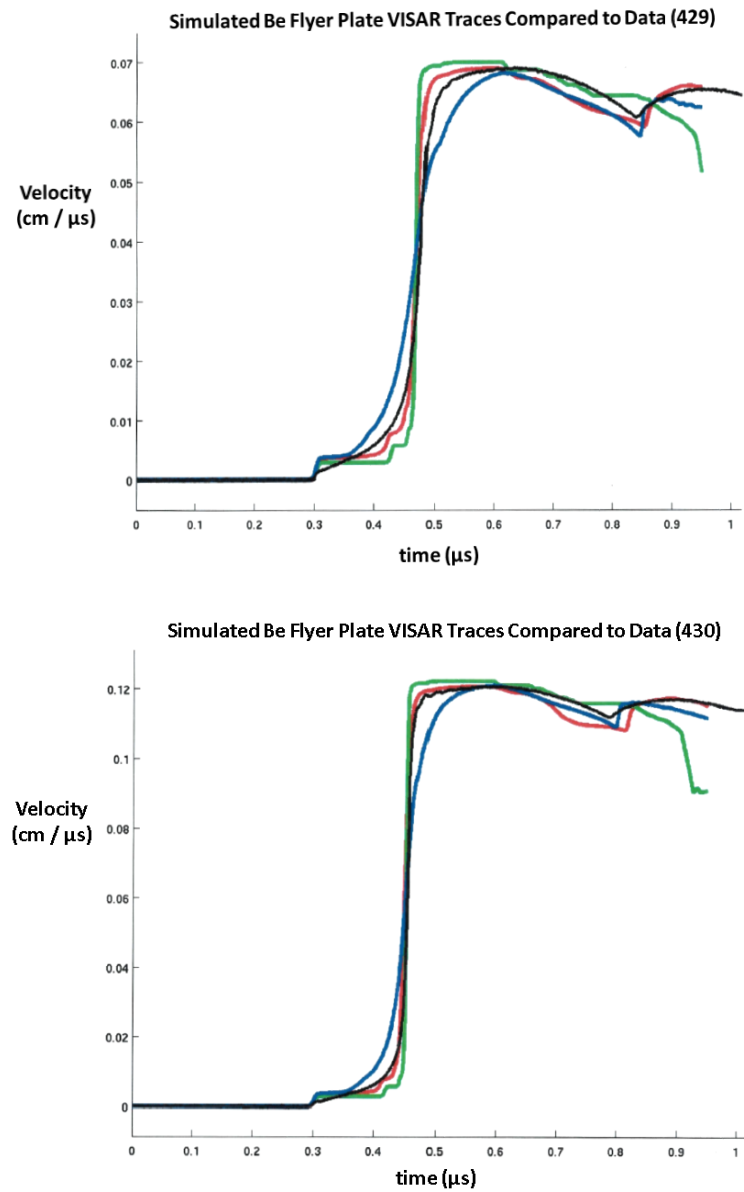


Figure 8: Chen PTW model (red), Sjuve PTW model (blue), and Pedicini SG model (green) compared to flyer data (black). Results are given for experiments 55-429 and 55-430.

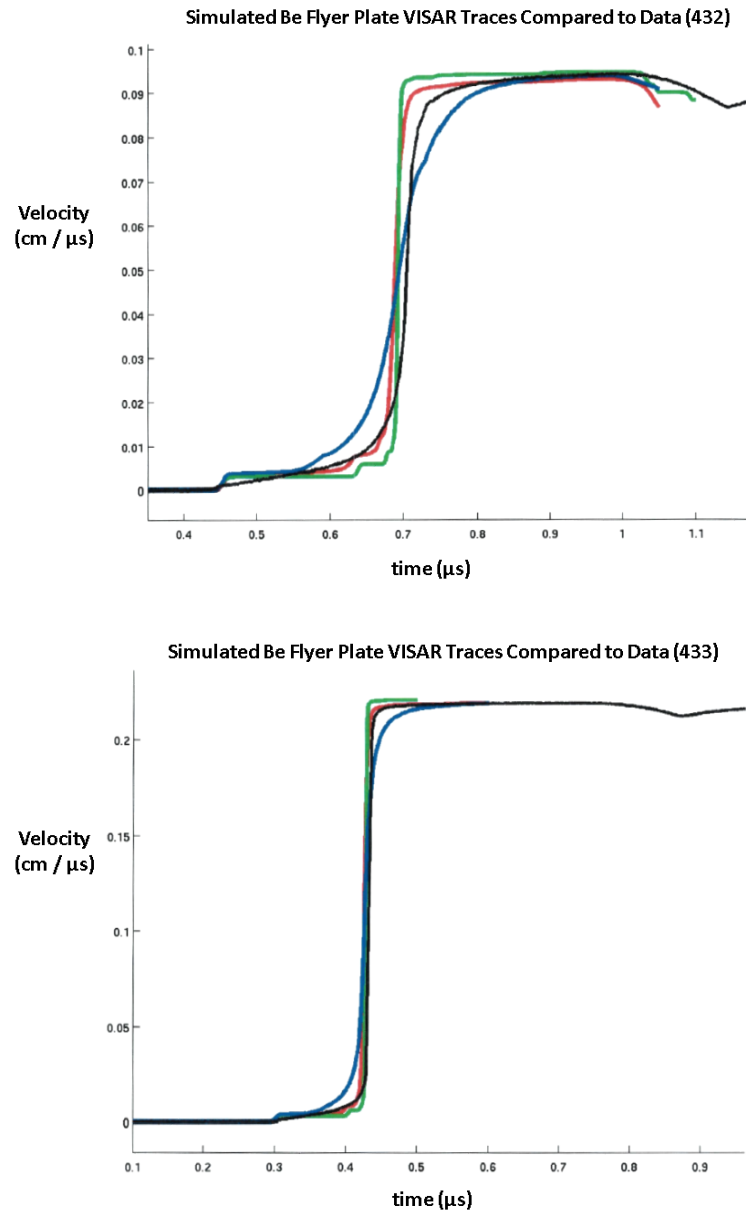


Figure 9: Chen PTW model (red), Sjuve PTW model (blue), and Pedicini SG model (green) compared to flyer data (black). Results are given for experiments 55-432 and 55-433.

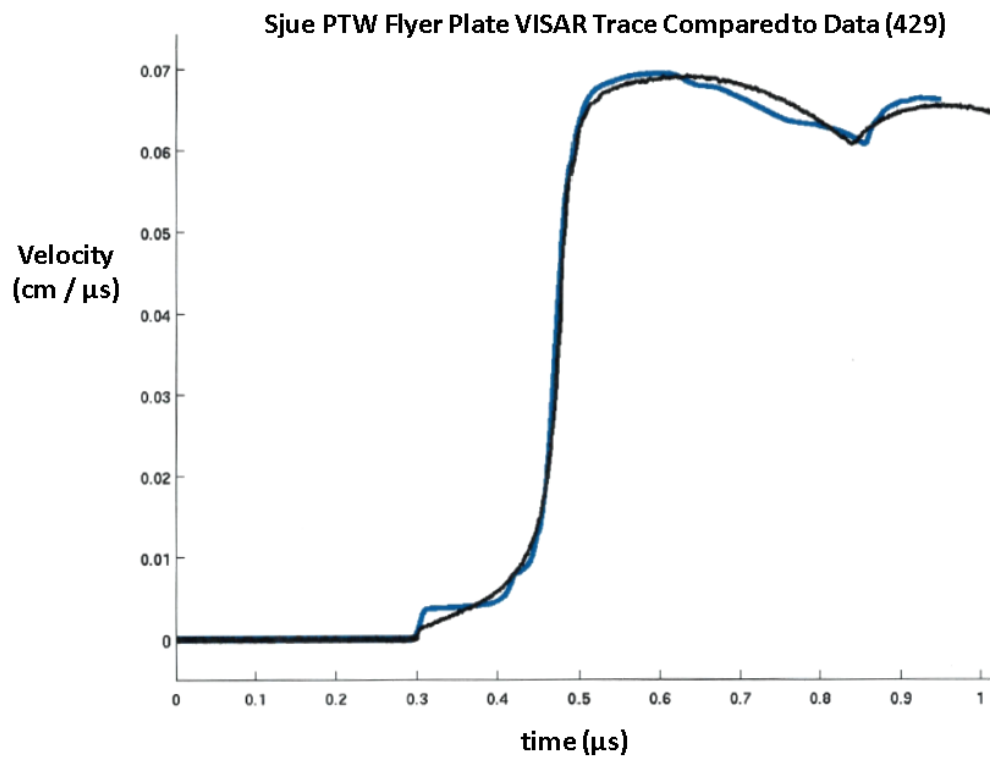


Figure 10: Experiment 55-429. Simulation of Sjue PTW model with y_2 set to 0.4. Data is in black. Simulation results are in blue.

4 Taylor Rod Experiments

In the past, Taylor rod experiments have been used to validate strength models at higher strain rates. The profiles from the recovered experimental Taylor rods are compared to the simulated profiles. At LANL, no Taylor rod impact experiments have been performed for beryllium. LLNL has conducted a few of these experiments for beryllium but the final profiles are not currently accessible at LANL.

This section will provide computational results from simulating beryllium Taylor rod experiments that were performed at the French institution Centre d'Etudes de Bruyères-le-Châtel [9]. The Centre d'Etudes de Bruyères-le-Châtel is one of the centers of the Commissariat à l'Energie Atomique (French Alternative Energies and Atomic Energy Commission). The center conducted several beryllium Taylor rod experiments at different velocities. The report [9] includes final profiles of the beryllium samples recovered after the Taylor rod experiments. These profiles were extracted from the paper with a Matlab program and are used to compare with simulated profiles from FLAG. The beryllium Taylor rods used in the Centre d'Etudes de Bruyères-le-Châtel experiments had an initial diameter and length of 8mm and 20mm, respectively. Table 4 lists the beryllium Taylor rod experiments performed at room temperature. Note that there are repeated experiments for a given velocity so that experimental error could be estimated. In the table, L_0 and L_f represent the initial and final rod length, respectively. The average strain and average strain rate were computed in the French report [9] with a formula that depends on the initial rod length, final rod length, and impact velocity.

In order to compare simulation profiles with the data from the French report, a set of simulations were performed at velocities of 150, 194, 216, 242, and 250 m/s. At all of these velocities, simulations were performed with the Chen PTW, Sjøue PTW, and Pedicini SG models. The maximum density, strain, and strain rate experienced by the beryllium rod were obtained from simulations with the Chen PTW model at four of the five velocities. This information is given in table 5. The results in tables 4 and 5 show that these experiments are limited to relatively low strain. The maximum

Table V: French AEC Beryllium Taylor Rod Experiments

Velocity m/s	L_0 mm	L_f mm	average strain	average strain rate, s^{-1}
150.1	20	19.30	0.044	4700
150.1	20	19.55	0.028	4600
150.6	20	19.43	0.036	4700
194.0	20	19.11	0.053	5700
194.7	20	19.05	0.055	5600
194.7	19.99	19.15	0.048	5600
216.0	20	19.04	0.055	6100
216.0	19.99	19.05	0.053	6000
242.1	20	18.80	0.067	6700
250.0	20	18.68	0.077	7200

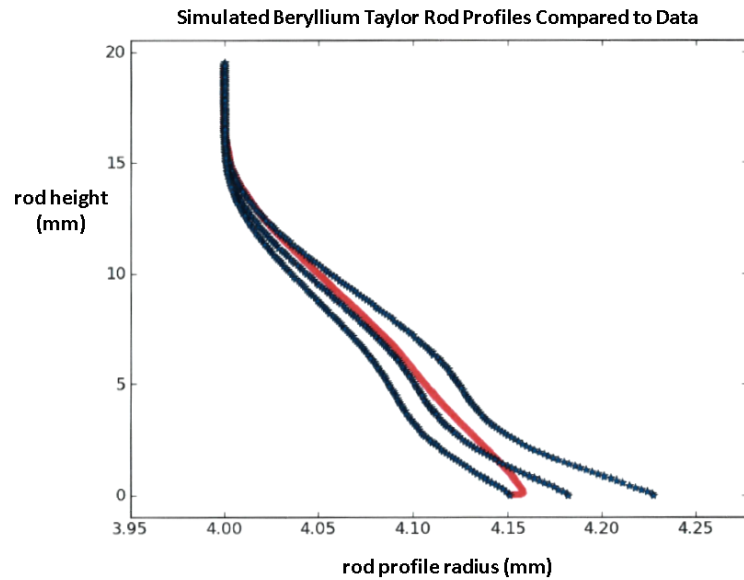
strain rates for these experiments are around $2e5$ and $4e5$ per second.

The next three figures give information on the sensitivity of the simulation results to changes in the strength settings. The figures give the simulated profiles obtained from the Chen PTW model, the Chen PTW model at $\pm 25\%$, and the Chen PTW model at $\pm 50\%$. Figure 11 is for a velocity of 150 m/s. Figures 12 and 13 are for velocities of 216 and 250 m/s, respectively. The results from these figures demonstrate that the Taylor rod simulations are sensitive to strength model settings. A change of 25% in the computed flow stress creates a noticeable difference in the simulated profile.

Table VI: Maximum density, strain, and strain rate from Taylor rod simulations

Velocity (m/s)	max density (g/cc)	max strain	max strain rate s^{-1}
150	1.88	0.09	$2e5$
194	1.89	0.14	$3e5$
242	1.9	0.18	$4e5$
250	1.9	0.19	$4e5$

Chen PTW Model (and at $\pm 25\%$) Simulated Taylor Rod Profiles



Chen PTW Model (and at $\pm 50\%$) Simulated Taylor Rod Profiles

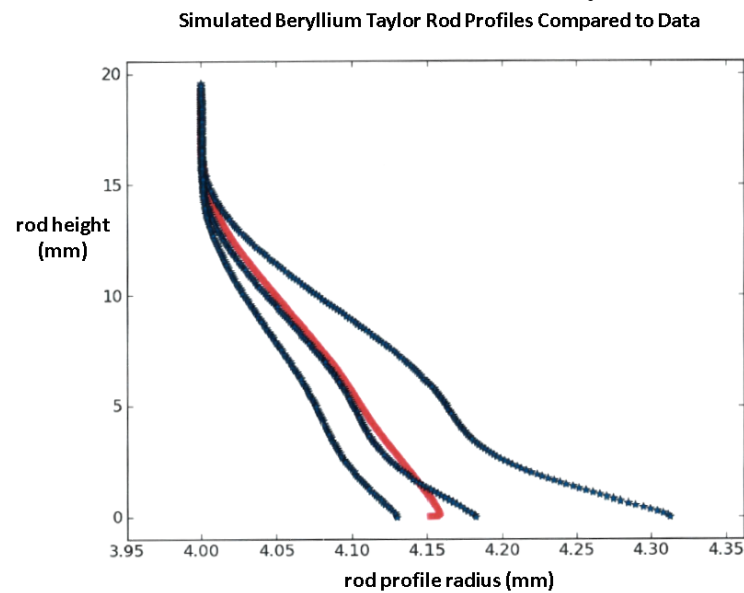
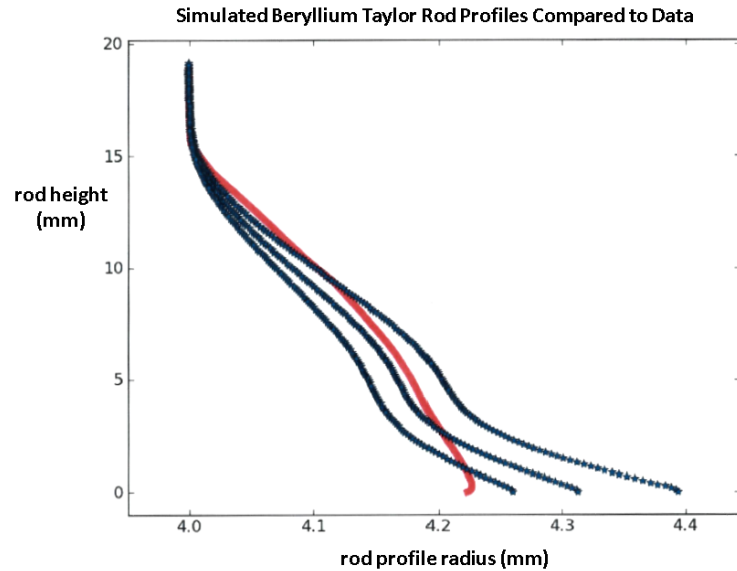


Figure 11: Simulation results for Taylor impact velocity of 150 m/s. Chen PTW model results are in blue. The experimental data is in red. The results with less deformation are the Chen PTW model at $+25\%$ and $+50\%$, respectively.

Chen PTW Model (and at $\pm 25\%$) Simulated Taylor Rod Profiles



Chen PTW Model (and at $\pm 50\%$) Simulated Taylor Rod Profiles

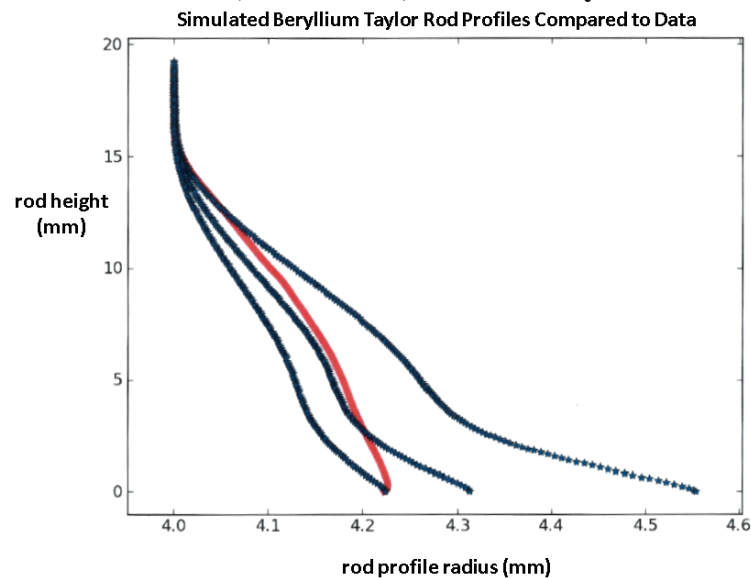
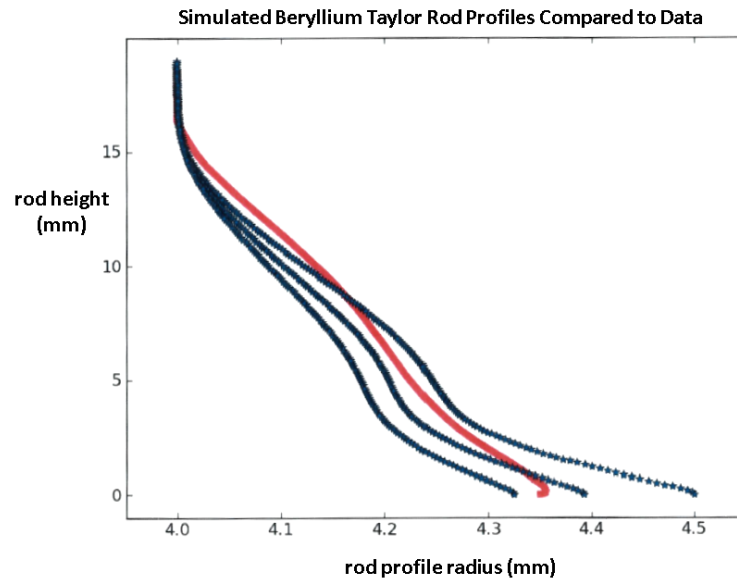


Figure 12: Simulation results for Taylor impact velocity of 216 m/s. Chen PTW model results are in blue. The experimental data is in red. The results with less deformation are the Chen PTW model at $+25\%$ and $+50\%$, respectively.

Chen PTW Model (and at $\pm 25\%$) Simulated Taylor Rod Profiles



Chen PTW Model (and at $\pm 50\%$) Simulated Taylor Rod Profiles

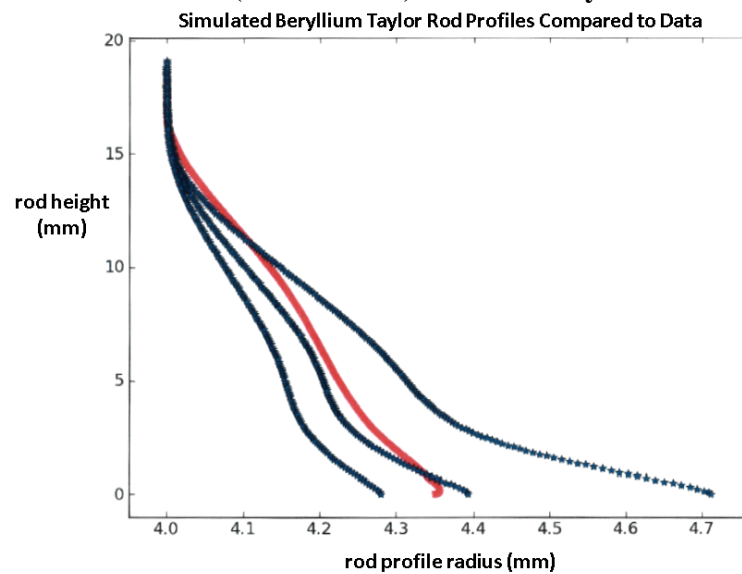


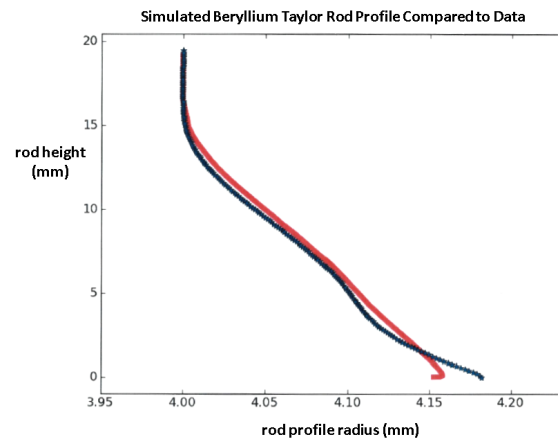
Figure 13: Simulation results for Taylor impact velocity of 250 m/s. Chen PTW model results are in blue. The experimental data is in red. The results with less deformation are the Chen PTW model at $+25\%$ and $+50\%$, respectively.

The next five figures compare the simulated profiles obtained from the Chen PTW, Sjue PTW, and Pedicini SG models. There is one figure for each of the five impact velocities simulated. The results show that the Chen PTW model provides simulated profiles that are the closest to the experimental data. The Sjue PTW model also provides an acceptable comparison to the experimental profiles. The figures show that the Pedicini SG model is significantly different from the data. The SG model is strain rate independent and the results are showing that the Pedicini SG model is under predicting the strength at the higher strain rates seen in the Taylor rod experiments.

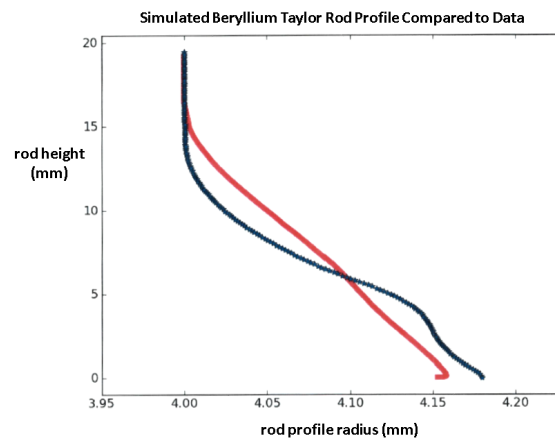
The French report also includes results from Taylor rod experiments where the beryllium has initial temperatures of 100 C, 200 C, and 300 C. All of these experiments had a rod impact velocity of about 218 m/s. The last three figures of this report give the comparisons of the simulated profiles with the corresponding experimental data with temperatures of 100 C, 200 C, and 300 C, respectively.

From all of the following figures, it appears that the simulated profiles from the Sjue PTW model are not smoothly varying. Part of the reason for this appearance is that the x-axis of the plots are at a much different scale than that of the y-axis. This difference in scale is needed to demonstrate the deformation of the beryllium rod. The beryllium rod does not deform much in these experiments and for an unadjusted image of the profile it would be difficult to perceive the deformation. A future step with this work would include a deeper investigation into the reasons behind the shape of the Sjue PTW simulated profiles.

Chen PTW model versus data. Results for impact velocity of 150 m/s.



Sky PTW model versus data. Results for impact velocity of 150 m/s.



Pedicini SG model versus data. Results for impact velocity of 150 m/s.

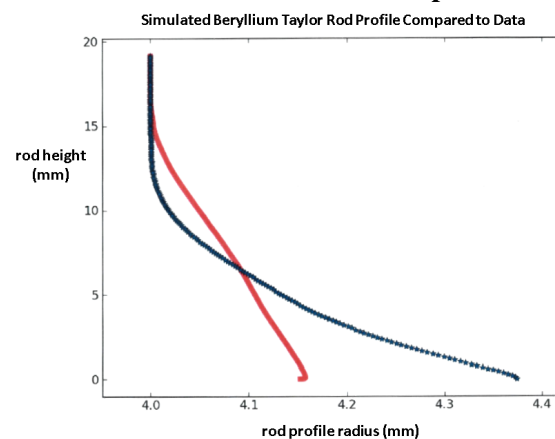
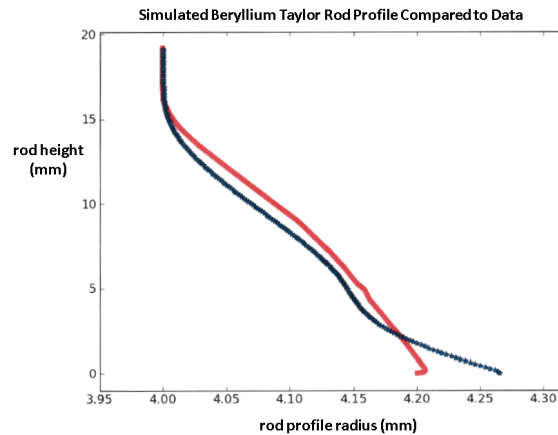
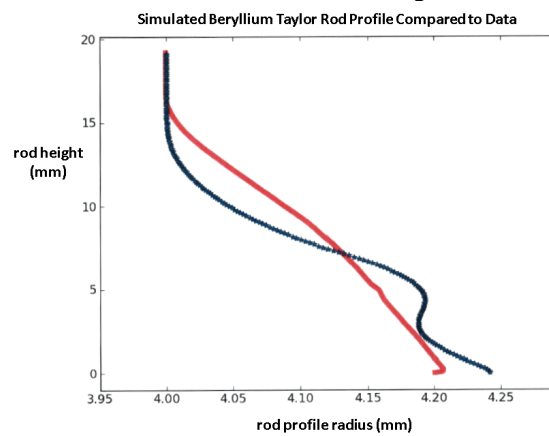


Figure 14: Simulation results for Taylor impact velocity of 150 m/s. The data is in red. Results are given for Chen PTW model, Sjue PTW model, and Pedicini SG model.

Chen PTW model versus data. Results for impact velocity of 194 m/s.



Sky PTW model versus data. Results for impact velocity of 194 m/s.



Pedicini SG model versus data. Results for impact velocity of 194 m/s.

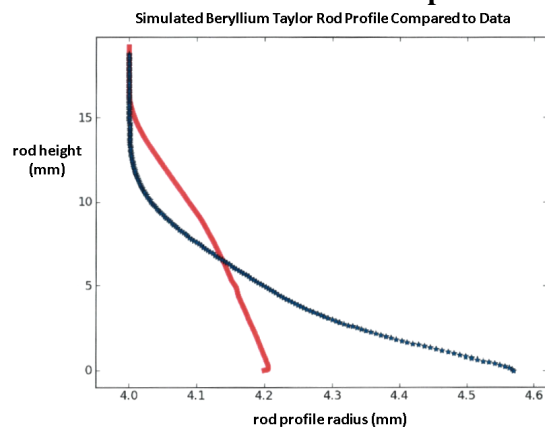
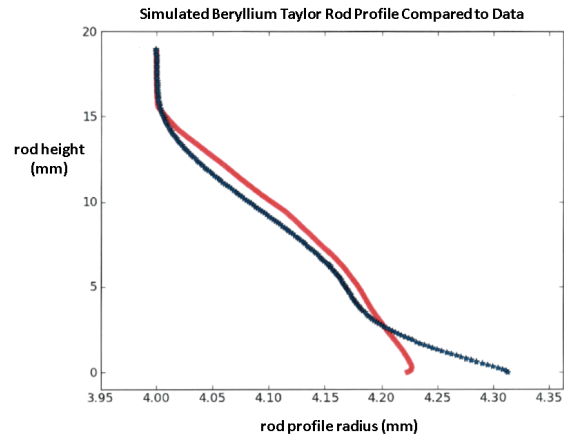
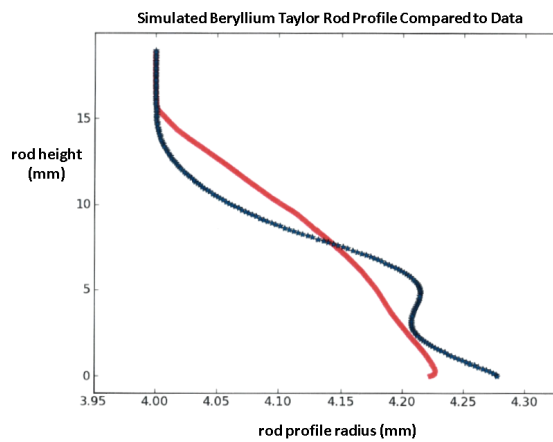


Figure 15: Simulation results for Taylor impact velocity of 194 m/s. The data is in red. Results are given for Chen PTW model, Sje PTW model, and Pedicini SG model.

Chen PTW model versus data. Results for impact velocity of 216 m/s.



Sky PTW model versus data. Results for impact velocity of 216 m/s.



Pedicini SG model versus data. Results for impact velocity of 216 m/s.

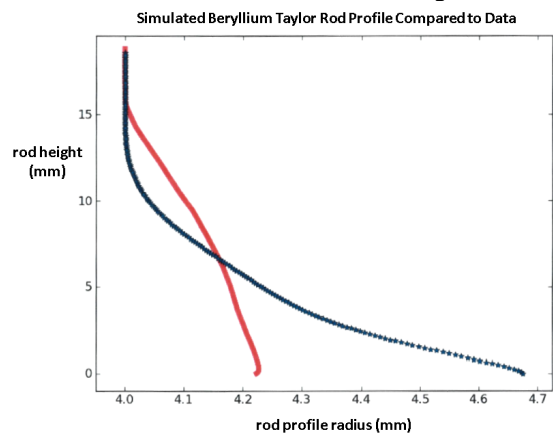
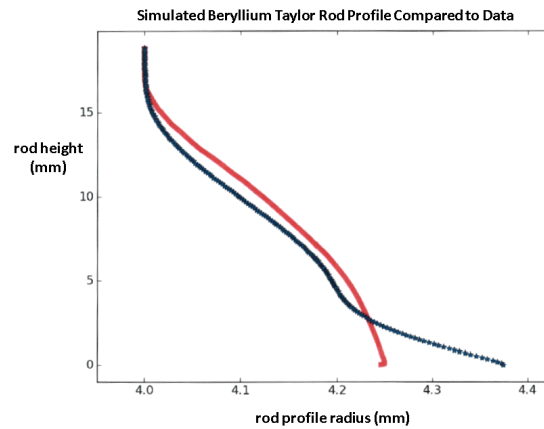
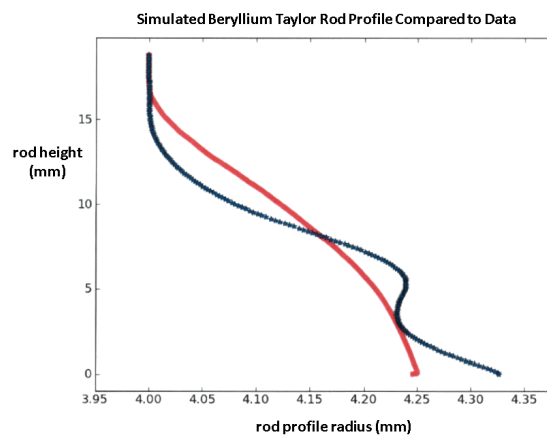


Figure 16: Simulation results for Taylor impact velocity of 216 m/s. The data is in red. Results are given for Chen PTW model, Sjøe PTW model, and Pedicini SG model.

Chen PTW model versus data. Results for impact velocity of 242 m/s.



Sky PTW model versus data. Results for impact velocity of 242 m/s.



Pedinci SG model versus data. Results for impact velocity of 242 m/s.

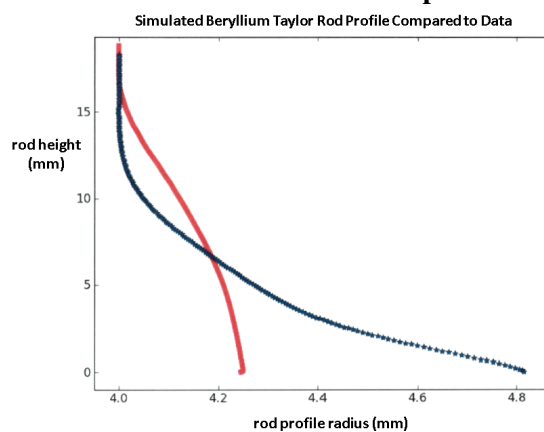


Figure 17: Simulation results for Taylor impact velocity of 242 m/s. The data is in red. Results are given for Chen PTW model, Sjøe PTW model, and Pedicini SG model.

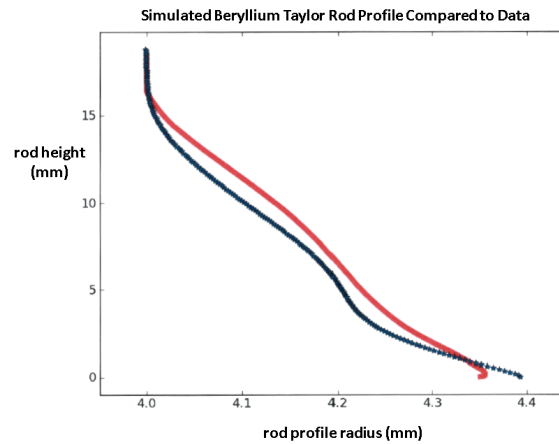
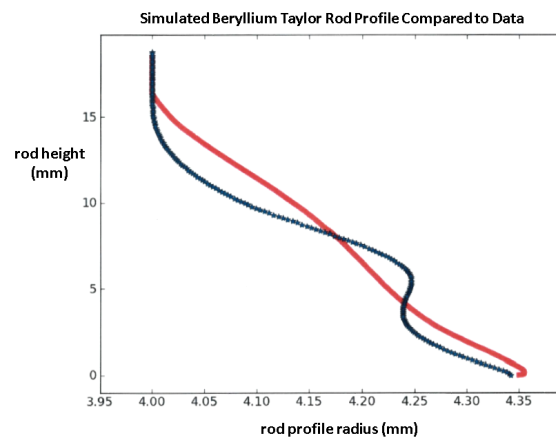
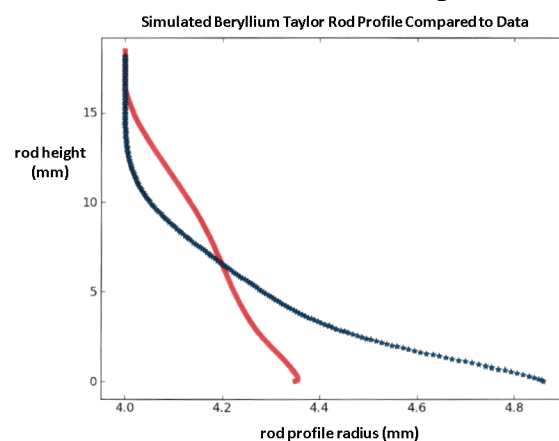
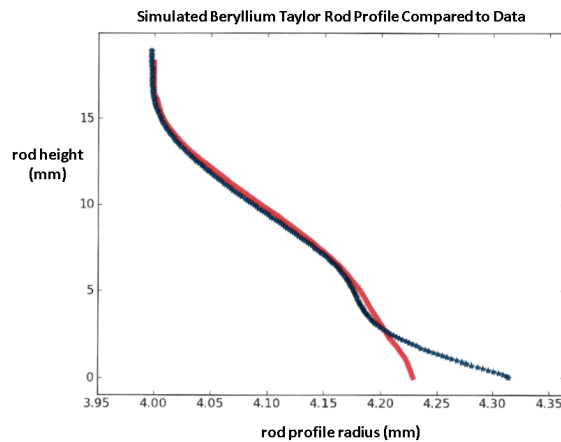
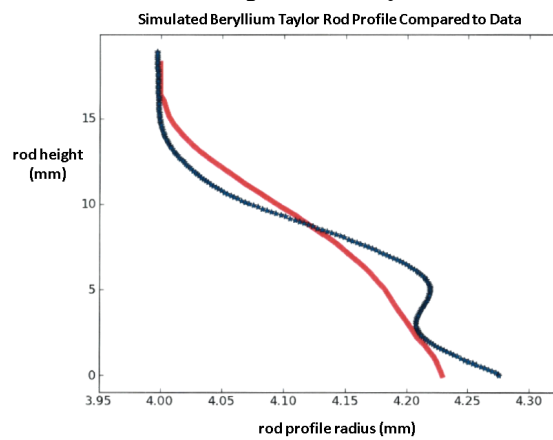
Chen PTW model versus data. Results for impact velocity of 250 m/s.**Sky PTW model versus data. Results for impact velocity of 250 m/s.****Pedicini SG model versus data. Results for impact velocity of 250 m/s.**

Figure 18: Simulation results for Taylor impact velocity of 250 m/s. The data is in red. Results are given for Chen PTW model, Sjeue PTW model, and Pedicini SG model.

Chen PTW model versus data. Results for impact velocity of 218 m/s and a temperature of 100 C.



Sky PTW model versus data. Results for impact velocity of 218 m/s and a temperature of 100 C.



Pedicini SG model versus data. Results for impact velocity of 218 m/s and a temperature of 100 C.

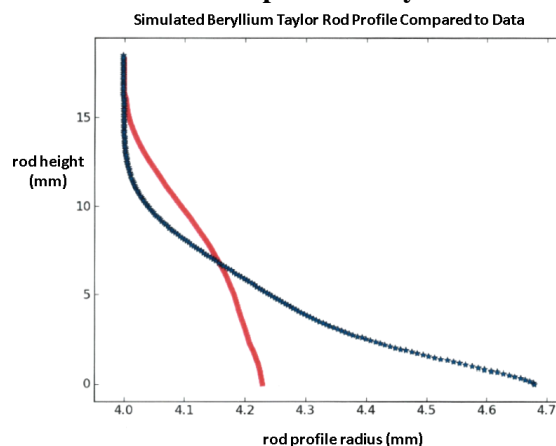
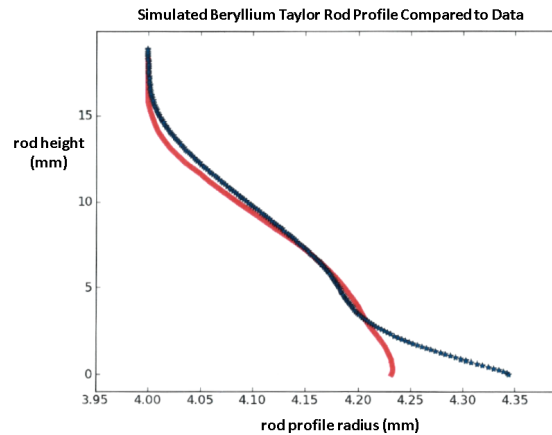
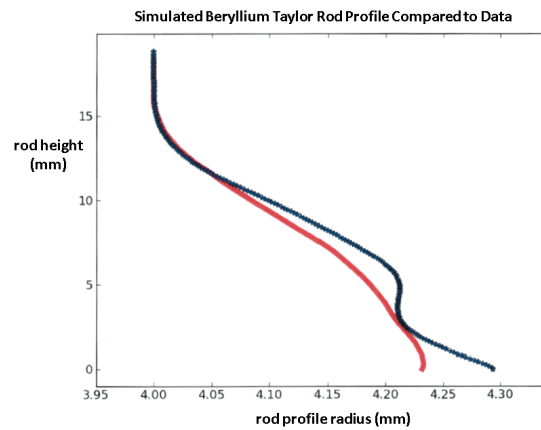


Figure 19: Simulation results for Taylor impact velocity of 218 m/s and a temperature of 100 C. The data is in red. Results are given for Chen PTW model, Sjue PTW model, and Pedicini SG model.

Chen PTW model versus data. Results for impact velocity of 218 m/s and a temperature of 200 C.



Sky PTW model versus data. Results for impact velocity of 218 m/s and a temperature of 200 C.



Pedicini SG model versus data. Results for impact velocity of 218 m/s and a temperature of 200 C.

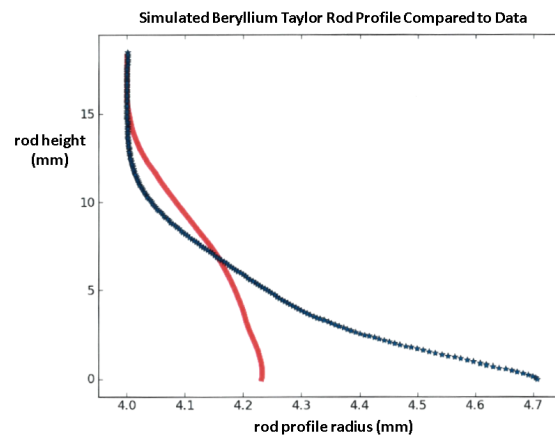
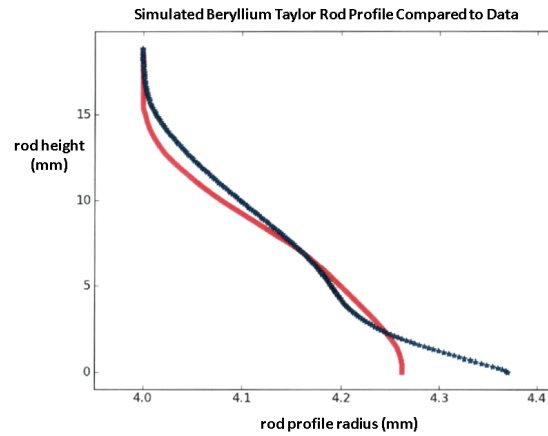
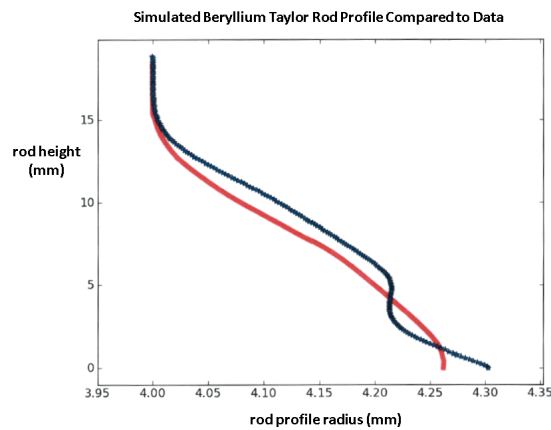


Figure 20: Simulation results for Taylor impact velocity of 218 m/s and a temperature of 200 C. The data is in red. Results are given for Chen PTW model, Sjeue PTW model, and Pedicini SG model.

Chen PTW model versus data. Results for impact velocity of 218 m/s and a temperature of 300 C.



Sky PTW model versus data. Results for impact velocity of 218 m/s and a temperature of 300 C.



Pedicini SG model versus data. Results for impact velocity of 218 m/s and a temperature of 300 C.

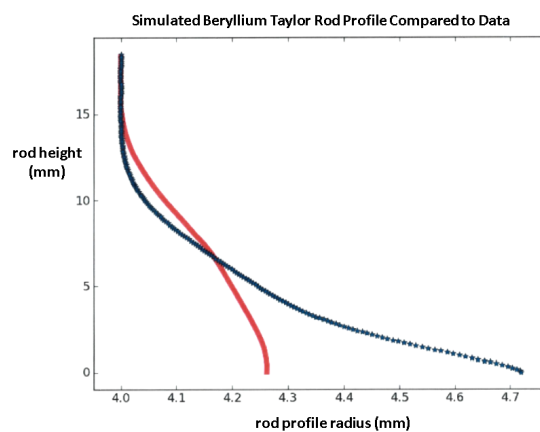


Figure 21: Simulation results for Taylor impact velocity of 218 m/s and a temperature of 300 C. The data is in red. Results are given for Chen PTW model, Sjuje PTW model, and Pedicini SG model.

5 Conclusion

This paper discusses recent work on validating PTW beryllium strength models with flyer plate and Taylor rod experimental data. The currently available flyer plate and Taylor rod data at LANL for beryllium is not sufficient for validating strength models due to the fact that the data is limited to low strain (typically less than 0.15). Also, based on simulations, the flyer plate data for beryllium is not sensitive to strength model settings. Of the six beryllium flyer plate experiments considered in this report, only one experiment demonstrated sensitivity to strength model settings when the settings are changed to induce a flow stress (or strength) difference of $\pm 25\%$. The other five flyer plate experiments do not show much sensitivity to strength settings, even when the settings are changed so that the computed strength changes by $\pm 50\%$. These issues imply the need for more high strain data at high strain rates for beryllium. The recent Z-machine experiments for beryllium is an example of data at high strain and strain rate (0.35 and $3e5s^{-1}$).

Another issue with the beryllium strength models is that the Hopkinson bar data, that is used to help calibrate the models at high strain rates (e.g., $3000 - 4300s^{-1}$), is limited to strain of about 0.15. This has resulted in significantly different calibrated PTW settings that can fit the Hopkinson bar and quasi-static data. These different calibrated PTW models can, then, have significantly different extrapolated behavior at high strain for high strain rates.

Also in this paper, the three strength models (Pedicini SG, Chen PTW, and Sjue PTW) are compared relative to flyer plate and Taylor rod data. The Pedicini SG model provides a good fit to the flyer plate data, but is not close to matching the experimental Taylor rod profiles. The Chen PTW model provides the best agreement to the flyer plate and Taylor rod data. The Sjue PTW model provides an adequate fit to the flyer plates and Taylor rods, while also giving the best match to the, high strain and high strain rate, Z-machine data.

References

- [1] Brown, J. L., Knudson, M. D., Alexander, C. S., and Asay, J. R. “Shockless compression and release behavior of beryllium to 110GPa” in *Journal of Applied Physics*, **116**, 2014.
- [2] Follansbee, P. S., and Kocks, U. F. “A constitutive description of the deformation of copper based on the use of the mechanical threshold” in *Acta Metallurgica*, **36**(1):81–93, 1988.
- [3] Chen, Shuh-Rong, and Gray III, G. T. “Summary of the PTW Model Parameters (U),” Los Alamos National Laboratory, Technical Report, 2004.
- [4] Preston, D. L., Tonks D. L., and Wallace, D. C. “Model of plastic deformation for extreme loading conditions” in *Journal of Applied Physics*, **93**:211–220, 2003.
- [5] Fugate, M., Higdon, D., Williams, B., Hanson, K., Wallstrom, T., Blumenthal W., and Chen, Shuh-Rong “Calibration of the Preston-Tonks-Wallace (PTW) Plastic Deformation Model: Fiscal Year 2010.” Los Alamos National Laboratory, Technical Report, LA-UR 10-00775, 2010.
- [6] Sjuje, S. “PTW model parameters” Los Alamos National Laboratory, Technical Report, 2015.
- [7] Prime, M. B., Adams, C. D., and Chen, Shuh-Rong. “Advanced Plasticity Models Applied to Recent Shock Data on Beryllium” Presentation Slides for APS SCCM, LANL Report, LA-UR 11-03766, 2011.
- [8] Steinberg, D. J. “Equation of State and Strength Properties of Selected Materials” Lawrence Livermore National Laboratory, Technical Report, UCRL-MA-106439, 1996.
- [9] Montoya, D. “Comportement Elastoplastique d’une nuance de Beryllium” Centre d’Etudes de Bruyères-le-Châtel, Technical Report, CEA-R-5595, 1992.