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Yield Analysis of Nuclear Fireballs

A. C. Delmastro, G. D. Spriggs

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Film Rescanning and Re-Analysis Project Progress Report

Disclaimer

Auspices Statement

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II. Introduction

During the 1940s, 50s, and 60s, there were 210 atmospheric nuclear tests. Every test was extensively recorded with high quality motion picture films and photographs, providing a unique historic record, containing ~10,000 films, with a total of ~22 million frames of information. Much of what is known about the effects of nuclear weapons has been obtained from these tests.

Of the 210 atmospheric nuclear tests, 185 tests can be analyzed, representing five different shot types: Airdrop, Tower, Balloon, Surface, and Barge. The other 25 shots were either safety experiments (i.e., low yield) or are currently classified.

One major focus of the Film Scanning and Re-Analysis project is to determine more accurate yields for each shot with more precise measurements. The yield corresponds to the amount of energy released during the explosion. Fireball yields are based on an equation derived by Sir Geoffrey Taylor[1],

$$R = \frac{1}{2K^{1/5}}\left(\frac{\theta Y_{sw}}{\rho_0}\right)^{1/5} t^{2/5} , \tag{1}$$

which relates the shockwave radius as a function of time to the amount of energy released during the detonation. *R* represents the shockwave radius and *K* is a proportionality constant that depends on the ratio of the heat capacities of the gas inside of the fireball, and θ is a geometric factor equal to 1 for an airdrop and 2 for a surface shot.

We can define the combination of variables on the right-hand-side of Taylor's equation as a quantity known as R_1. That is,

$$R_1 = \frac{1}{2K^{1/5}}\left(\frac{\theta Y_{sw}}{\rho_0}\right)^{1/5} . \tag{2}$$

At an absolute time corresponding to ~t_{min}, the shockwave begins to follow Taylor's equation for a short period of time (referred to as the asymptotic region). The proportionality constant in Taylor's equation, R_1, can be easily measured. The yield can then be determined via,

$$\left(\frac{\theta Y_{sw}}{\rho_0}\right) = K\left(2R_1\right)^5 . \tag{3}$$

The shockwave is easily observed at times greater than ~t_{min}. However, the shockwave cools as it expands. Once it reaches the Draper temperature (798 K), the shockwave disappears off the film. This is due to the fact that nuclear fireballs act as blackbody radiators and, once the Draper temperature is reached, the shockwave front no longer emits light in the visible light spectrum. Below the Draper temperature, all of the light is emitted in the infrared region. Since most films can only capture light in the visible spectrum (except for certain specialized films that are sensitive to infrared). As a result, yield determination are made in the vicinity of ~t_{min}.

Measuring the shockwave is not an easy feat. During the atmospheric testing era, scientists used a Kodagraph, which projected a fireball image onto a circular grid that was used to measure the radius. Several workers would read the same film to help eliminate any discrepancies and/or biases introduced during the reading process.

Fig. 5.2 Kodagraph Film Reader

Image 1: Kodagraph used to measure nuclear fireballs during the atmospheric nuclear testing era.

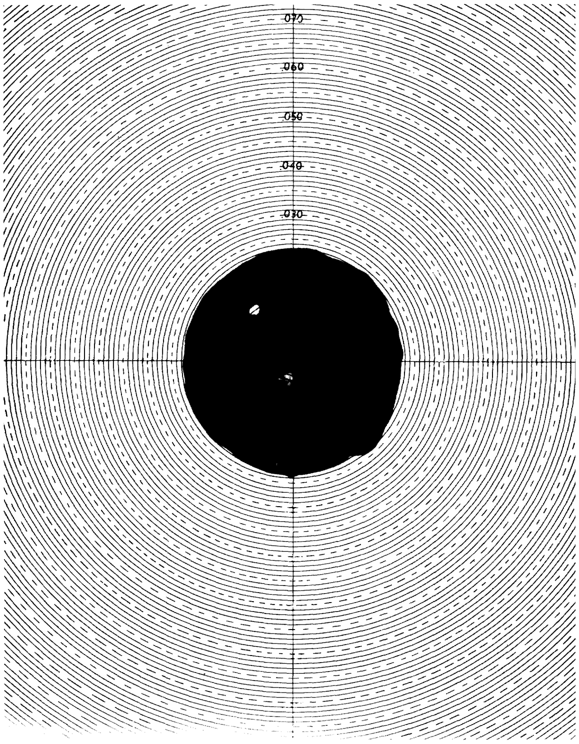

Fig. 5.1 Fireball Image with Overlay Grid

Image 2: Example visualization of fireball projection with overlay grid.

This method of using fireball projections with a Kodagraph to measure the fireball radius produced significant error and was prone to bias. Modern-computer techniques allow for high resolution measurements of the scanned films. Despite the improvement in modern-day technology, certain film types allow for more accurate radius measurements than others.

Rapatronic cameras are high-speed magneto-optical shutter, single-frame cameras, which provided photographic records of the size of the fireball at various points in time during the evolution of the shockwave front. Rapatronic photography concentrated in the time interval 0 to 100 microseconds. These cameras could provide very accurate measurements of the fireball radius at very precise points in time.

In comparison, even though Fastax and Eastman cameras could run at relatively high speeds, the *time per frame* was still on the order of 0.4 milliseconds per frame. Since these types of cameras were not synced to the time-of-detonation, it was very difficult to establish an accurate time scale for these types of cameras.

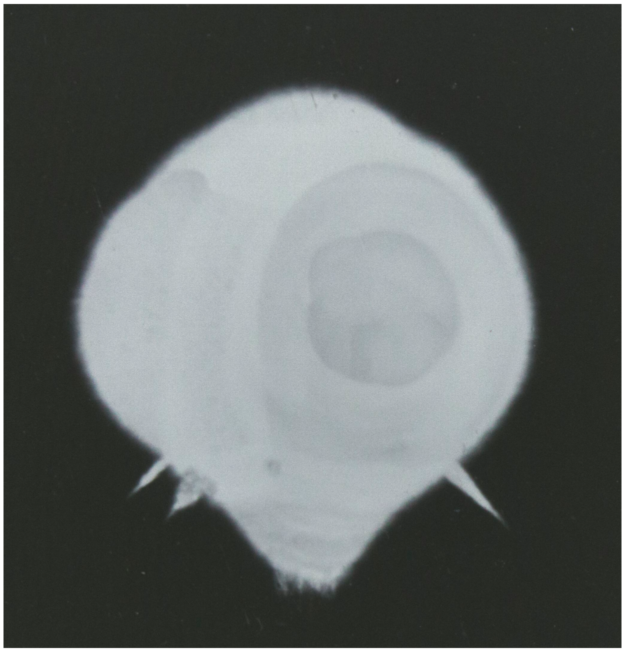

Image 3: Rapatronic Plate – Bee_28023 at 1 ms

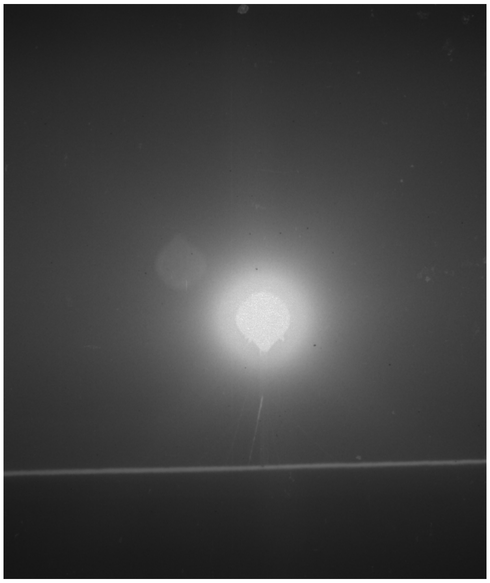

Image 4: Fastex Camera – Bee_28010 at 1 ms

Both images (3&4) were obtained from the same camera station, and the relative size of the two images are drawn to scale. Therefore, due to the high resolution and precise timing nature of Rapatronic plates, these plates offer valuable data in calculating the yields of the numerous nuclear detonations.

III. Research Objectives

The objective of this interim report is to describe recent efforts to calculate accurate yields for all 185 unclassified atmospheric shots using new measurements from the original films. These revised yields will be directly compared to the historical yields from NV 209, by EG&G in 1963, and by Eilers in 1999.

IV. Methodology

The fireball films and the Rapatronic plates were re-analyzed using a software application called PixelStick. Unfortunately, not all fireballs are perfectly spherical. As demonstrated below, fireballs do exhibit irregular shapes caused by the type of shot as well as by the mass-to-yield ratio. While surface shots have a hemispherical shape, barge shots have an ellipsoidal shape, where the height of the shockwave grows faster than the horizontal width:

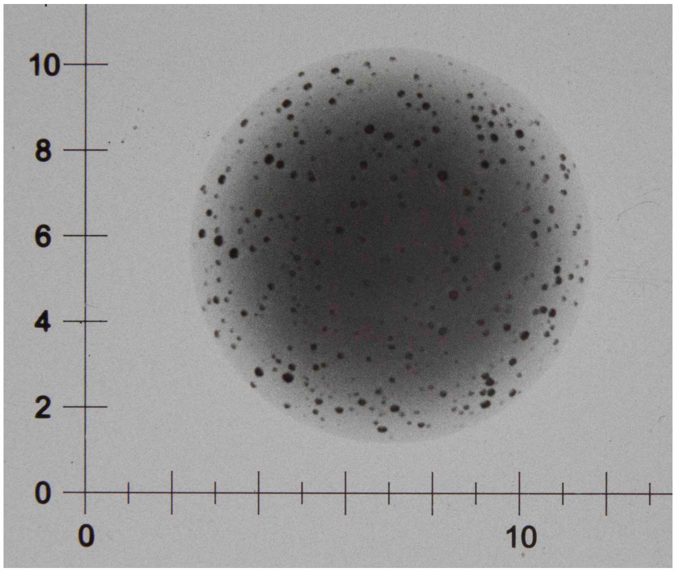

Image 5: An example of a Rapatronic Plate from an airdrop (Climax) with scaling axes

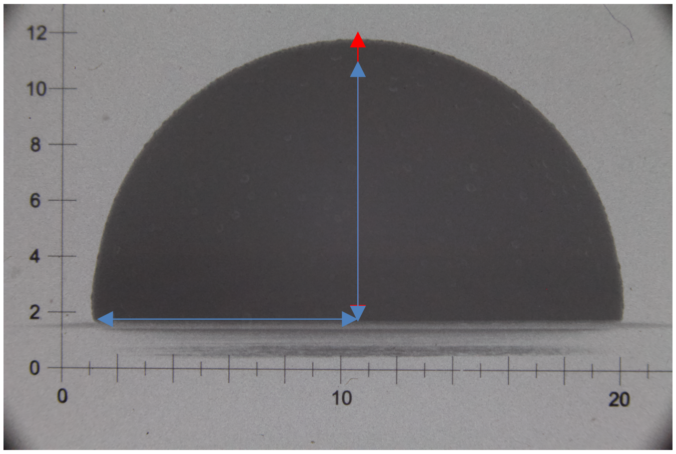

Image 6: An example of a barge shot (Pisonia_53041)

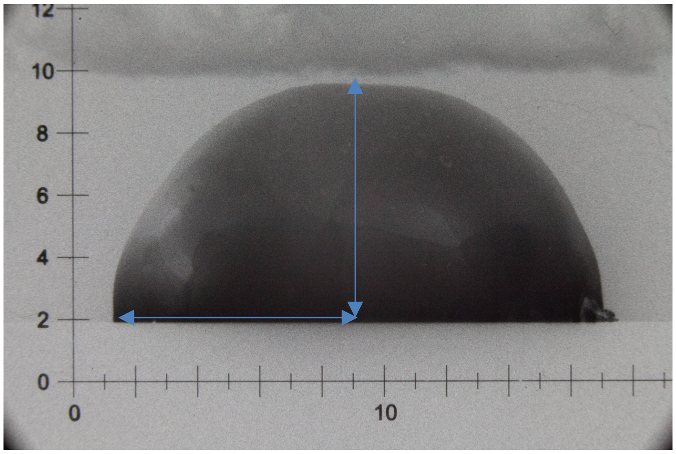

Image 7: An example of a surface shot over land (Mike_16150).

Balloon shots also cause the fireball to be distorted in the vertical direction as well as creating "wings" where the balloon is tethered to the ground via a wire. The bulge at the top of the fireball is the remnants of the helium balloon and is ignored during radius measurements.

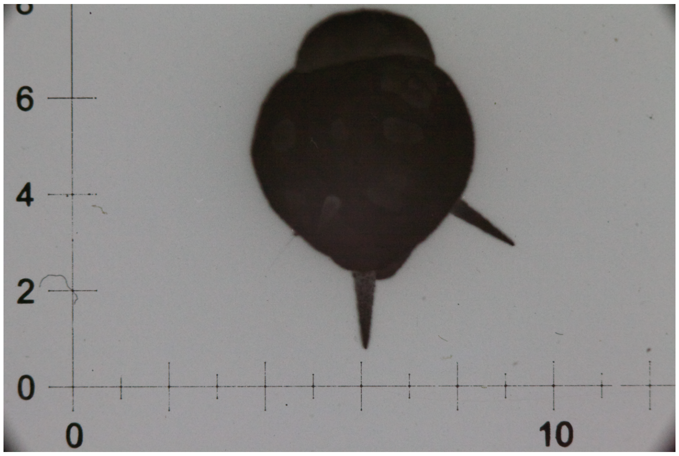

Image 8: An example of a balloon shot (Newton_43654).

Tower shots characteristically are very distorted, which is caused by the shockwave interacting with the various walls of the tower cab.

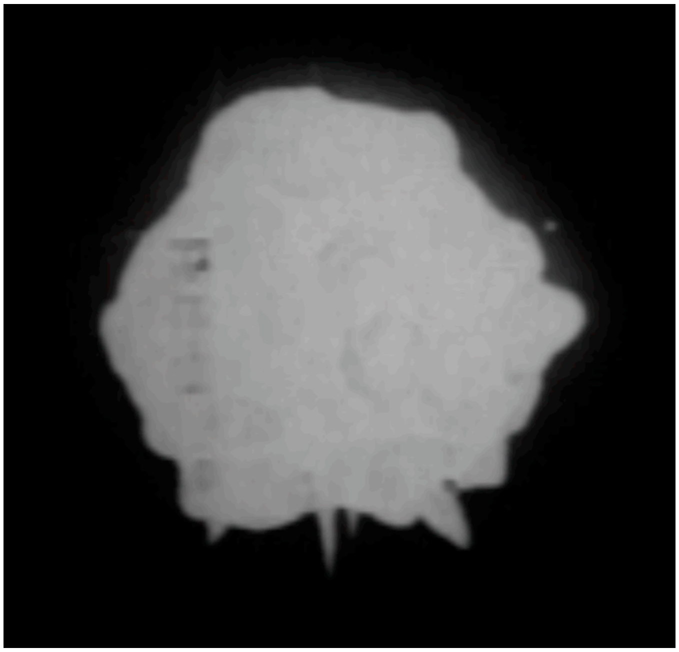

Image 9: Example of a high mass-to-yield ratio shot

Since these fireballs are not perfectly spherical, it makes measuring the diameter more difficult. As a result, when measuring the diameter, it is important to choose a diameter whose spherical volume will encompass the full volume of the irregularly-shaped fireball, including all the protruding bumps.

Once the radii for each Rapatronic plate have been calculated, the scaled radius,

$$R\left(\frac{\rho_o}{\theta Y}\right)^{\frac{1}{3}}, \qquad (5)$$

can be determined and plotted against HYCHEM's prediction and Taylor's solution:

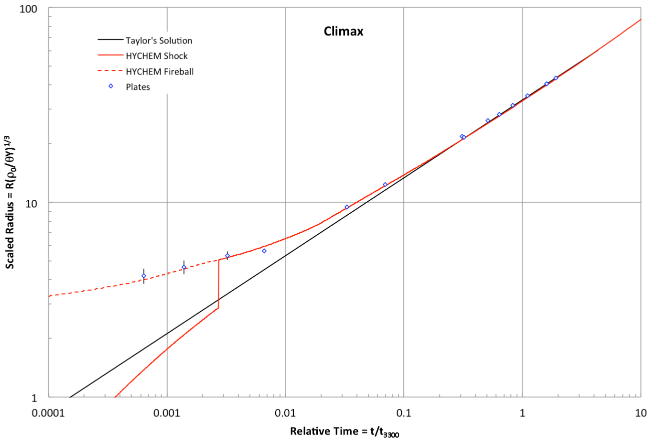

Figure 2: Scaled radius as a function of relative time (Climax)

All radius values at relative times greater than 1 can then be used to calculate the yield using equation (3).

For shots in which we could not find the Rapatronic plates, the rotating-prism cameras were re-analyzed. As described earlier, the fireball films are not synced to the time of detonation and, as such, an accurate time scale is very difficult to establish. Nevertheless, if several rotating-prism cameras of the same test are re-analyzed, the results can be averaged to obtain a fairly average yield estimate.

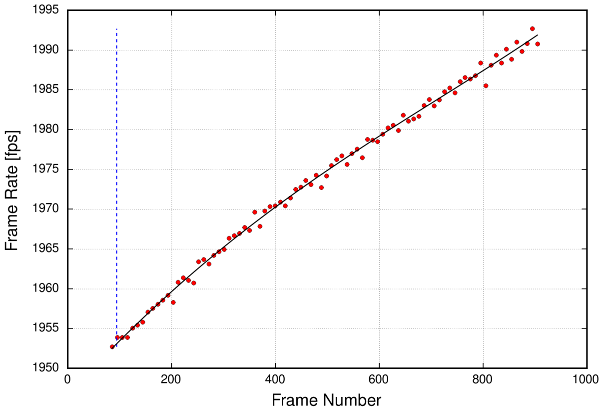

Figure 3: Example of a Frame rate vs. frame number curve (Wasp Prime 29300)

V. Historical Analysis

As mentioned earlier, the correct value of K has been highly debated throughout the atmospheric nuclear testing era. As discussed in reports dating from 1947 to 1956, EG&G used a value of 1.294e-14 [2]. In 1963, the value of K was readjusted to K = 1.272e-14.[3]. In 1999, Eilers et al. modified the value to K = 1.166e-14 [4]. The current value of K used for yield measurements in the Film Scanning and Re-Analysis Project is K = 1.224e-14. This value was obtained by normalizing the fireball yields to the average radchem yields.

If one assumes the shockwave radii measured by EG&G are correct but uses the different values of K to estimate the yields, some major differences appear. This is demonstrated in figure 4, which shows the ratio of the revised yields using the original EG&G data with respect to the historical yields from 1956, 1963, and 1999. Eilers used a lower value of K; therefore, the ratio with respect to Eiler's yields is approximately greater than 1. However, K is not the only contributing factor to the yield. Differences in air density values also estimate different yields. As a result, the ratio is not necessarily equal to a constant value; instead, there is significant scatter for all three ratios.

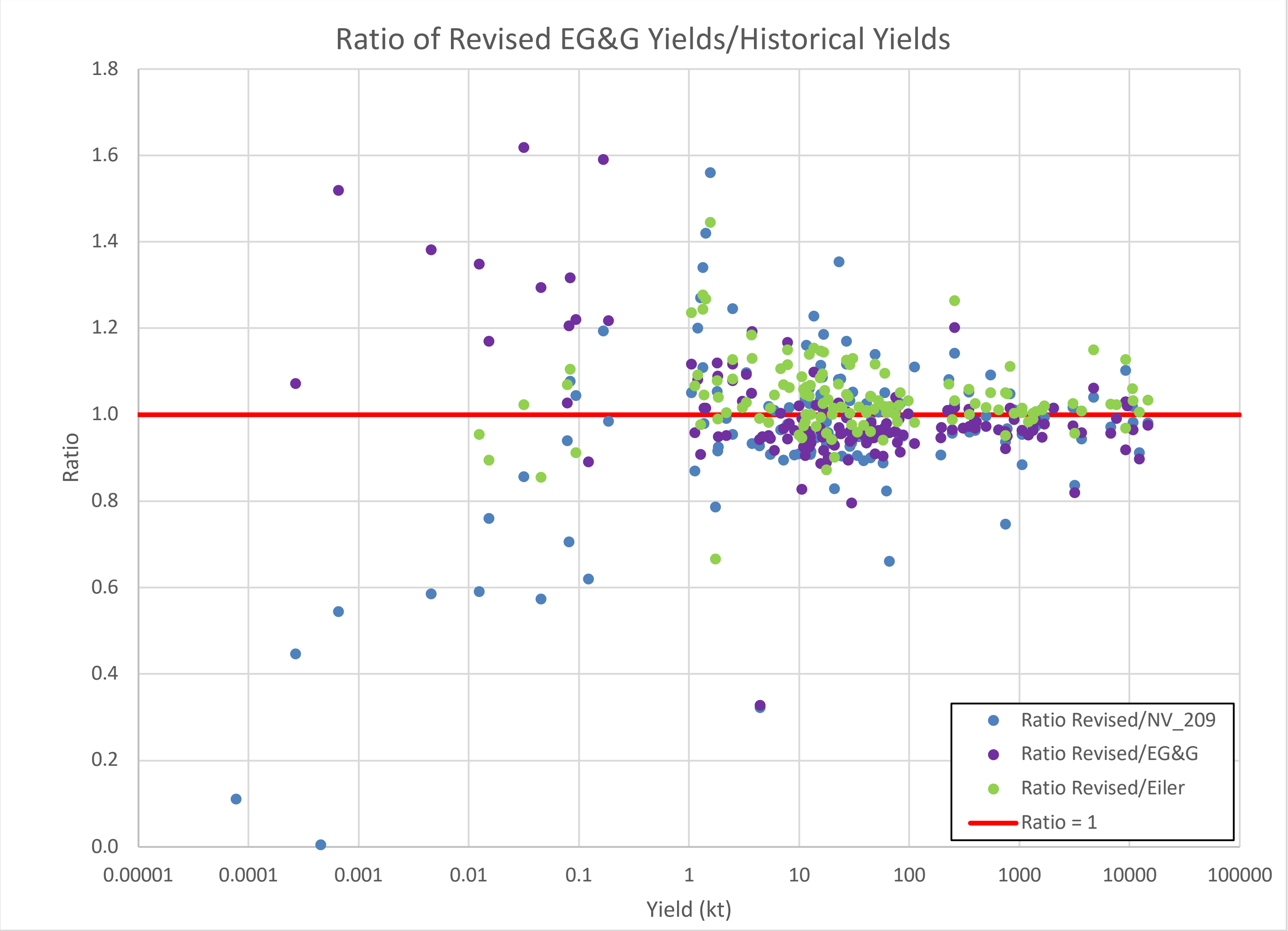

Figure 4: Comparison of ratios of revised EG&G yields and historical yields

VI. New Preliminary Results

In this recent work, 72 shots have been re-analyzed using modern image-processing techniques. The estimated error of these new yield estimates is ~2.5%. This is significantly less than the error from the historical yields. This error also incorporates the 1% error due to the air density. It appears that, for lower yield shots, the ratio is greater than 1. As the yield increases, the ratio stabilizes around a ratio of 1, though there remains a significant amount of scatter.

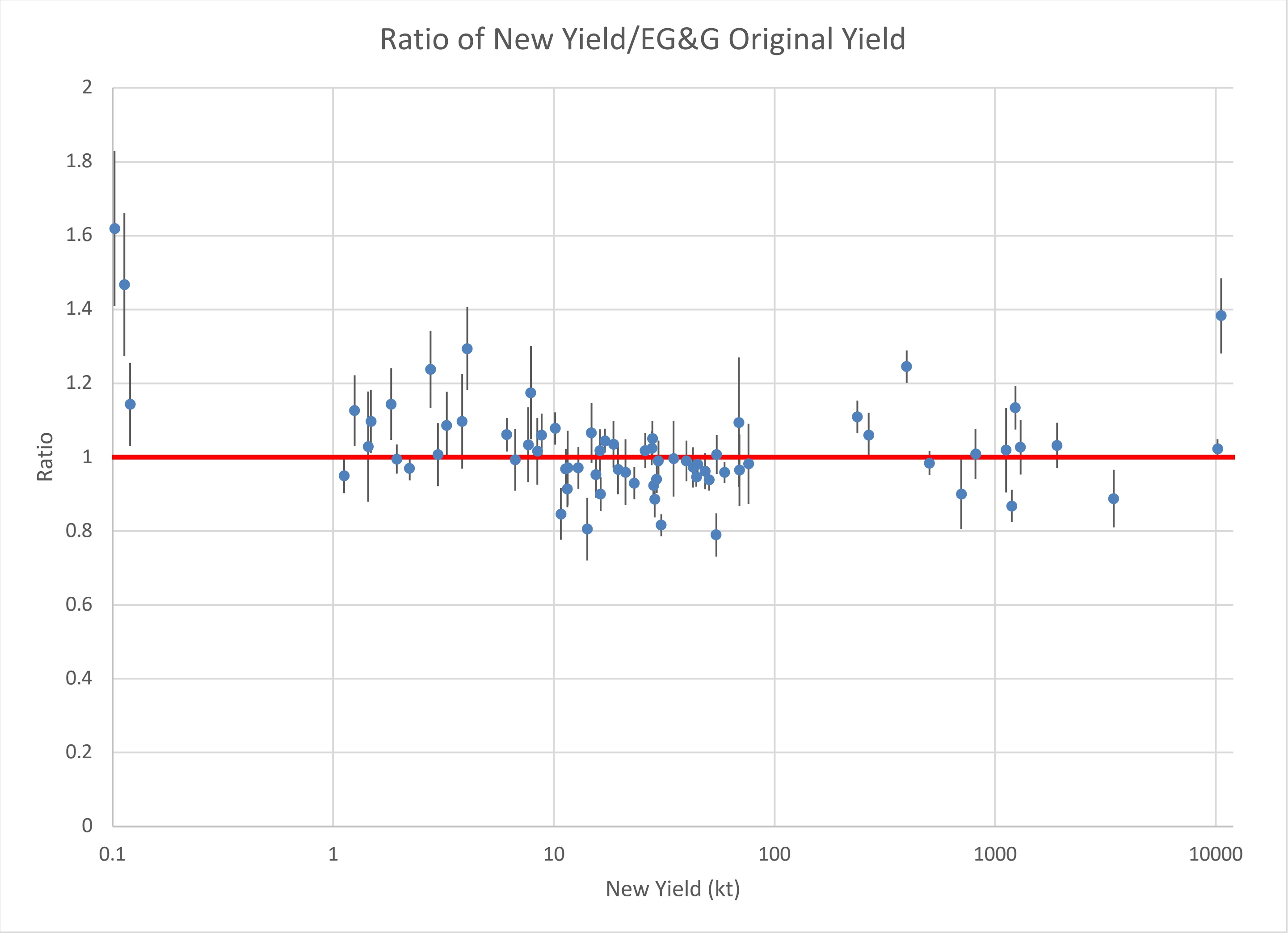

Figure 5: Ratio of New Yield to the Original EG&G yields from 1963

VI. Future Research

Every nuclear test that has Rapatronic plate data in the vicinity of t_{min} has been re-analyzed to obtain a more accurate yield estimate. However, there remains many nuclear tests that have not been re-analyzed for yield since the Rapatronic plate data does not extend into the t_{min} region. For these tests, we are currently re-analyzing rotating-prism fireball films.

When re-analyzing the fireball films, the radius for each frame is currently being measured using *PixelStick*. Measuring each frame by hand, however, is a very long and tedious task, especially for fireball films of high-yield shots or with fast frame rates.

A new computer code is being developed by Aaron Kawahara (HEDP summer student) to automatically measure the radius of each frame. By automating this procedure, it will save time as well as remove analysts' bias, thus lowering error in measurement. Not only will the new radii measurements be useful for calculating more accurate yield estimates, these data will also be very helpful in estimating the surface temperature of a nuclear fireball.

The Rapatronic plate data at early times is also being used to determine a more accurate time scale for each film. We are currently working on a technique involving multiple films of the same tests to improve these data. An example of a multiple film analysis is shown in Figure 6. Based on these data, the uncertainty of the yield is currently estimated to be less than 0.5%.

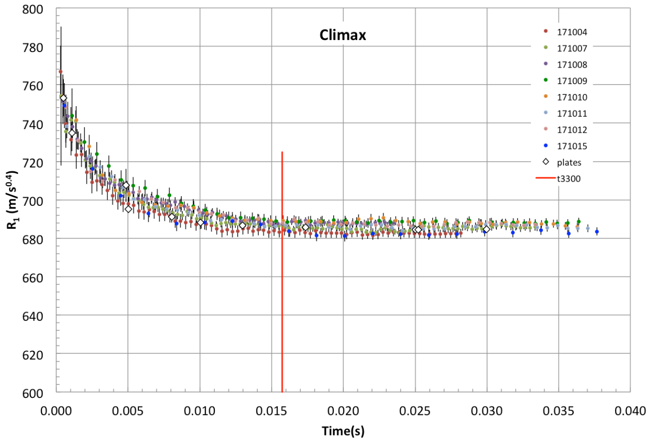

Figure 6: Measured values of R_1 for Climax

VII. References

[1] Taylor, G. (1950). The Formation of a Blast Wave by a Very Intense Explosion. I. Theoretical Discussion. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *Volume* 201, No. 1065, pp. 159 – 174.

[2] (March 1956) *Technical Photography, Operation Castle*, EG&G Report EGG-WT-955.

[3] Cox, A. N., Eilers, D. D., and Glover, E. M. (1963). *A Provisional Calibration of Hydrodynamic Yield Scales*, Los Alamos Scientific Laboratory, Report LAMS-2792.

[4] Eilers, D. D., Westervelt, D. R., and Davis, C. G., (1999). *Fireball Yields: Absolute Energy Scale*, Los Alamos National Laboratory, LA-CP00-100.

VIII. Acknowledgements

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