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Characterizing In-Flight Temperature of Explosively Formed Projectiles in CTH

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Abstract

Code validation against experimental data is vital in building confidence for the use of simulation software in modeling and system design. Temperature data is of particular interest in the study of hypervelocity impact, however the experimental measurement of temperature in such a regime is difficult. Novel developments in measurement techniques have enabled the measurement of in-flight hypervelocity projectile temperature. This is done by saturating the projectile with a magnetic field, in flight, and tracking its decay, which is related to material conductivity and therefore temperature. This study seeks to use CTH to computationally model experiments conducted by Uhlig and Hummer in which in-flight temperature of an explosively formed projectile (EFP) was measured. Comparing CTH results to physical observations serves as a benchmark for the accuracy of internal temperature calculations. Transient temperature results were shown to vary greatly with chosen strength model, with highest accuracy (3.4%) being attained with the Johnson Cook model. These results were on the same order as previously done ALEGRA simulations, though with differing variations between strength models, and EFP structure matches well with experimental x-ray.

Keywords: Explosively Formed Projectile, CTH, Transient Temperature Response

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1. Introduction

Computational approaches are becoming more and more prevalent. As such, a significant effort has been given to validating and benchmarking codes against experimental data to ensure accuracy in design and modeling. Temperature data is among the most difficult to acquire given limitations of measurement techniques. Recent development, however, have allowed for in-situ measurement of temperature within hypervelocity projectiles.

Developed by Uhlig and colleagues, experiments are designed such that the projectiles of interest pass through a series of inductance coils and are therefore saturated with a detectable magnetic field. Downrange, the decay of magnetism is tracked via passive sensing coils [1-4]. The decay time of the projectile's magnetic field is directly proportional to the material conductivity, which can be further correlated to in-situ temperature [5]. A schematic setup can be seen in Figure 1. Measured projectiles included slugs from both shaped charges and explosively formed projectiles.

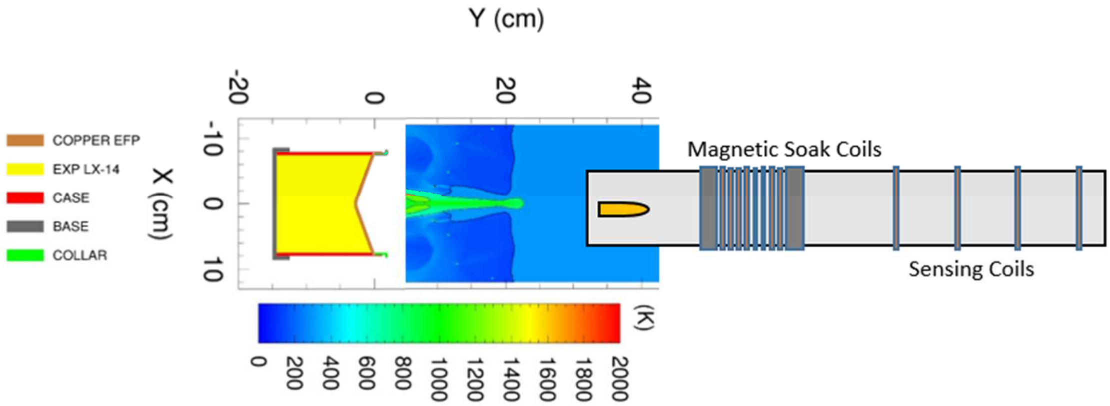

Fig. 1. A representative schematic, including the computation domain discussed here, of the temperature diagnostic used by Uhlig [1]. The projectile of interest is saturated with a magnetic field via soak coil, the decay of which is measured via inductance down range. Measurements were made at standoff of 45 and 65 cm respectively for shaped charge experiments.

Reported here, explosively formed projectile experiments were modeled using the CTH hydrocode, in an effort to benchmark computationally calculated projectile temperature against experimental measurements [6, 7]. A mesh resolution study was performed, with projectile velocity and slug radial temperature profile serving as convergence criteria. Various strength models were used to quantify the sensitivity of jet temperature to mechanical work. Other factors, such as the influence of fracture, were additionally explored. While experiment temperatures were indirectly calculated based on magnetic field decay and related conductivity, temperature calculations from CTH will be extracted directly for comparison. Previous studies using ALEGRA have simulated the electromagnetic field behavior and perform the same analysis as Uhlig to extract temperature [4].

2. Computational Setup

A two dimensional cylindrical domain was selected, to take advantage of axial symmetry, and enabling greater computational efficiency. The EFP itself was based on the same experimental setup used by Uhlig [1], including a copper liner, stainless steel casing, aluminum collar, polycarbonate base, and lastly the LX-14 explosive driver.

Throughout the initial detonation, deformation, and projectile formation, the copper liner experience drastic change in temperature and pressure, and as such the chosen equation of state (EOS) must be robust enough to incorporate such variations up to and, potentially, including melt. For this reason, a Sesame table was chosen over alternatives such as a Mie-Gruneisen EOS, though given the relatively lower pressures (when compared to other explosive setups), Mie-Gruneisen could be a viable choice in modeling. More straightforward in selection, the LX-14 explosive required the use of a burn model and was therefore approximated using the Jones-Wilkins-Lee (JWL) model.

Because of the large stresses and plastic deformations undergone, hydrodynamic behavior of the liner is expected and has been observed experimentally. However, the strength contributions cannot be neglected and have a fundamental role in the formation of the slug. This being the case, various constitutive models are implemented for comparison including Johnson-Cook (JO) [8], Steinberg-Guinan-Lund (SGL) [9], Preston-Tonks-Wallace (PTW) [10], and Mechanical Threshold Stress (MTS) [11]. Computational models used are included in Table 1.

Table 1. Computational models used in the simulation of an AC-14 shaped charge.

Material	Copper Liner	LX-14	304SS Casing	6061Al Collar	Polycarb. Base
Equation of State	Sesame Table	Jones-Wilkins-Lee	Mie-Gruneisen	Mie-Gruneisen	Mie-Gruneisen
Strength Model(s)	JO, SGL, PTW, MTS	Hydrodynamic	EPPVM	EPPVM	EPPVM

Resolution of computational domain was considered, to ensure the proper convergence of temperature and velocity values. Starting with a cell size of 0.1 cm/cell flat mesh, this was incrementally decreased to 0.02 cm/cell. Convergence was seen in both slug temperature and velocity at 0.03 cm/cell and was considered adequate. With this mesh, the characteristic thickness, that of the copper liner, has 16 cells through it and so may be sufficiently resolved. Slug velocity was found to be 3.1 km/s in good agreement with experimentally observed 3 km/s.

3. Results and Discussion

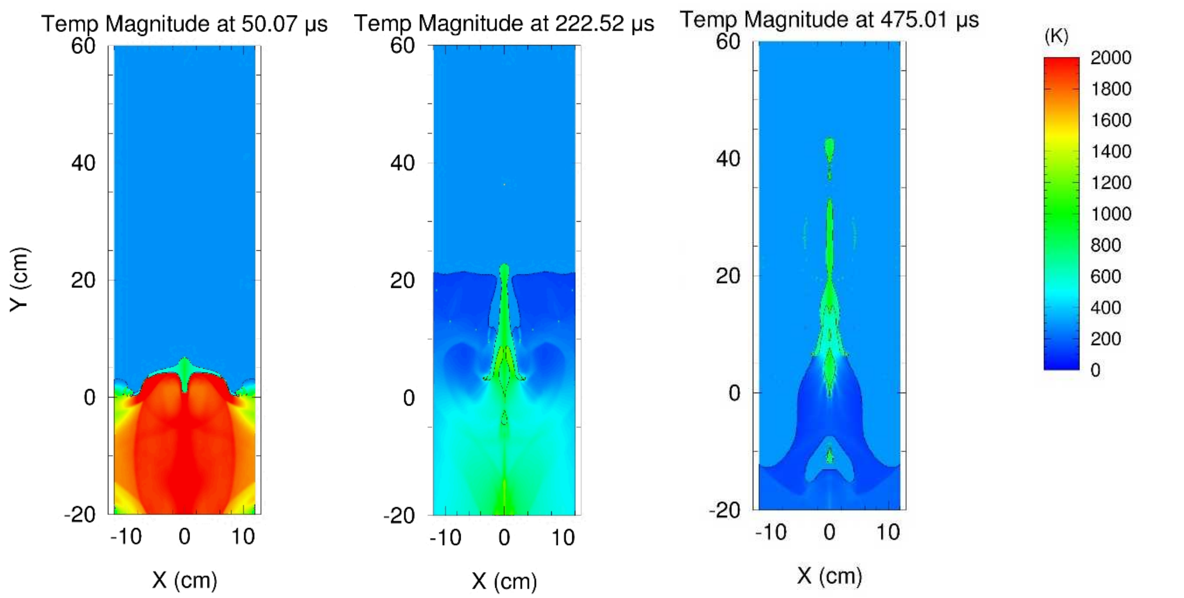

Fig. 3. Representative frames of the simulated shaped charge at times 50, 222.5, and 475 microseconds after detonation. Setup shown includes air and copper strength is modeled with PTW. A Galilean transformation of -2.1km/s is included to keep EFP in a consistent spatial domain.

The EFP initiated by an LX-14 explosive was simulated in CTH using the aforementioned parameters (Table 1). As would be expected, the blast wave propagating through the explosive, impinges the copper liner and forces a slug outward at approximately 3 km/s. Overall slug structure was consistent and compared well with experiment, despite slight variations between strength model being evident in separation, deformation, and temperature (Figure 4).

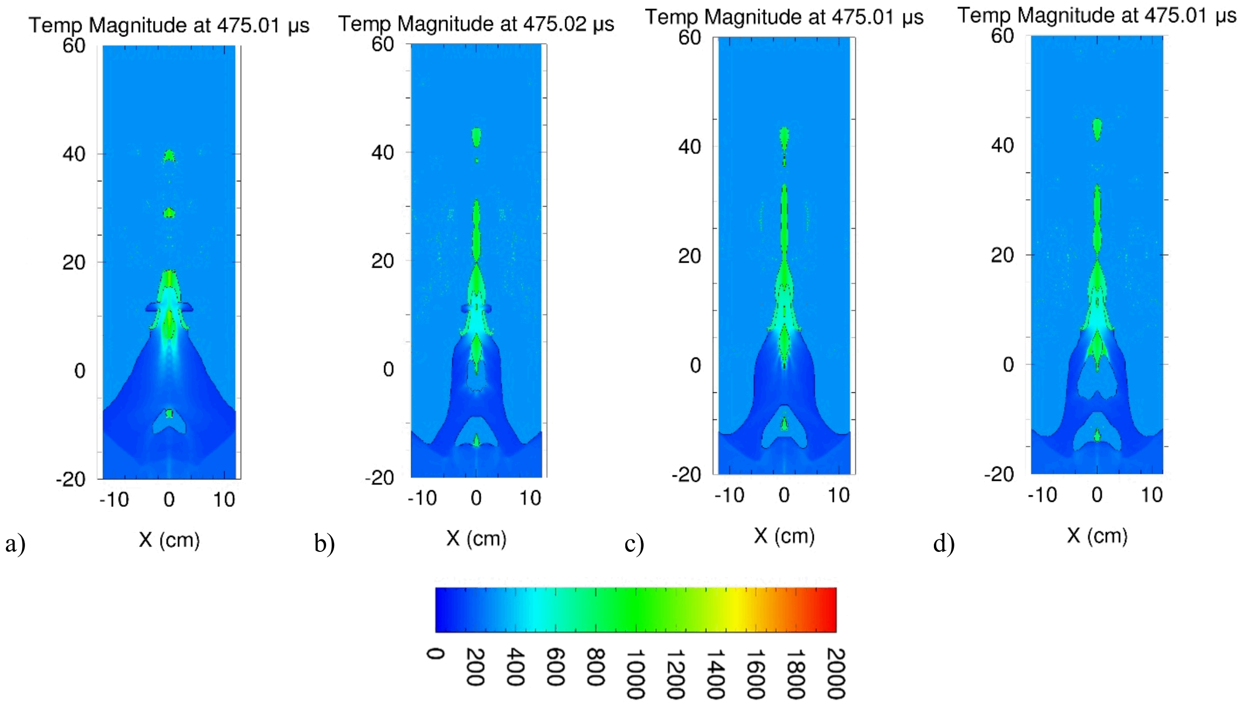

Fig. 4. Shaped charge jet structure and temperature post separation at 475 microseconds post detonation. a) SGL, b) JO, c) PTW, d) MTS.

First, consider the simulated temperatures. To allow for direct comparison to experiment, a radial temperature profile of the slug was analyzed. Several of these were taken longitudinally along the slug, allowing for variations within the bulk to be considered. The average of all profiles were then compared directly to the slug values experimentally measured. All simulations were comparable in accuracy to previous studies done in ALEGRA and, consistent with those works, temperature results varied greatly with chosen strength model. In the case of CTH, temperature was over predicted, with the Johnson-Cook model matching closest with experiment (3.4% error).

Given the softer, more concave, geometry of an EFP, there is lesser plastic deformation during liner collapse than within a shaped charge, with the material maintaining strength but attaining a much lower velocity. Neglecting heat transfer over such a small time scale, the only energy into the liner is the pressure-volume work energy and the material deformation, being conveyed through the EOS and strength models respectively, are the only contributions to increasing material temperature. The relationship between stress and temperature in this case is not trivial, copper first experiences both strain and strain-rate hardening prior to thermal softening and failure, with each regime having influence on the temperature.

The JO model relates yield stress and temperature as inversely proportional, where, as the ratio between material temperature and melt temperature goes to unity, the yield stress goes to zero, though the ratio is augmented by a material constant power law. Simplified, as the temperature approaches material melt, the yield stress goes to zero and the material begins to flow [8] When materials are at high temperatures near melt, this can be a problem as strength immediately goes to zero and, in our case, the copper would have artificially low strength. As mentioned, given the geometry (lesser stress concentration) of typical EFP systems, deformation is lesser than other explosively driven penetrators. As such, EFP slugs do not generally attain melt temperatures. Although JO dictates the relation of strength with respect to temperature (not only temperature), implicitly linked as they are, this infers a greater resistance to deformation is retained overall and so less overall temperature increase.

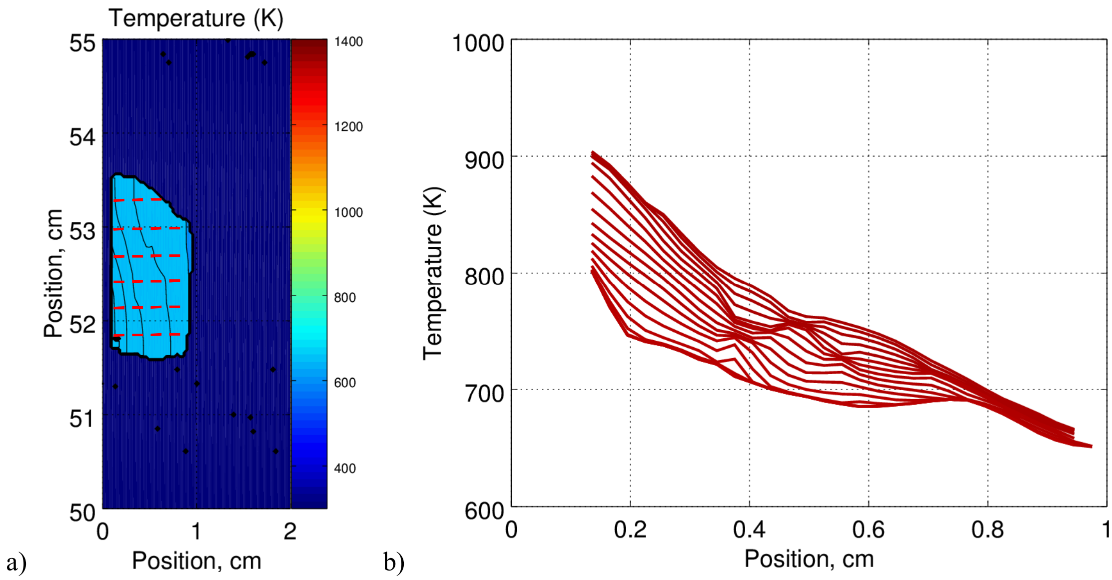

Fig. 5. a) MATLAB contour plot, used to analyze bulk jet temperature, note only material temperature of copper is considered. Red lines signify how radial profiles are generated b) Radial jet temperature profiles moving longitudinally up the jet tip.

Figure 5 demonstrates how the computational bulk slug temperature was calculated. Spatial temperature data was first extracted from CTH for each analysis, at which point a MATLAB scripts was written to generate a spyplot equivalent contour plot. From this, one dimensional radial lines (denoted as dashed lines) where extracted longitudinally in the y-direction, providing a series of radial temperature profiles. These were, in turn averaged giving the providing the bulk value reported.

Table 2. Comparison of CTH simulated bulk jet temperature against experimental data and ALEGRA simulations [3].

Software	Strength Model	Temp. (K)	Experimental Temp. (K)	Percent Error
CTH	Johnson-Cook	750	725±60	3.4%
	Steinberg-Guinan-Lund	950		31%
	Preston-Tonks-Wallace	820		13%
	Mechanical Threshold Stress	850		17%
ALEGRA	Johnson-Cook	675		6.9%
	Steinberg-Guinan-Lund	750		3.4%
	Preston-Tonks-Wallace	500		31%

SGL, PTW, and MTS, on the other hand, model the relationship between yield strength and temperature in a much more nonlinear manor. All three have some form (or combination of forms) of exponential, logarithmic, and even error function factors dependent on material temperature, and so depending on the specific behavior, the yield strength could either increase or decrease much more quickly [9-11]. However, this is inconsistent with results. For example, using the Steinberg-Guinan-Lund model results in the highest of measured bulk temperatures, while also showing a lesser amount of deformation, meaning higher yield strength is retained. Notably, CTH and ALEGRA simulations are inconsistent such that CTH calculations tend to be higher than the experiment as opposed to ALEGRA cooler predictions.

Now refer again back to Figure 4, with the potential role of each strength model now in mind. Despite calculated temperature varying around a hundred Kelvin or about the observed 725K, and discrepancies in EFP formation (slug geometry and separation), by in large, CTH predictions of EFP temperature behavior agree well with experimental measurement. This is especially true when considering the implicit experimental measurement error of 60K.

In addition to temperature, CTH predicts overall behavior of the EFP formation and trajectory well. The notable exception is the SGL model given, as was previously mentioned, the lesser amount of deformation undergone due to a sustained yield strength. Comparing CTH synthetic radiographs with those taken experimentally demonstrate the similarities as can be seen in Figure 6.

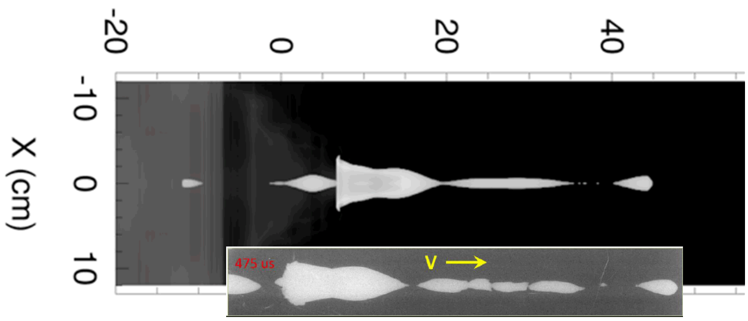

Fig. 6. CTH synthetic radiograph (PTW strength model), compared to images taken during an experiment.

To further investigate the implications of strength on EFP in-flight temperature, the additional factor of fracture model was including. For simplicity in the evaluation, a Johnson-Cook Fracture model was chosen [12]. Fundamentally, fracture is another form of plastic deformation, and so serves as another dissipative mechanism. That being the case, and with energy into the system being maintained, having another mechanism serving as an energy sink would increase the overall temperature of the material. Alternatively, material fracture increases the overall deformation of the material, or makes further deformation easer and so raising material temperature.

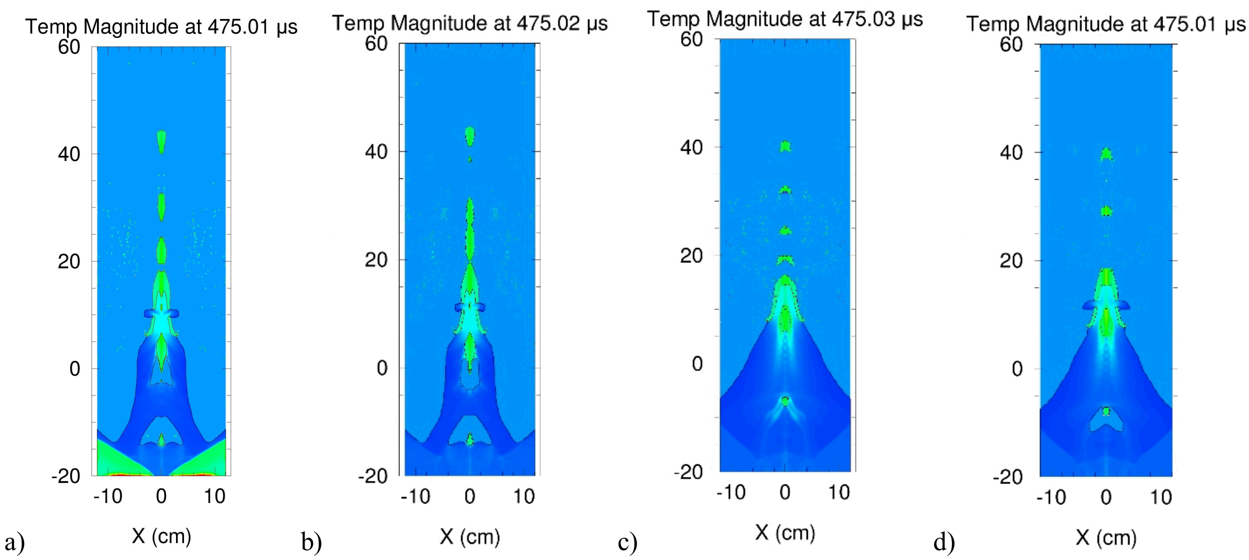

Fig. 7. Influence of including a fracture model in EFP formation. a) JO/Fracture. b) JO. c) SGL/Fracture. d) SGL.

Figure 7, shows both Johnson-Cook and Steinberg-Guinan-Lund strength models with and without Johnson-Cook Fracture. This is most apparent in the change in deformation between visuals. As would be expected, when fracture is included there are more separation points within the EFP body. In the cases of both SGL and PTW strength models, the addition of fracture manifests as expected from the previous discuss with a raise in temperature. However, the combination of JO strength and fracture models goes against this trend, lowering the temperature and incidentally the error to exactly that of the average experimental bulk temperature. It could be feasible that when fracture occurs, specifically separation between portions of the EFP body, there is no longer the tension between various portions of the projectile. Meaning, the addition of fracture can both increase and decrease over mechanical work on the EFP and so temperature increase.

Table 3. Comparison of CTH simulated bulk jet temperature against experimental data, all with the addition of Johnson-Cook Fracture.

Software	Strength Model	Temp. (K)	Experimental Temp. (K)	Percent Error
CTH	Johnson-Cook	725	725±60	0%
	Steinberg-Guinan-Lund	1000		38%
	Preston-Tonks-Wallace	841		16%

4. Concluding Remarks

Explosively formed projectiles are still, in many cases, uncharacterized experimentally, making modeling of such systems difficult. Both constitutive features and thermodynamic characteristics are vital in accurately predicting formation and projectile properties. With recent developments in in-situ temperature measurement of hypervelocity projectiles, data is now available to aid in the development of analytical and computational models describing the plastic formation of EFP projectiles.

Variations in strength model are particularly important given the large amount of plasticity seen in projectile formation, as well as unique behavior at observed strain rates of 10^4 to 10^5 s^{-1}. Assuming equal system energy at detonation, each strength model budgets differing amounts of energy to varies strain, and mechanical work phenomena, and thus calculation of internal energy and so temperature change. In this study, Johnson-Cook, Steinberg-Guinan-Lund, Preston-Tonks-Wallace, and Mechanical Threshold Stress models are used to simulate an LX-14, stainless steel encased, copper lined, explosively formed projectile. Strength modeling is the critical factor in modeling for temperature benchmarking as the only energy into the material is that of deformation and pressure-volume work. Comparing across the board, Johnson-Cook most accurately predicts bulk temperature to under 4% error with experimental observations, with error being 0% (in relation to the experiment mean) when Johnson-Cook Fracture is included. All other models are between 10% to over 30% warmer than observed. While deviations of a similar magnitude occurred with previous simulations done in ALEGRA, those were consistently cooler than experiment.

Overall, CTH was shown to accurately simulate the described EFP experiment, especially when considering error implicit to experimental measurements, which would reduce error even more.

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