Chapter 5   Appendix 12

SULFUR ACTIVATION AT HIROSHIMA

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After the atomic bomb explosion in Hiroshima, Yamasaki and Sugimoto were able to measure the fast neutron activation of sulfur in the mastic holding insulators on electric poles (Appendix 5-2). Details of the sample collection and measurement procedure have been described by Hamada.[1,2] The activation reaction $^{32}S(n,p)\ ^{32}P$ has a neutron energy threshold of about 2.5 MeV. The ^{32}P decays by beta-particle emission with a half-life of 14.2 days.

In 1958, Yamasaki revised his original data by correcting for self-absorption in the samples and by using new half-life data. The revised sulfur activation data were first compared by Kerr[3] to calculated sulfur activation versus ground range using the one-dimensional, isotropic source output provided for Hiroshima by Preeg.[4] A comparison similar to Kerr's of the measured activation data with calculations is shown in Figure 1. The results in Figure 1 were discouraging. The transport calculation using the Preeg source is higher than the measured data by over a factor of two close to the hypocenter. Another discouraging aspect is the scatter in the measured sulfur data points. For example, there are points at larger ground ranges that have higher activities than smaller ground ranges. One normally expects the variation to be a rather smooth, nearly exponential decrease with distance.

Because the sulfur activation is by high-energy neutrons and because the geometry of the insulators on the electric poles is simple enough to permit accurate calculations, good agreement between calculation and measurement would lend credence to the procedures being used to reassess the doses to the survivors. Fortunately, a number of developments led to better agreement.

The Preeg source was an early, one-dimensional model of the Hiroshima bomb. Whalen and his colleagues at Los Alamos National Laboratory[5] made two-dimensional, coupled radiation and hydrodynamic calculations for the Hiroshima bomb that were better suited to its cylindrical symmetry. They provided an energy- and angle-dependent output of neutrons and gamma rays from the Hiroshima weapon that is used as the source term for the calculation of the free-field, air-over-ground, neutron, prompt gamma ray, and secondary radiation fields in the new dosimetry system (Chapters 2, 3, and 9).

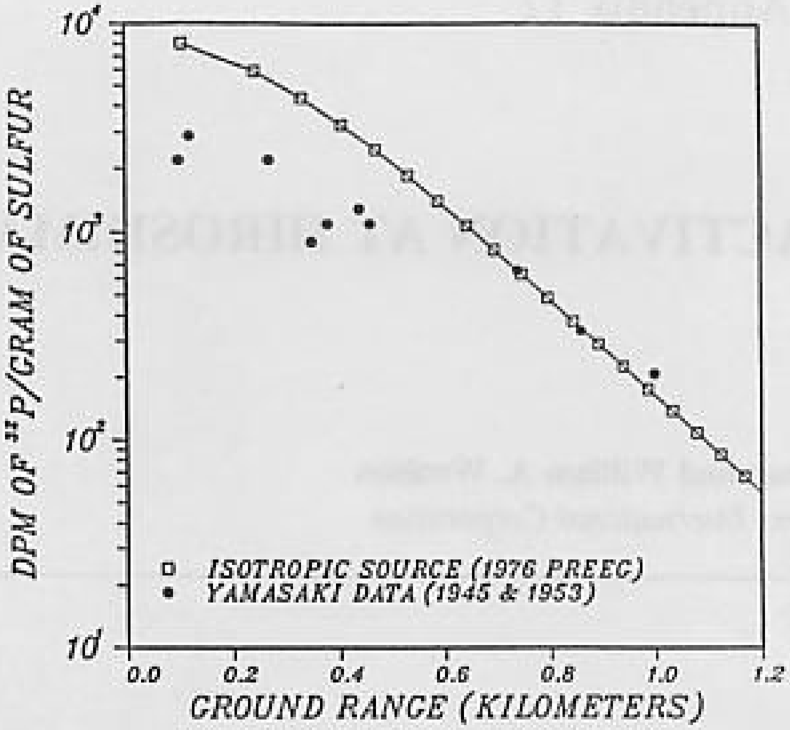

Figure 1. An early (1980) comparison of sulfur activation calculations with measurements

Furthermore, since the comparison in 1981, Hamada[2] made additional corrections to the sulfur activation data. These corrections include a more complete analysis of the self-absorption of the samples, an analysis of their purity, revised locations, and an estimate of the uncertainty in the reported activies.

The work reported here uses the two-dimensional output calculation of the Hiroshima explosion to calculate the sulfur activation and compares the results with Hamada's revision of the measurements.

Because the axis of the bomb was not vertical when it exploded, the sulfur activation is not simply a function of ground range; it is a function of both the range and the azimuthal location of the insulator with respect to the bomb trajectory.

The Approach

Our approach to calculating the activation of sulfur was to use the one-dimensional, discrete ordinates method in the adjoint mode. When run in the adjoint mode, the output from the discrete ordinates calculation is the energy- and angular-dependent source importance function. This function provides the activation at a distance from the source per source neutron emitted in a given energy and polar angle (with respect to a source-detector axis) bin. This importance function is then folded with the energy- and anglular-dependent source computed by Whalen to provide the sulfur activation. The details of the coupling procedure are given in Appendix 12a.

The use of the one-dimensional adjoint method assumes that homogeneous air is a good approximation for the transport. That is, we neglect the presence of the ground. This assumption was checked by comparing with the two-dimensional air-over-ground transport calculation by Pace[6] (see Chapter 3) for the Hiroshima explosion. The agreement was within a few percent to ground ranges up to a 1000 m. Since the activation is a fast neutron response, most of the neutrons that interact in the ground and scatter back out into the air lose enough energy to be below the sulfur threshold. Thus, the contribution to the sulfur activation from ground scattered neutrons is negligible.

Another assumption we made was to use a spherical shape for the insulator to calculate the self-shielding. The porcelain insulator has two-dimensional symmetry; thus the self-shielding of the sulfur is actually a function of the incident direction. However, calculations performed by Pace[6] for the insulator show less than a 5% variation between the spherical and the two-dimensional shape. This 5% variation is certainly within the other uncertainties involved in the calculational procedure and in the measurement process.

Sensitivity Calculations

We first conducted a series of calculations to help understand the relative effect of various components of the overall calculation. We investigated the effect of the angular distribution of the source, the insulator self-shielding, and the bomb heading and tilt.

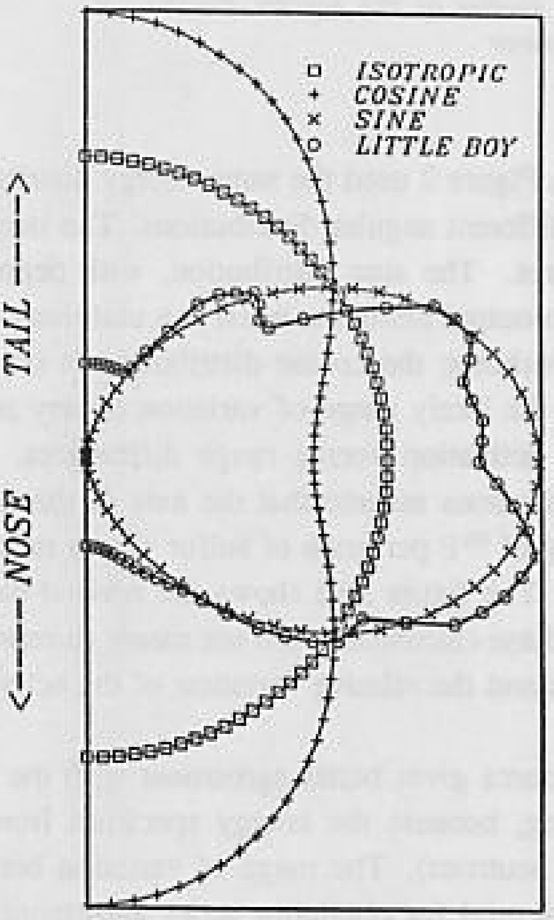

Figure 2. Relative distributions in angle of neutrons emitted from the sources used in sensitivity studies

Figure 2 shows several source distributions that we used to understand the effect of the angular variation. The heavy dotted line with circles as data points is the polar angle distribution of the Hiroshima source calculated by Whalen. The length of the vector from the center to a given point on the curve gives the relative neutron fluence in that direction

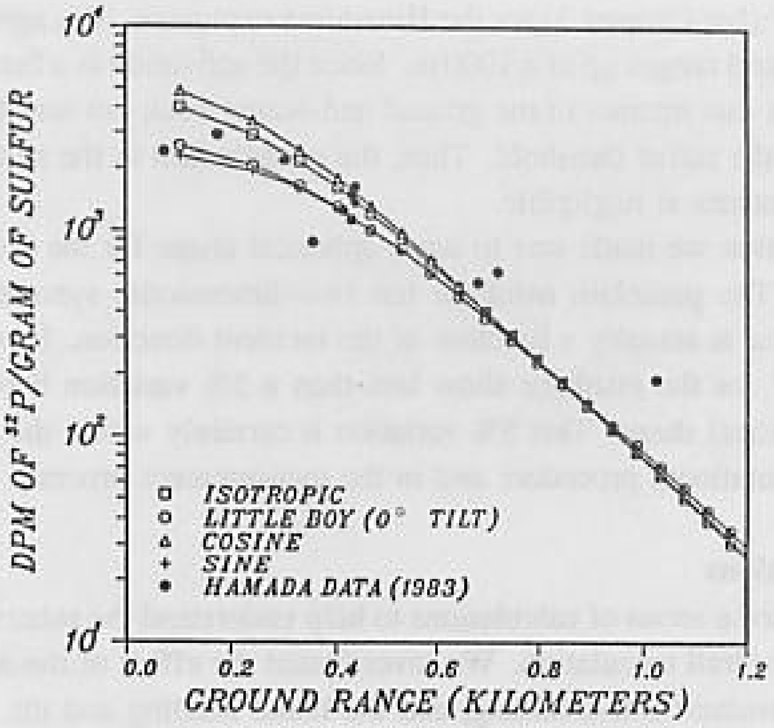

Figure 3. The results of the sensitivity studies of the angular distribution of the source

for neutrons above 2.5 MeV. The other curves in Figure 2 used the same energy distribution as calculated for the Hiroshima bomb but used different angular distributions. The isotropic distribution, for example, is identified by squares. The sine distribution, with depressed output along the axis of the device and maximum output along the waist is a mathematically simple distribution that is similar to that at Hiroshima; the cosine distribution is one that is nearly the opposite. These distributions span the likely range of variation of any source calculation and permit the examination of the activation versus range differences. The calculations performed using these angular distributions assume that the axis of the device is perpendicular to the ground plane. The activity of ^{32}P per gram of sulfur versus range for these source distributions is shown in Figure 3. The figure also shows the revised data of Hamada[2] for the ^{32}P measurements. To repeat, these calculations are not meant to represent the Hiroshima source; they were made to understand the relative variation of the activation for widely different angle-dependent sources.

Note, in Figure 3, that even the isotoropic source gives better agreement with the measurements than the previous calculation of Preeg, because the energy spectrum from the new calculation is softer (has more low-energy neutrons). The range of variation between the sine and the cosine sources indicates the potential for obtaining better agreement with the measurements with alterations in the emission with angle. Note, however, that the data points at the larger ground ranges are considerably higher than the calculated values. Also, the effect of the source anisotropy disappears beyond about 600 m ground range. Since this is a high-energy reaction, involving forward directed neutron transport, one expects that the kerma in tissue for both neutrons and gamma rays, which are isotropically generated from neutron interactions in the air and ground, will show considerably less anisotropy than the

Table 1. Effects of Insulator Self-shielding, Bomb Tilt, and Bomb Heading on Sulfur Activation Calculations for Hiroshima

Bomb Tilt				
Tilt angle	−15°	0°	15°	
Relative activation	0.92	1.0	1.08	
Bomb Heading				
Heading	250°	262°	265°	
Relative activation	1.025	1.0	0.989	
Insulator Self-shielding				
Porcelain thickness (cm)	0	1.5	2.5	3.5
Relative activation	1	0.94	0.90	0.86
Porcelain+bound water thickness (cm)	0	1.5	2.5	3.5
Relative activation	1.0	0.88	0.81	0.75

sulfur activation. Since the first survivors in the RERF Life Span Study appear at about 700 m as a function of ground range at Hiroshima, these results indicate that one can neglect the anisotropy in the source for purposes of survivor dosimetry.

The effects of bomb tilt, bomber heading, and the insulator self-shielding on the activation are shown in Table 1. The bomb tilt (i.e., the angle of the axis of the bomb with respect to the vertical) can produce up to an 8% variation in the activation from the untilted bomb for the extrema (tilted away from or towards the detector). A bomber heading between 250 and 265° results in a small 2% variation from the activation at the nominal heading of 262°.[7]

The self-shielding by the porcelain produces, at most, about a 15% reduction in the activation according to our calculations (Table 1). However, experiments conducted by Tajima and Oda[8] to measure the attenuation by the insulator of fast neutrons from D-D and D-Be reactions resulted in attenuation factors reported as 0.52 and 0.77 depending on the orientation. Further research is needed to understand fully the experimental data and its relation to self-shielding calculations such as the effect of the different neutron spectra and experimental geometries. One attempt to explain the differences was to assume the porcelain somehow contained the bound water present in the pre-fired material, since hydrogen has a large effect on neutron transport.[7] The results of attenuation calculations for porcelain with the bound water are shown in Table 1. The attenuations calculated are not enough to explain the experimental data.

Further analysis of the porcelain composition, insulator size, and the experimental data needs to be performed before this issue can be satisfactorily resolved. However, a nominal dry porcelain thickness of 2.5 cm was chosen for the rest of the computations.

Results of Calculations

This section presents the results of our calculations incorporating the effect of bomb tilt, the bomber heading, and the azimuthal and ground location of the insulators. The location of the insulators with respect to the hypocenter and a bomber heading of 262° are shown in Figure 4. The 10 sample locations denoted with a letter followed by a number identify the sample data of Yamasaki and Sugimoto and are shown at the azimuth and ground range relative to the new RERF hypocenter used by Hamada in his reanalysis of the original 1945 data. The data from three additional samples (denoted 1, 3, and 16) rejected by Yamasaki and

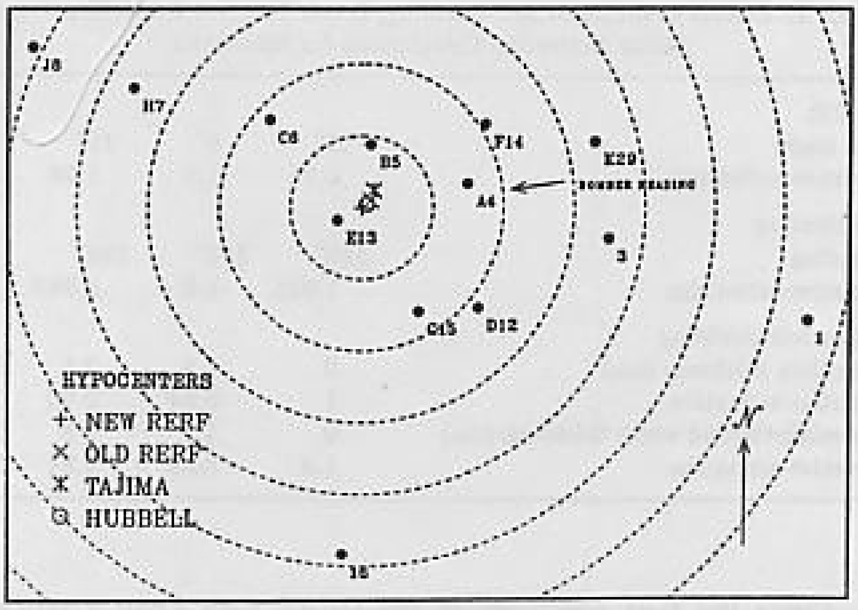

Figure 4. Insulator and hypocenter locations. The dashed circles are at 200 m intervals from the new RERF hypocenter

Sugimoto due to insufficient activity have been reanalyzed by Hamada (Appendix 5-10) and are shown in Figure 4. There is also some additional data for three samples initially reported by Arakastu in 1953 and reanalyzed by Shimizu and Saigusa (Appendix 5-8). No azimuthal information was given for these three samples. The ground ranges given by Shimizu and Saigusa are 470, 660, and 1080 m. The concentric circles in the figure indicate 200 m radial ground range intervals.

Our calculation of the sulfur activation incorporating all of this information is shown in Figure 5. In order to show all of the measured data points and their uncertainties, the activity in disintegrations per minute (dpm) of ^{32}P at the time of the bombing per gram of sulfur have been added to the background measured and reported by Yamasaki and Sugimoto. This background is shown in Figure 5 at 3700 dpm. The ground ranges used in making the plot are relative to the new RERF hypocenter. The neutron spectral and angular distribution used is that calculated by Whalen for a yield of 15 kt. The open symbols on the plot indicate calculated values and the dark symbols indicate measured values. The heavy vertical line on the left (associated with the first 12 samples in the legend box) indicates the spread in the calculated values for various combinations of bomber headings (250 to 265°) and bomb tilt angles (12 to 17°). The three points denoted by 1, 3, and 16 are far enough from the hypocenter that the bomber heading and tilt considered have a negligible effect on the calculated values. The heavy vertical line on the right (shown for the Arakatsu data) indicates the spread in the calculated values for the stated ground range uncertainty of ± 50 m. This uncertainty is large enough to encompass all four of the hypocenters considered in the analyses. The lighter vertical lines and arrows indicate the uncertainty in the measured dpm as given by the two reevaluations of the original data. All of the data in Figure 5 are also given, for reference, in Table 2.

With four exceptions, our calculations are within the uncertainty of the measurements as shown in Figure 5. For those points where the calculation is larger than the measured value, a possible explanation is localized shielding from a building. There is no information about such additional shielding. Our calculations exhibit variations with bomber heading and bomb tilt angle similar to those shown by the measurements. There is a dramatic improvement in the agreement between calculations and measurements in Figure 5 as compared with the preliminary comparison in Figure 1.

This comparison of the measurements of sulfur activation with calculated values provides evidence for the adequacy of the energy-angular distributions from the source, calculated by Whalen, combined with the transport calculations through the air to the detector. Revisions in future computations with better insulator self-shielding and improved understanding of the uncertainty and potential bias in the measured data may alter the comparison in detail, but they will probably not alter the overall agreement shown here.

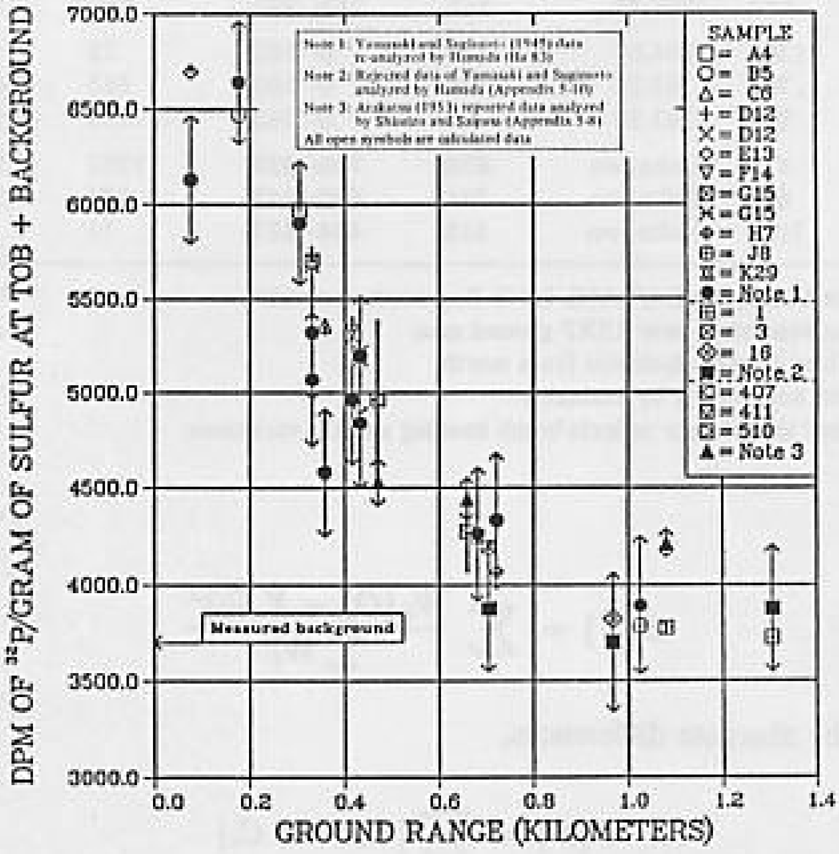

Figure 5. Calculated and measured activities of ^{32}P, at the time of the bombing, per gram of sulfur. The solid symbols are the measurements with their estimated uncertainties. The open symbols are the calculations. The heavy vertical lines are estimates of the range of uncertainty in the calculations, as explained in the text

Yield of the Hiroshima Bomb

Given the good agreement shown in Figure 5, we attempted to reestimate the yield of the Hiroshima explosion by finding the yield giving the best agreement with the measured data. Two measures were used: a weighted least squares,

Table 2. Calculated and Measured Sulfur Activation at Hiroshima[a]

Sample	Location[b]		Disintegrations/minute of Phosphorous-32 per Gram of Sulfur ATB			
	Ground Range	Azimuth[c]	Measured	Uncertainty Range[d]	Calculated	Uncertainty Range[e]
A4	305 m	77.34°	2200	1870-2530	2271	2271-2430
B5	178	7.38	2940	2617-3263	2771	2758-2886
C6	358	313.24	880	546-1214	1656	1608-1656
D12	433	130.46	1140	798-1482	1515	1515-1584
			1500	1185-1815		
E13	76	243.74	2430	2089-2770	2996	2996-3030
F14	417	56.34	1260	920-1600	1628	1626-1704
G15	331	151.10	1370	1014-1726	2006	2006-2075
			1620	1264-1976		
H7	721	74.62	630	277- 983	366	351- 366
J8	1025	297.41	190	0- 549	81	78- 82
K29	682	295.79	560	213- 907	550	550- 592
1	1305	104.07	174	0- 502	22	22- 23
3	705	97.23	174	0- 502	493	493- 562
16	968	182.98	0	0- 362	118	118- 118
407	470	Unknown	830	706- 955	1262	841-1684
411	660	Unknown	741	630- 852	573	364- 782
510	1080	Unknown	510	434- 587	71	45- 98

[a] Calculated using Whalen/LANL Little Boy neutron source
[b] Location relative to new RERF ground zero
[c] Azimuth as degrees clockwise from north
[d] Measured uncertainty by evaluator
[e] Calculated uncertainty reflects bomb heading and tilt variations

$$S(Y) = \sum_i \frac{W_i\,(O_i - Y\,C_i)^2}{\sum W_i} \tag{1}$$

and the sum of the absolute differences,

$$S(Y) = \sum_i |O_i - Y\,C_i| \tag{2}$$

where the sum is over the data points, and

$S(Y)$ = the error functional to be minimized to determine the yield, Y,
W_i = the weighting factor for the i-th data point,
O_i = the measured activity of ^{32}P per gram in the sulfur, and
C_i = the calculated activity per gram for the i-th data point.

In the weighted least squares, the weight functions were chosen to be unity (equivalent to using the least squares method) or the inverses of the variances in the measured data. Two sets of variances were used in this case: the data provided by Hamada and used in Figure 5 and an analysis of the uncertainties provided by Roesch.[9] Since the calculated

Table 3. Yield Estimates for the Hiroshima Explosion

Ground Zero	Weighting Factors	Porcelain and Thickness (cm)		
		No Self-shielding	Dry 2.5	With Bound Water 2.5
Hubbell	Roesch	11.4[b]	12.5[b]	14.0[b]
	Hamada	11.7	12.9	14.4
	Unity	11.6	12.8	14.3
	SAD[a]	11.3	12.5	14.0
New RERF	Roesch	11.4	12.6	14.1
	Hamada	11.7	12.9	14.4
	Unity	11.6	12.8	14.3
	SAD	11.1	12.3	13.7
Old RERF	Roesch	11.4	12.6	14.0
	Hamada	11.7	12.9	14.4
	Unity	11.6	12.8	14.3
	SAD	11.6	12.8	14.4
Kimura-Tajima	Roesch	11.4	12.6	14.1
	Hamada	11.7	12.9	14.4
	Unity	11.6	12.9	14.4
	SAD	11.9	13.2	14.6

[a] SAD = Sum of Absolute Differences

[b] Bomb tilt is 12° and heading is 262°

sulfur activation is obviously dependent on the hypocenter chosen, we used each of the four published hypocenters as another parameter in examining yield estimates for the Hiroshima explosion. The results of all these calculations are shown in Table 3.

Using these models, including the assumed 2.5 cm thick porcelain for self-shielding, the best estimate of the yield of the Hiroshima explosion is 13 kt. The uncertainty in this estimate includes the uncertainty in the knowledge of the physical situation (bomber heading, tilt, atmosphere, and insulator configuration), the experimental data, and the calculations. We believe the distribution about our estimate is asymmetric. Our data indicate the yield probably could not be lower than 12 kt but could be as high as 15 kt.

References

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