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New Yield Estimates for Nuclear Detonations Over Water

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One of the primary methods used by the United States to estimate the yields of atmospheric nuclear tests performed in the 1940's, 50's, and 60's was to film each detonation with a high-speed camera, measure the blast radius as a function of time, and then use Taylor's spherical blast wave equation to calculate the source energy (i.e., the yield). For surface detonations, the yield in Taylor's equation was assumed to be twice as large as the actual yield to account for the energy reflected from the surface, assuming the ground was a perfect reflector. Recent simulations of surface detonations over water (referred to as *barge shots*) have shown that Taylor's equation must be modified further to account for material entrainment and heat losses. We have computed this lost energy using a high-order radiation-hydrodynamics code to determine the reduction in blast radius vs. time. By analyzing simulation data in the same manner as film data, we have determined that a yield correction factor of 1.27± 0.04 should be applied to the barge shots.

Keywords: atmospheric nuclear test; blast wave; radiation-hydrodynamics; numerical simulation

I. INTRODUCTION

Most blast effects of nuclear detonations scale with yield. Accurate yield estimates are essential to the development and validation of computer codes used to simulate nuclear weapon effects in a wide variety of environments. Between 1945 and 1962, the United States conducted 210 atmospheric tests.[1] The film strips that recorded these tests are currently being re-evaluated at Lawrence Livermore National Laboratory in an effort to more accurately determine the nuclear yields. Visual inspections have identified significant asymmetries in the blast waves for detonations over water, as seen in Figure 1.[2] In particular, the shockwave radius in the vertical direction is typically ~10% larger than its horizontal radius. Furthermore, we have observed that the visible light emission time of the fireballs (aka *glow time*) over water are approximately ~25%

of the glow time for free-air fireballs of similar yield. We have long suspected that the anomalies in symmetry and glow time were due to a combination of water entrainment and its heat of vaporization. The purpose of this technical note is to quantify the errors associated with blast asymmetry on the historical yield estimates performed by Edgerton, Germeshausen, and Grier (EG&G. Inc.).

II. THEORY

Taylor derived an equation for the radius of a spherical blast wave as a function of time, for a given energy deposition in an atmosphere of uniform density.[3] In order to account for interactions between the blast wave and Earth's surface, we can write a modified version of Taylor's equations as follows,

$$R = R_0 \left(\frac{\theta Y}{\rho_a} \right)^{1/5} t^{2/5} \tag{1}$$

where R is the shockwave radius, R_0 is a constant that depends on the adiabatic index (γ) of air, Y is the yield (source energy), ρ_a is the ambient air density, t is time, and θ is a constant we have added to Taylor's equation in order to model differences between a spherical shockwave ($\theta=1$) and a hemispherical shockwave ($\theta=2$). Consistent SI units are assumed for all variables. In a more condensed form, the blast radius can be written,

$$R = R_1 t^{2/5} \tag{2}$$

where R_1 is defined as,

$$R_1 = R_0 \left(\frac{\theta Y}{\rho_a} \right)^{1/5} \tag{3}$$

A common experimental practice for yield determination is to plot a series of R_1 values calculated from the pressure transducer data and/or film measurements of R vs. t; i.e.,

$$R_{1,i} = \frac{R_i}{t_i^{2/5}} \tag{4}$$

These plots exhibit a region of approximately constant R_1 value during brief times when the shockwave is behaving in accordance with Taylor's equation. Once the R_1 value of an event has been established, the yield can be calculated as

$$Y = \frac{\rho_a}{\theta} \left(\frac{R_1}{R_0} \right)^5 \tag{5}$$

If the shockwave expansion follows Taylor's solution then the yield estimate from this procedure will closely correspond to the true yield of the device. However, if the expansion has been slowed by material entrainment, heat lost to vaporization etc., as we suspected happens in barge shots, then this procedure will underestimate the actual yield.

III. METHODOLOGY

We investigated the effects of blast wave asymmetry on yield estimates by performing series of computer simulations using the Miranda code.[4,5,6,7,8] Miranda solves the radiation-hydrodynamics equations for multicomponent flows in an Eulerian frame of reference. The Navier-Stokes (hydro) equations are spatially discretized with a tenth-order compact-finite-difference scheme and temporally integrated with a fourthorder Runge-Kutta method. The code solves the radiation transport equation with a second-order fully implicit gray diffusion algorithm. We verified the code against Taylor's equation for a 100-kiloton blast in air, with a constant adiabatic index of 1.4, and found the shock location in the simulation matched Taylor's prediction to within the one-meter spacing between mesh points.

The production runs of blasts over water were performed using tabular Planck and Rosseland opacities, a tabular equation of state for air, and a two-phase analytic equation of state for water.[9] For grid cells containing both water and air, Miranda combines the separate equations of state according to a mixing algorithm, which brings both species into pressure and temperature equilibrium.[10,11] The simulations were initialized in hydrostatic equilibrium, with pressure and density gradients balancing gravity, such that, for the zero yield case, both air and water remained quiescent.

Two series of runs were performed to benchmark the calculations. In the benchmark series, we simulated detonations of various yields over a perfectly reflecting surface with no entrainment. The radius vs. time data were analyzed in the aforementioned manner involving frame by frame radius analysis to confirm that the calculated yields matched the yields input to the simulations. In the second series of runs, the ideal surface was replaced by water and all the associated physics of material entrainment, heat transfer, phase changes etc. were included. As anticipated, the simulated blasts over water became asymmetric, as shown in Figure 2, and a significant amount heat was absorbed by the water.

IV. RESULTS

Using the benchmarked simulation data, we computed a unitless surface correction factor for water by taking the ratio of R_1 values,

$$C_{surf} = \left(\frac{R_{1,ideal}}{R_{1,water}} \right)^5 . \tag{6}$$

Figure 3 displays the correction factor for eleven cases, ranging from ~1 to ~14,000 kilotons. Uncertainties in these correction factors stem from small variations in R_1, which we quantify by their standard deviations and display as error bars. The correction factors all fall within the range 1.27± 0.04, indicating that the barge shots had yields ~27% higher than their historical estimates. Our numerical reassessment therefore suggests that the yields of all the barge shots should be revised upwards by 27% ± 4%.

To substantiate this correction factor, the shockwave arrival-time data along the surface for the barge shots from Operation Castle were compared to a solution given by Kinney and Graham. Figure 4 shows the comparison between the arrival-time data found in the test director report, WT-902 (EX), and the Kinney and Graham solution. The data was scaled using the uncorrected yields quoted in NV-209. Figure 5 shows the same data, but scaled using the newly-measured, corrected yields obtained from the Film Scanning and Reanalysis Project. As can be noted, there is a significant improvement in the comparison.

V. CONCLUSIONS

The systematic underestimation of nuclear yields for Pacific Ocean tests was partially a result of failure to account for the reduction in shock speed along the water's surface compared to shock speed across an ideal surface. With the advent of high-performance computing, numerical simulations have become capable of capturing previously neglected physics; e.g., the mass of water vaporized by the fireball and entrained by the shock, such data is not directly available in the films. By matching simulations to key observables in the films, data from the simulations can then be extracted and used as surrogate experimental data. Further studies involving both films and simulations are currently underway.

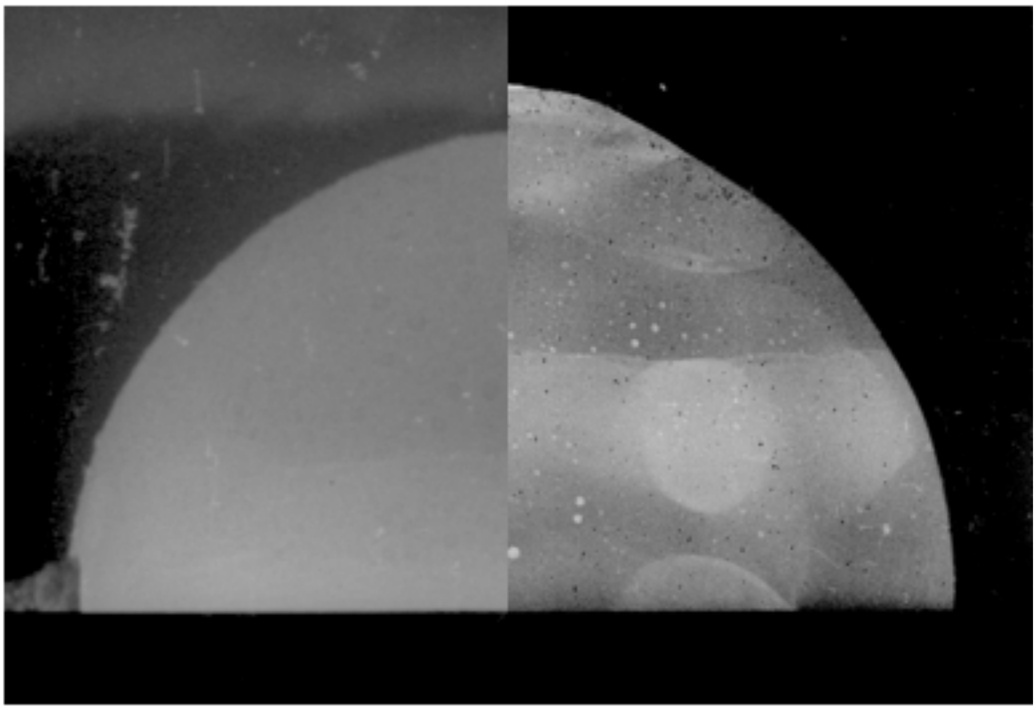

Figure 1. The Bravo event over land (left) vs. the Yankee event over water (right). The feature at the base of Bravo is an instrumentation tunnel vaporizing from the X-rays.

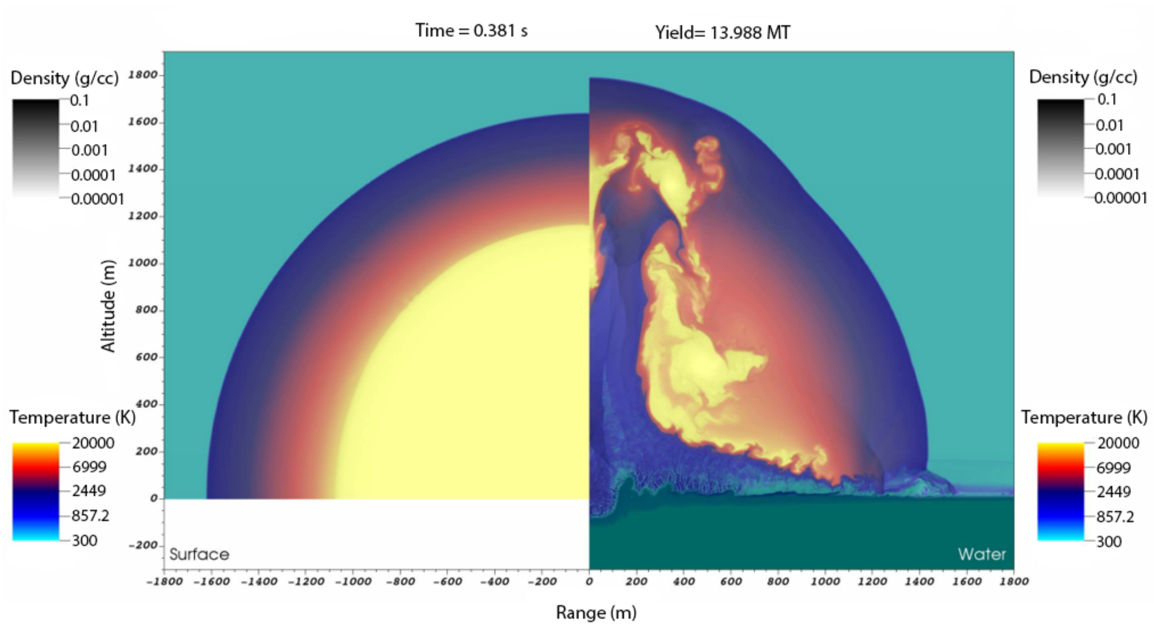

Figure 2. Miranda simulations of a blast over a perfectly reflecting surface (left) vs. a blast over water (right).

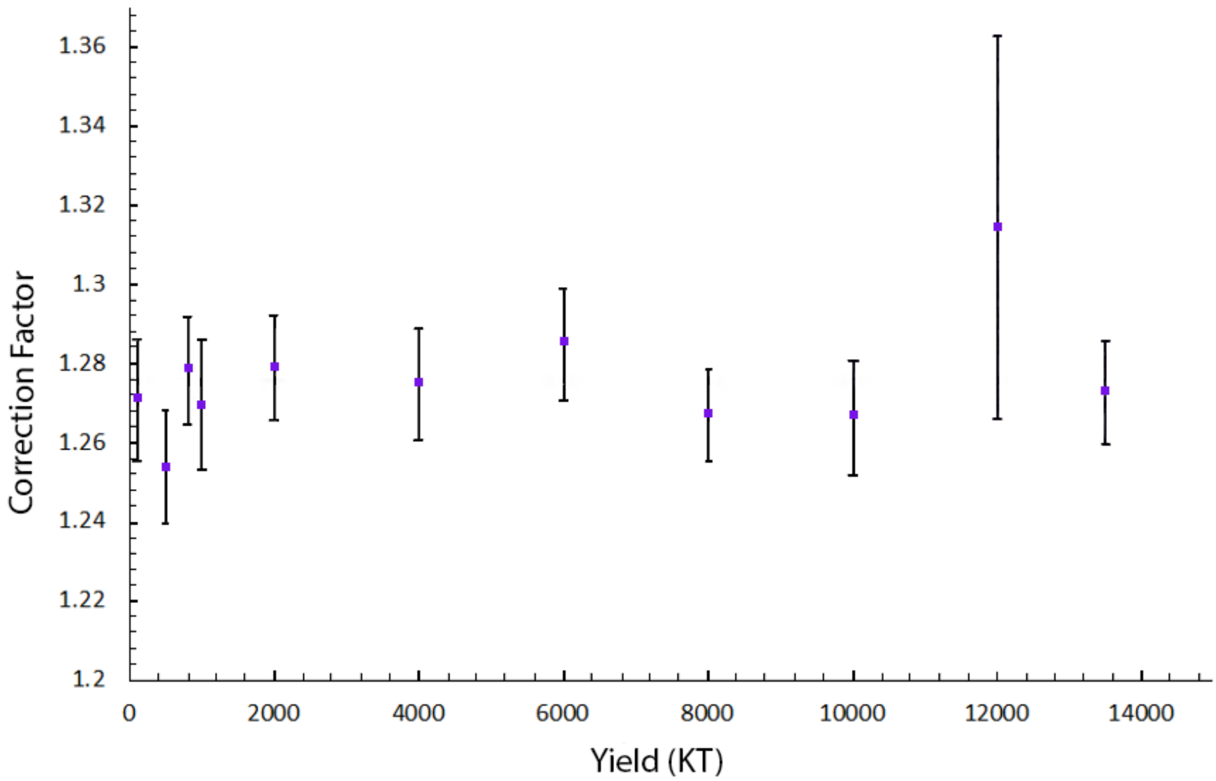

Figure 3. Surface correction factors obtained from the simulations.

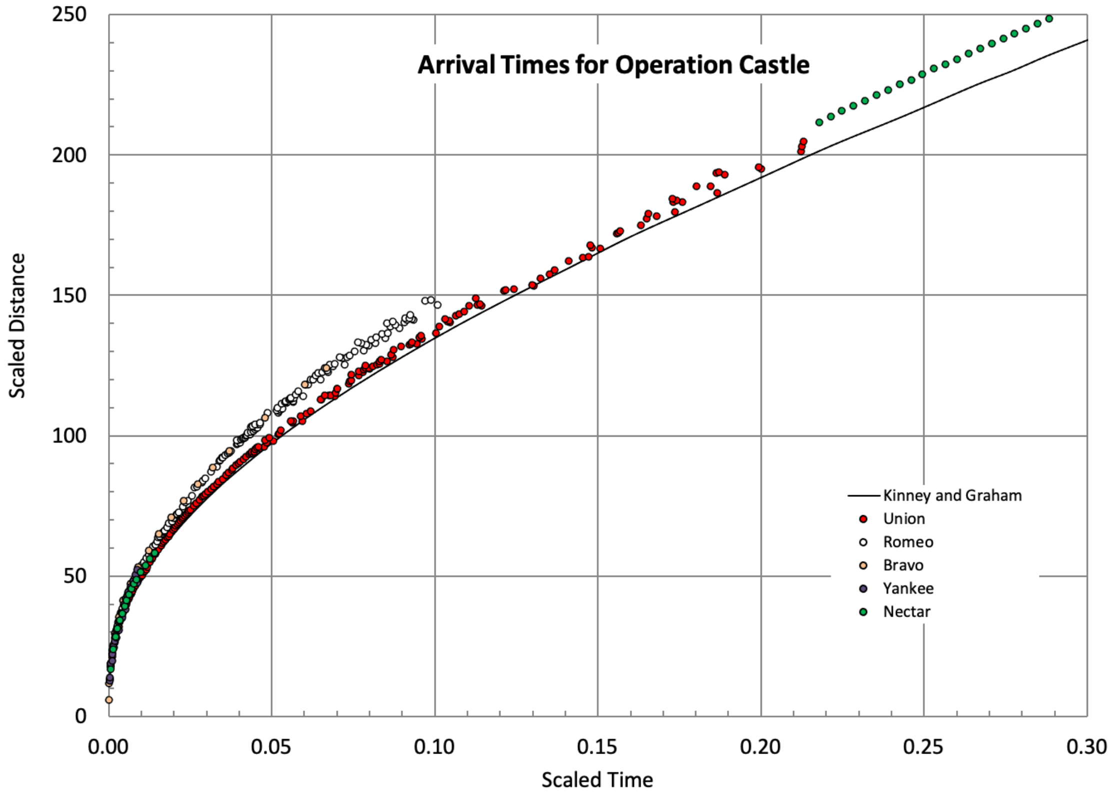

Figure 4. A comparison of the shockwave arrival-time data along the surface for the barges shots in Operation Castle. The scaled distances and scaled times were calculated assuming the uncorrected yields quoted in NV-209.

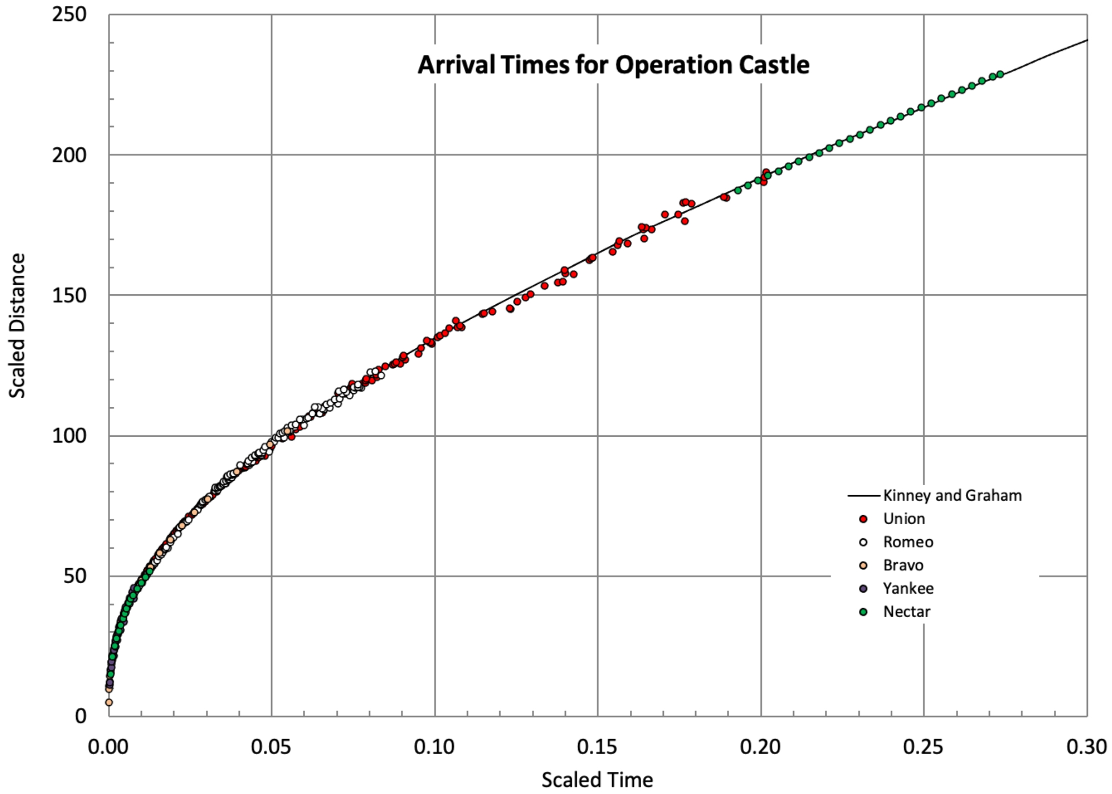

Figure 5. A comparison of the shockwave arrival-time data along the surface for the barge shots in Operation Castle. The scaled distances and scaled times were calculated using the newly measured corrected yields obtained from the Film Scanning and Reanalysis Project at LLNL.

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