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TITLE: SOURCE AND REPLICA CALCULATIONS

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SOURCE AND REPLICA CALCULATIONS

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ABSTRACT

The starting point of the Hiroshima-Nagasaki Dose Reevaluation Program is the energy and directional distributions of the prompt neutron and gamma-ray radiation emitted from the exploding bombs. A brief introduction to the neutron source calculations is presented. The development of our current understanding of the source problem is outlined. It is recommended that adjoint calculations be used to modify source spectra to resolve the neutron discrepancy problem.

I. INTRODUCTION

The calculation of the Hiroshima and Nagasaki sources involved not just those two calculations, but other calibration calculations. Because there were many other tests of Nagasaki type bombs with diagnostic measurements, the need for calibration calculations of the Nagasaki type bomb was not thought to be so necessary. The 1965T (Tentative) dose assignments for both Nagasaki and Hiroshima were done using dose as a function of distance from Nevada Test Site (NTS) measurements of Nagasaki type bombs.[1] The only adjustments were for different source intensities and air densities. Source output calculations of the Fat Man (Nagasaki) device and two NTS test devices were done in support of the Nagasaki dose assignment. Source output calculations of the Little Boy (Hiroshima) device, the NTS Upshot-Knothole Grable test device, the ICHIBAN critical assembly and the Little Boy Replica critical assembly were done in support of the Hiroshima dose assignment. In addition, calibration calculations were made of the Lawrence Livermore National Laboratory (LLNL) Iron pulsed spheres experiments and of the Oak Ridge National Laboratory (ORNL) Iron Benchmark Experiment. Source output calculations of the Health Physics Research Reactor (HPRR) and calibration calculations of the LLNL oxygen and nitrogen pulsed spheres and Army Pulsed Reactor Facility (APRF) activation experiments were made in support of the air transport calibrations.

All of the Los Alamos neutron source and calibration calculations were done with versions of the MCNP Monte Carlo code.[2]

II. BOMB SOURCE CALCULATIONS

A. Nagasaki and Hiroshima Bombs

The Fat Man bomb, Figure 1, exploded over Nagasaki was a spherical plutonium implosion design with some associated firing equipment. Thus a spherical (1 dimensional) model of the bomb is a good approximation. Three other bombs of this design were fired in test situations. The assigned yield of the Nagasaki bomb is 21 ± 2 kilotons (kt) (1 kt = 10^{12} calories).[3] Calculations of the prompt neutron and gamma-ray output of the Fat Man device were made in 1975 by Preeg and in greater detail in 1981 by Streetman.[4,5]

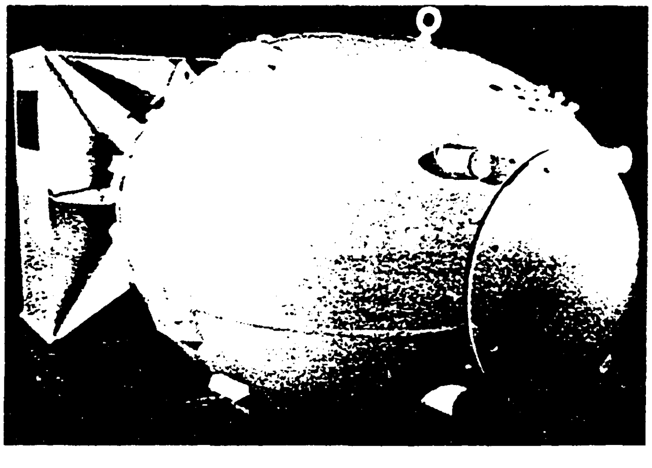

Fig. 1. The Nagasaki bomb (Fat Man).

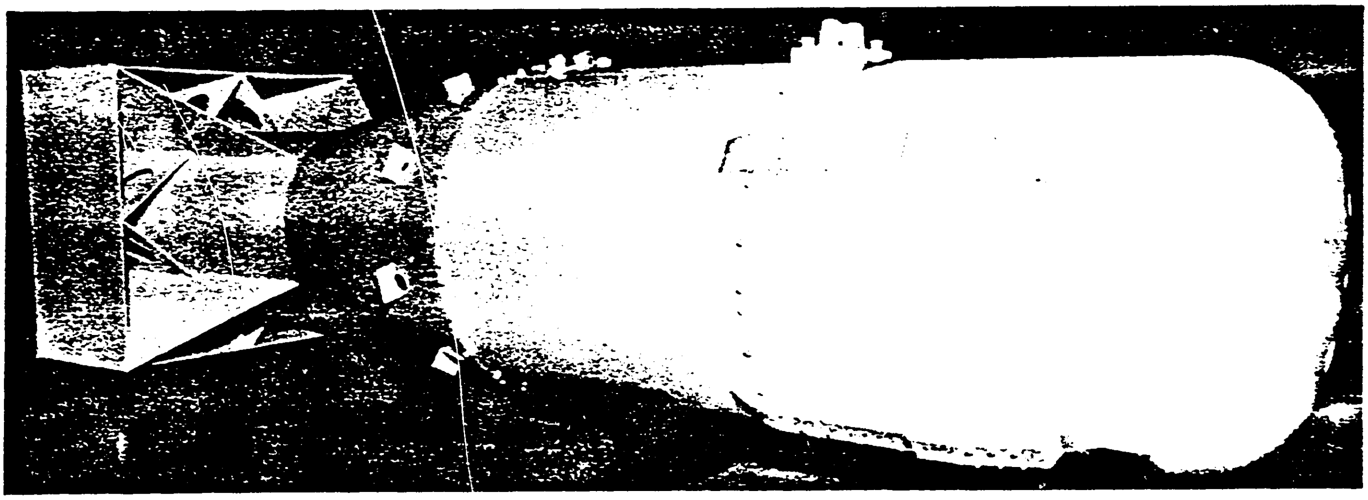

Fig. 2. The Hiroshima (Little Boy).

The Little Boy bomb, Figure 2, exploded over Hiroshima was a uranium gun design in which two subcritical masses of uranium are brought together to create a supercritical mass. The assigned yield of the Hiroshima bomb is 15 ± 3 kt.[3] Neutron and gamma-ray output calculations of a 1-dimensional mock-up of the Little Boy device were made in 1975 by Preeg.[4] Output calculations of the actual 2-dimensional Little Boy were made in 1982 by Kammerdiener and Streetman at the Los Alamos National Laboratory (LANL) and by Sloan at LLNL.[6,7] After a certain feature in the LLNL code was fixed, the calculated neutron spectra were in 30% agreement. Using files produced by the hydrodynamic calculation of 1982, Streetman repeated the neutron output calculations with better statistics in 1990.[8]

The Hiroshima and Nagasaki source spectra are compared with each other and with a ^{235}U fission spectrum in Figure 3. The bare fission spectrum is relatively quite hard compared to the bomb spectra, lying one to two decades above the bomb spectra for neutron energies in the MeV region. The neutrons which started with MeV energies in the fissile material of the bombs have been down-scattered in energy in their passage out of the bombs. The thermalization of the neutrons in the massive amount of high explosive material of the implosion bomb is evident in the Nagasaki spectrum where 99% of the source spectrum neutrons are in the bomb thermal energy region. Thermal neutrons on the ground under the bomb will prove to be important later, but are unrelated to this enormous cloud of thermal neutrons which is just a localized source of nitrogen capture gamma rays. The Hiroshima spectrum is dominated by the thick iron case of the bomb.

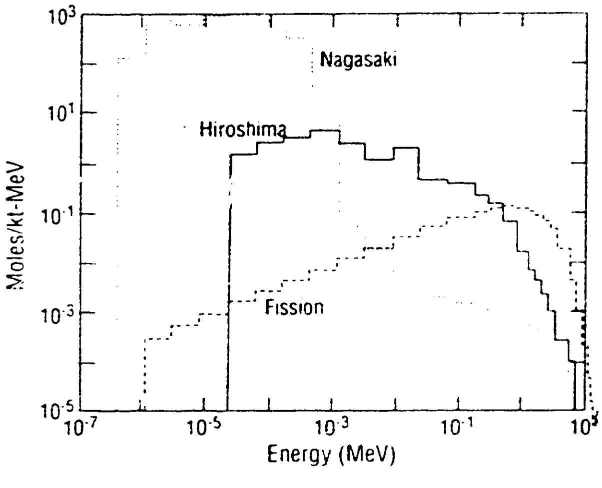

Fig. 3. Nagasaki, Heroshima, and Uranium fission comparative neutron spectra.

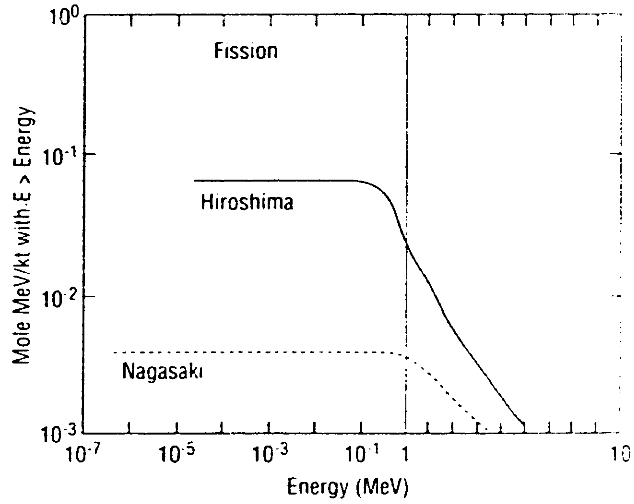

Fig. 4. Nagasaki, Hiroshima and Uranium fission comparative neutron energy spectra in the form of the integral of the neutron energy from E to 20 MeV.

Another view of the of the same three spectra is shown in Figure 4. In this view, the integral from E to 20 MeV of the energy carried by the neutrons is plotted against the energy E. This provides a crude measure of the source neutron dose. Note that the Nagasaki neutron source dose is relatively small compared to the Hiroshima neutron source dose. (But remember that each of the neutrons in the cloud of thermal neutrons will create a 7 MeV nitrogen capture gamma ray.) Nearly all of the neutron energy in the fission and Nagasaki spectra is carried by neutrons with energy above 1 MeV. The Hiroshima spectrum differs in that less than half of the neutron energy is carried by neutrons with energy above 1 MeV. This difference in spectra is important to the transport of the source neutrons.

The angular distribution of the Hiroshima bomb neutrons is shown in Figure 5. The neutrons come out of the waist of the bomb in a pancake distribution

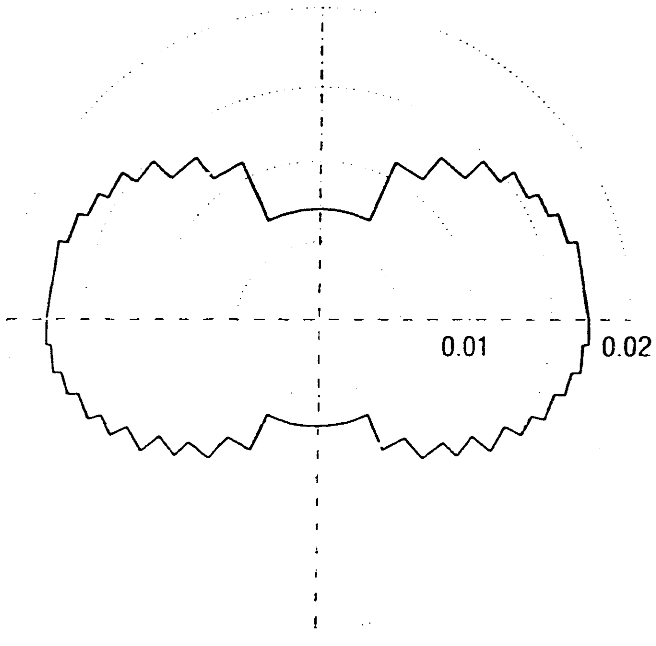

Fig. 5. Angular distribution of Hiroshima neutrons (Mole/kt-steradian).

B. NTS Bomb Source Calculations

1. Two NTS device output calculations. These devices, tested at the NTS, were Nagasaki-like devices. Calculations of the prompt neutron and gamma-ray output of these devices for calibration were made in 1981 and 1983 using the same codes and techniques as used for the Fat Man calculations.[7,9] This output could be used for calibration of air-transport calculations with neutron activation measurements made at the NTS.

2. Upshot-Knothole Grable output calculations. This device was the 280 mm Artillery Fired Atomic Projectile tested at the NTS. Calculations were made in 1980 of the prompt neutron and gamma-ray output of this device using the same codes and techniques as used later for the Little Boy calculations.[7] This output could be used for calibration of air-transport calculations with neutron activation measurements made at the NTS.

III. HIROSHIMA BOMB CALIBRATION CALCULATIONS

A. ICHIBAN Critical Assembly

The ICHIBAN critical assembly was a just-critical, 1-dimensional spherical mock-up of the waist configuration of the Little Boy bomb (which was a 2-dimensional cylindrical configuration). The critical assembly had been constructed in 1965 in the ICHIBAN program to obtain measured neutron and gamma-ray transmitted output per fission which could be used to establish the source dose of the Hiroshima explosion.[1] Two sets of neutron spectrum measurements were available[10,11]. The two measured spectra were in disagreement, a feature typical of most of the experiments in the dose re-assignment program. Good agreement between MCNP calculations and the Bigger's measurement was obtained.[7]

B. Little Boy Replica

1. Experiments. The Little Boy Replica was assembled in 1982-3 from non-fissile Little Boy parts stored from 1945 and newly fabricated fissile parts. Two sets of fissile parts were built for two distinct types of experiments. A set of parts (1982) of just critical mass when inserted fully into the Replica was used for neutron spectra measurements by a number of experimenters. The arrangement of the Little Boy Replica on the Comet Critical Assembly Machine is shown in Figure 6. A uranium core could be raised into the interior of the assembly by a hydraulic ram and screw mechanism of the machine.

A variety of measurements were made using different techniques.[12-20] Another set of parts (1983) which duplicated the Little Boy supercritical fissile parts was used to obtain a modern critical separation measurement. With this separation established, the criticality of the parts when fully assembled could be calculated and the maximum yield of the explosion, assuming proper functioning, could be calculated. The result of this chain of calculations was an estimate of 15 + 2 kt as the maximum yield of the Hiroshima explosion. That is, the critical separation measurement rules out yields greater than 17 kt.

2. Comparison of calculated spectra with measurements. MCNP calculations were made to obtain spectra at each of the measurement locations shown in Figure 6.

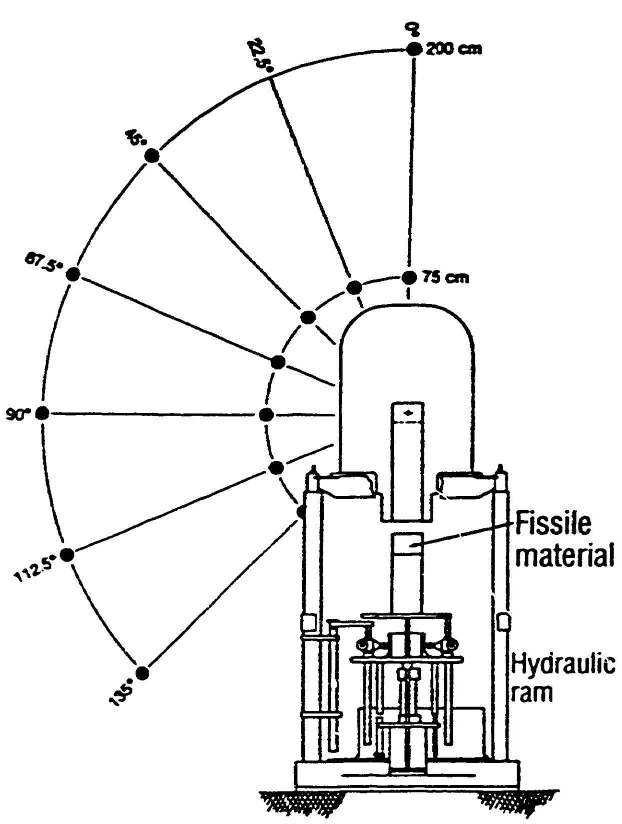

Fig. 6. Little Boy Replica mounted on COMET assembly stand showing measurement locations. The hydraulic ram lifts the fissile parts into the Replica.

A comparison of one calculated and measured spectra at the 75 cm 90 degree waist location is shown in Figure 7.

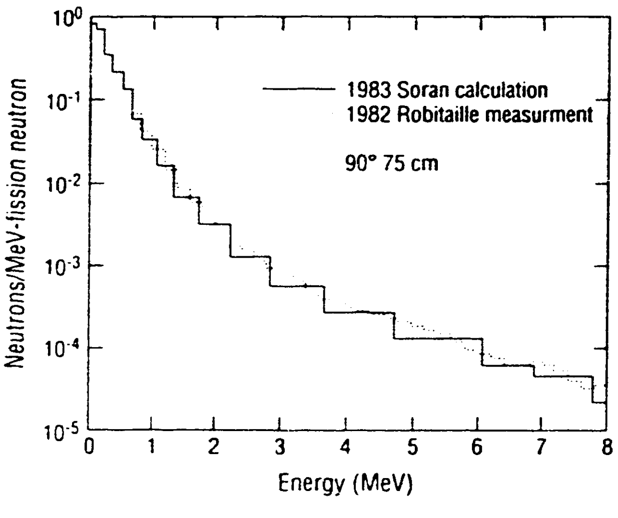

Fig. 7. Calculated and measured REPLICA neutron spectrum at 75 cm 90 degrees.

Comparisons off the 90 degree waist location do not look as good. Several other comparisons of the calculated and measured spectra (at 90 degrees) are shown in Figures 8-10 More complete comparisons are shown in reference 21. The comparisons are shown as the ratio of the calculated and measured integral of the fluence between a minimum energy, E, and 20 MeV or as the ratio of calculated and measured (initial) ^{32}P activity induced in sulfur pellets exposed to the neutrons from the Replica (plotted at 2 MeV). A comparison of the baseline MCNP calculation using continuous energy ENDF/B-III Fe cross sections with the measurements is shown in Figure 8a. Ratios are shown at values of E_{min} of 0.025 eV, 10 keV, 0.6 and 1 MeV, with the sulfur activation ratio plotted at 2 MeV. The ± 25% spread in the measurements is apparent. For comparison, an MCNP calculation using 175 group ENDL Fe cross sections is compared with the measurements in Figure 8b. Even with the ± 25% spread in the measurements, the superiority of the continuous energy ENDF/B-III Fe cross sections is apparent. A similar comparison of MCNP calculations using continuous energy ENDF/B-III and -IV Mod 4 Fe cross sections is shown in Figures 9a and 9b. Only comparable points are shown. In this case, the -IV Mod 4 Fe cross sections lead to slightly more consistent patterns (In 1990, ENDF/B-V Fe cross sections were used in a recalculation of the Little Boy output.) A comparison of the baseline MCNP calculation with a 37 group ORNL S_n calculation is shown in Figures 10a and 10b.[22] As in the comparison in Figure 8, the superiority of the continuous energy MCNP calculation is apparent.

C. Other Hiroshima Bomb Calibration Calculations

1. Iron Pulsed Sphere Calculations. In the LLNL Pulsed Sphere Program, time of flight measurements were made of the spectra of neutrons exiting hollow spheres of material with a pulsed 14 MeV neutron source in the center.[23] Calculations of the LLNL iron pulsed spheres were done for evaluation of the available ENDF/B-IV and ENDF/B-V Fe cross sections.[24] Comparisons of calculations and measurements are shown in Figures 11a and 11b. These comparisons are really rather poor. Time of flight comparisons are shown in reference 24.

2. ORNL Iron Benchmark Experiments.[25] The experiment consists of a beam of reactor neutrons impinging on slabs of iron up to 92 cm in thickness. Measurements of the transmitted neutrons were made with Bonner Ball (BF_3 surrounded by CH_2) detectors placed about a meter behind the iron slabs at various angles to the incident beam. Comparisons of calculated to measured detector response in the 0 degree direction are shown in Figure 12a using ENDF/B-IV Fe cross sections and in Figure 12b using ENDF/B-V cross sections. These comparisons are really rather poor. Comparisons at other angles are shown in reference 24.

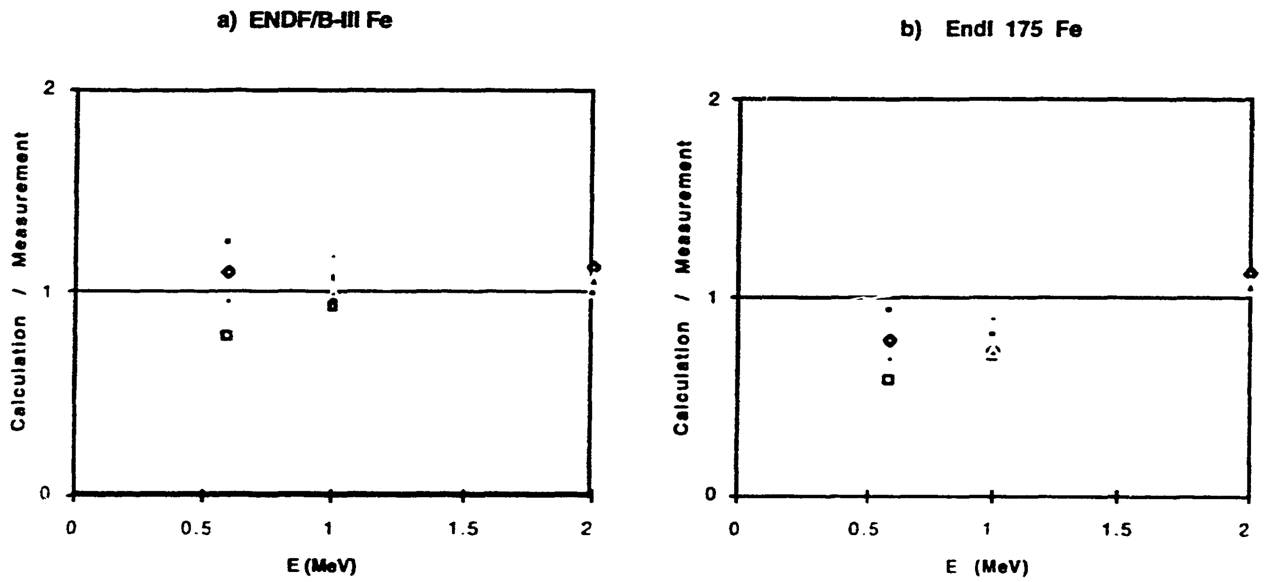

Figure 8. REPLICA calculation-to-measurement ratios comparing calculations using ENDF/B-III continuous energy and ENDL 175 group Fe cross sections.

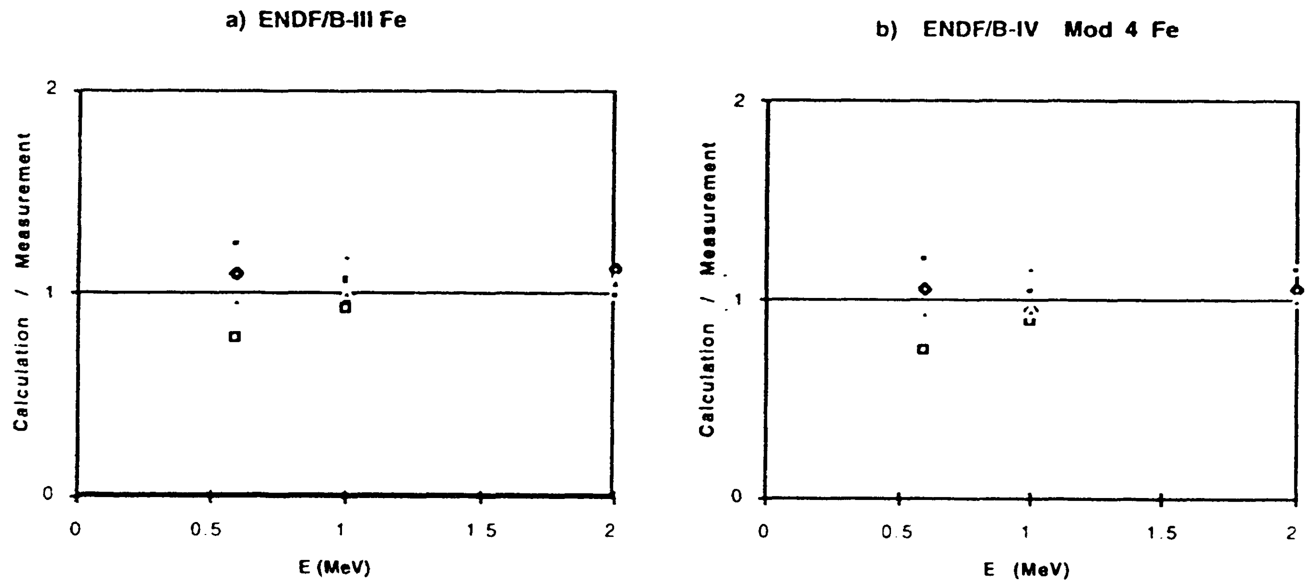

Fig. 9. REPLICA calculation-to-measurement ratios comparing calculations using ENDF/B-III continuous energy and ENDF/B-IV MOD 4 Fe cross sections.

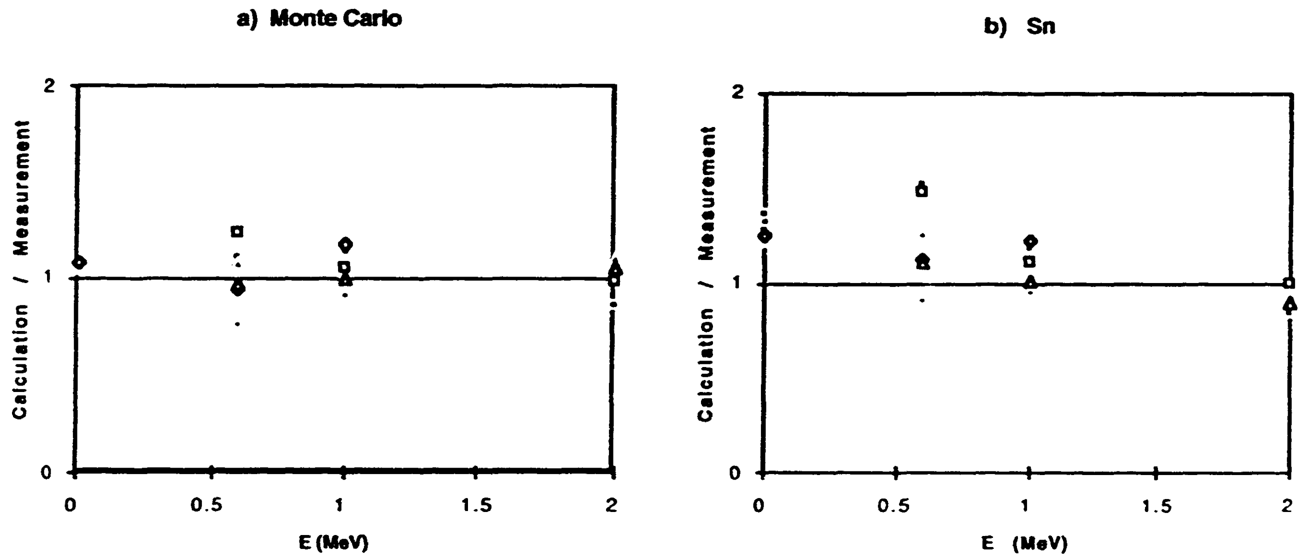

Fig. 10. REPLICA calculation-to-measurement ratios comparing Monte Carlo calculations using ENDF/B-III continuous energy and S_n calculations using 37 group Fe cross sections collapsed from Vitamin E.

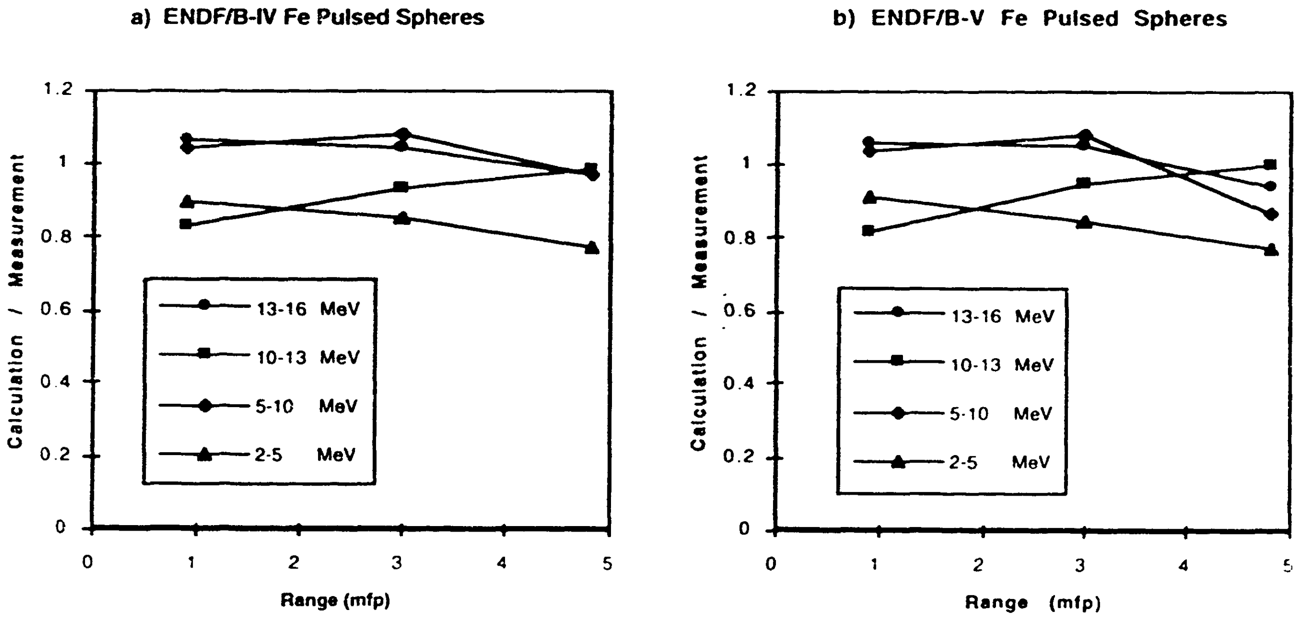

Fig. 11. LLNL Iron Pulsed Spheres calculation-to-measurement ratios comparing calculations using ENDF/B-IV and ENDF/B-V continuous energy Fe cross sections.

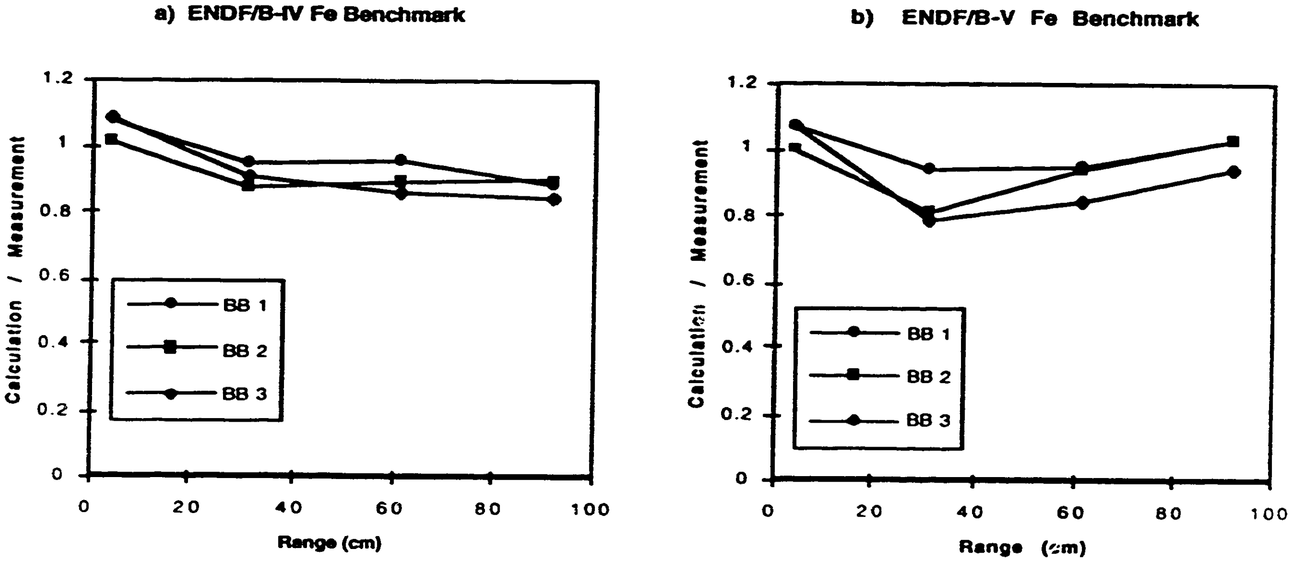

Fig. 12. ORNL Iron Benchmark Experiment calculation-to-measurement ratios comparing calculations using ENDF/B-IV and ENDF/B-V continuous energy Fe cross sections.

IV. AIR TRANSPORT CALIBRATION CALCULATIONS

A. Health Physics Research Reactor (HPRR) Calculation

Early in the Dose Reassessment Program, it was apparent that the calculated HPRR neutron spectrum used for air transport calibration calculations was in error. LANL provided a quick alternative spectrum from a calculation of an HPRR model with no shielding.[26] This source spectrum was later replaced with a more accurate SAIC calculation of the shielded reactor.

B. Nitrogen and Oxygen Transport Calibration Calculations

1. Nitrogen and Oxygen Pulsed Sphere Calculations. Calculations of the LLNL nitrogen and oxygen pulsed spheres were done for evaluation of the available ENDF/B-IV and -V N and O cross sections.[26] After the N and O cross section re-evaluation, calculations were done to evaluate the ENDF/B-VI cross sections.[27] The comparison of calculated-to-measured fluences in various energy bins as a function of the thickness of the nitrogen pulsed spheres is shown in Figure 13a for ENDF/B-V cross sections and in Figure 13b for ENDF/B-VI cross sections. The ENDF/B-VI cross sections give a decided improvement in the comparison with measurement.

2. APRF Air Transport Calculations In these experiments, measurements of neutron spectra and neutron activations are made at distances up to 1.6 km from an HPRR reactor suspended 14 m above the ground by a gantry. This geometry and reactor source was used to compare the effect of changing N and O cross sections. The effect of the different cross sections on three calculated results is shown in Figure 14. The items compared are sulfur activation to measure differences in high energy (> 2 MeV) transport, neutron kerma to measure differences in dose, and the sub-cadmium neutron fluence to measure differences in low energy neutron activation fluence. The most notable difference caused by the change in cross sections is the near factor of two reduction in sulfur activation neutrons at 1.6 km with little change in the number of sub-cadmium neutrons at 1.6 km.

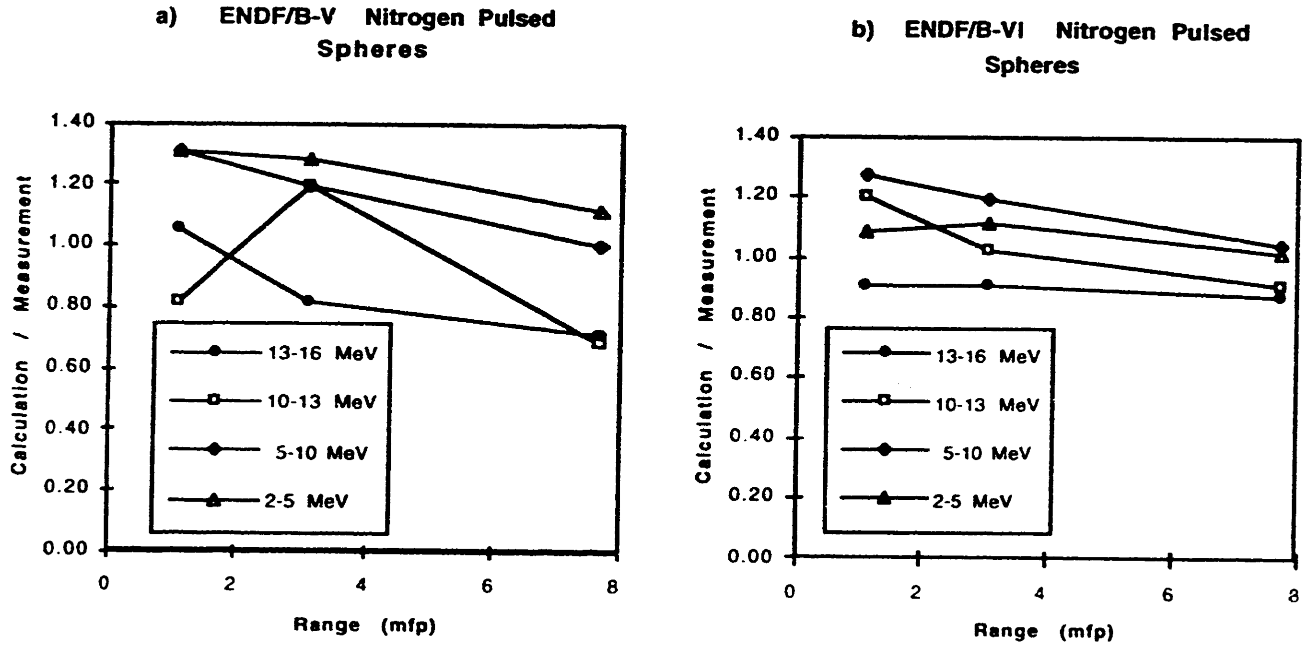

Fig. 13. LLNL Nitrogen Pulsed Spheres calculation-to-measurement ratios comparing calculations using ENDF/B-V and ENDF/B-VI continuous energy nitrogen cross sections.

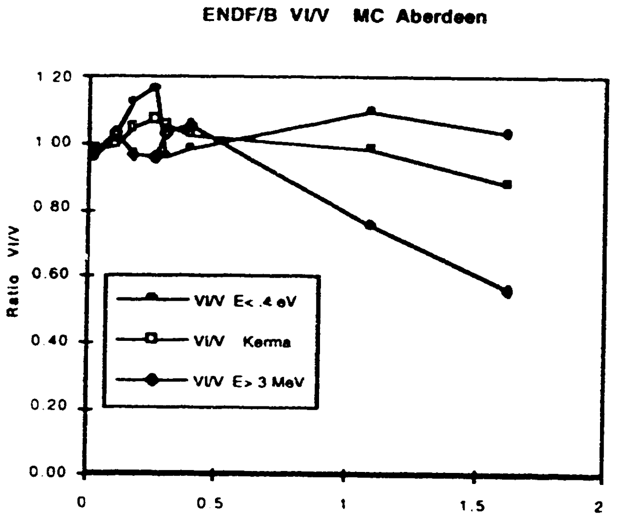

Fig. 14. Ratios of calculated thermal fluence, neutron kerma and sulfur activation vs. range with APRF source and geometry comparing ENDF/B-VI to ENDF/B-V nitrogen and oxygen cross sections

V. The Neutron Discrepancy

The existence of an apparent discrepancy between calculated and in-situ measured neutron activations was identified in the final report describing the 1986 Dose System, DS-86.[28] Over the years, additional measurements confirmed that there was a serious (and similar) discrepancy between the calculations and the in-situ measurements of thermal neutron activation at both Nagasaki and Hiroshima. The nature of the thermal neutron discrepancy was that the calculated thermal neutron activation fell off faster as a function of distance than the measured activation, so that at 1.5 km the calculated activation was only 0.10 of the measured activation. The discrepancy at Hiroshima was regarded as much the more serious because the neutron component of the total neutron and gamma-ray radiation dose was much larger at Hiroshima than at Nagasaki (Figure 4).

It has always been recognized that the calculated thermal neutron activation at distance at Hiroshima could be raised by postulating a neutron source spectrum for the Hiroshima bomb that was as hard as the Nagasaki source spectrum, that is, a source spectrum that contains relatively more neutrons above 1 MeV than the Hiroshima source as calculated at Los Alamos using standard nuclear weapon calculation codes and conventions. The difference in the source spectra hardness is reflected in the calculated neutron thermal activation relaxation lengths at 1 km (e-folding lengths), 165 m and 130 m for the calculated Nagasaki and Hiroshima sources respectively, Table 1. Over the years there have been many suggestions offered for hardening the Hiroshima source spectrum. These suggestions have generally been of the nature of postulating bare uranium fission neutrons escaping the Hiroshima bomb case through cracks of varying dimensions and orientations. A recent popular suggestion has been to postulate neutrons escaping directly upwards as though the tail of the bomb had fallen off. It has been difficult to invent mechanisms that would allow the direct escape of neutrons from the bomb. Because neutrons travel in straight paths between collisions, many small cracks would have no effect on the output neutron spectrum unless the many small cracks were miraculously aligned in perfectly straight lines with the exit paths of the neutrons. This is rather improbable. If somehow, there were large cracks in the case, (in just the right place and symmetrically arranged), or the tail had fallen off, the effect should have been noticeable in reducing the yield of the bomb. Fortunately the results of the DNA Composite Source study in the summer of 1993 (described elsewhere in these proceedings) should end this line of speculation.[8] In this study, the simultaneous effect of adding bare reactor fissions to the Hiroshima source at different heights of burst on the calculated sulfur (high energy) neutron activation, thermoluminescent (TLD) activation and thermal neutron activation was determined. In all cases, adding bare reactor neutrons to the Hiroshima source made the comparison of calculated and measured sulfur activation get worse faster than the comparison of calculated and measured thermal neutron activation improved. (The TLD comparison is relatively insensitive to the assumed spectrum.)

A very compressed summary of the major changes in the comparison of measured and calculated Hiroshima - Nagasaki neutron activations between 1986 and 1993 is presented in Table I. The great improvements in agreement shown in the table are due to additional measurements made by Japanese and American researchers, but primarily to the persistent DNA program of experimental measurement and calculation improvement. The major comparisons to be made between 1986 and 1993 are keyed together in the table. The use of the new nitrogen and oxygen cross sections led to the reduction in the calculated Nagasaki sulfur activation relaxation length (a) and better agreement with data from tests of Nagasaki like bombs. The use of the new nitrogen and oxygen cross sections and changes in S_n techniques led to a 30% reduction and closer agreement with measurements of sulfur activation near the hypocenter at Hiroshima (b). The large changes in the <u>measurements</u> of thermal neutron activation at Nagasaki (d) bring the measurements into better agreement with other Pacific and Nevada Test Site measurements (e). This, together with the increase in the number of neutron groups used in the calculation (f) have removed the factor of 10 disagreement between calculation and measurement at Nagasaki mentioned above. The use of different S_n techniques and 176 group rather than 46 group cross sections has reduced the calculated thermal activation near the hypocenter at Nagasaki by nearly a factor of two and (finally) brought the S_n results toward the Monte Carlo results Note that the calculated thermal neutron relaxation lengths at 1-2 km (c), (the proximate cause of the neutron discrepancy) have not changed at either city.

The net result of the DNA measurement-calculation effort has been to bring the Nagasaki neutron calculations into agreement with the revised measurements and to leave the neutron discrepancy problem only at Hiroshima. The results of the DNA Unconstrained Source study in the summer of 1993 offer hope that the neutron discrepancy at Hiroshima may also be removed; although in a totally unexpected fashion. One of the unconstrained Hiroshima source models developed to match the sulfur and thermal neutron measurements, had a large spike of neutrons with energies between 2.2 and 2.7 MeV and absolutely no neutrons with energies above 2.7 MeV in the spectrum. In conjunction with the associated calculations of adjoint neutron importance this offers a hope that the Hiroshima neutron activation measurements can be matched with a source spectrum that is softer, not harder, than the current calculated source spectrum. This is extremely encouraging because it is in the direction that comparisons of calculated and experimental measurements of neutron transmission through thick shields of iron (similar to the thick iron case of the Hiroshima bomb) have indicated the calculated source spectrum should go.[24,27,29,30] The experimental evidence that the neutron spectrum transmitted through iron should be softer than what we calculate has always been a problem with trying to produce a harder Hiroshima source spectrum.

VI. RECOMMENDATIONS

The Hiroshima source spectrum can only be calculated with neutron cross sections which are available. For iron, these have been ENDF/B-III, -IV and -V cross sections. Recently, ENDF/B-VI cross sections have become available for use in continuous energy Monte Carlo calculations. It is to be expected that these newer cross sections will provide better calculation matches to the integral experiments: the LLNL iron pulsed spheres experiments, the ORNL Iron Benchmark Experiment, the Californium source in a 76 cm iron sphere, and the ORNL Fusion Reactor Shielding Experiments.[23,25,29,30] If this expectation is born out by calibration calculations of the integral experiments and the Replica experiments, using the new ENDF/B-VI cross sections, then a new calculation of the Hiroshima source spectrum would be warranted.

Table I Summary of 1986 and 1993 Calculation and Measurements

Sulfur Activation Comparisons	Key	Nagasaki	Hiroshima
1986			
Calc relaxation length at 1 and 2 km (m)	a	220	220
Meas relaxation length at 1 and 2 km (m)			
Crossroads Able (m)	a	190	
Zebra over water (m)	a	202	
Zebra over land (m)	a	197	
Calc/Meas sulfur activation near hypocenter	b	?	1.18
1993			
Calc relaxation length at 1 and 2 km	a	207	
Calc/Meas sulfur activation near hypocenter	b	?	0.90
Thermal Neutron Activation Comparisons			
1986			
Calc relaxation length at 1 and 2 km (m)	c	159-182	129-163
Meas relaxation length at 1 and 2 km (m)	d	229	185
Ranger Fox /corrected to Nagasaki	e	197/194	
B-J Charlie /corrected to Nagasaki	e	200/186	
B-J Dog /corrected to Nagasaki	e	198/181	
U-K Badger /corrected to Nagasaki	e	190/178	
Calc Data location weighted relaxation length (m)	f	128	125
Meas Data location weighted relaxation length (m)	d	205	180
Calc/Meas activation near hypocenter 46 group S_n calc	f g	1.35	1.61
1993			
Calc relaxation length at 1 and 2 km (m)	c	165-180	130-156
Meas relaxation length at 1 and 2 km (m)	d e	180	189
Calc Data location weighted relaxation length (m)	f	155	133
Meas Data location weighted relaxation length (m)	d	158	189
Calc/Meas activation near hypocenter 176 group S_n calc	f g	0.85	1.49
Calc/Meas activation near hypocenter Cont Energy M C	g	0.72	?

Notes:

a New air cross sections improve agreement with measured sulfur activation for Nagasaki-like bombs.

b New air cross sections and change in S_n method affecting fluence under the bomb improves calc/meas near hypocenter.

c Calculations of thermal activation at range did not change at either city.

d Measurements at Nagasaki changed, agreeing better with

e Nevada measurements

f Calculation at Nagasaki changed close-in because of change in S_n calculation and new 176 group cross sections.

g Further change at Nagasaki with Continuous Energy Monte Carlo calculation

However, in the past few years: 1) Because of a change in S_n algorithms, the calculated sulfur activation near the hypocenter at Hiroshima has decreased by 30%. This leads some to suggest that the yield of the Hiroshima bomb must have been greater than 15 kt. Curiously, they don't suggest that the yield of the Nagasaki bomb must have been greater than 21 kt, although the same change in S_n algorithm has the same effect at Nagasaki. 2) Because of the use of the re-evaluated nitrogen and oxygen cross sections, the calculated sulfur activation at the APRF at 1.5 km has decreased by a factor of two. The calculated sulfur activation length at Nagasaki now agrees with measurements made on NTS tests of Nagasaki-like bombs. 3) Because of the change from using 46 to 176 group cross sections in the S_n calculations, the thermal neutron activation near the hypocenter has decreased by 40% at Nagasaki but by only 10% at Hiroshima. A continuous energy Monte Carlo calculation lowers the calculated thermal neutron activation by another 15%.

It would be a futile task to attempt inventing models of cracks or explosion perturbations to change the spectrum of the Hiroshima (or Nagasaki) bomb to keep up with these changes in air transport calculations and the changes in measurements. A practical approach, because it would work, would be to define the Hiroshima source spectrum and angular distribution using adjoint results from the same codes and cross sections used for the forward air transport calculations. This was nearly accomplished during the DNA 1993 Source Study. The existing Hiroshima source spectrum could then be modified to match the measured data using the air transport code du jour. This suggestion would require some small additional development to produce two parameter, energy and angle, adjoint sources. Implementing this suggestion would also allow the source to be updated when an uncontaminated background measurement is made at Hiroshima.

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