# A précis of the Dosimetry System 2002 (DS02)

*Resolution of the Hiroshima Neutron Discrepancy*

By
Jamie Smith
0040623

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> *"The radiation dose for atomic-bomb survivors is the end product of a series of complex and physically sophisticated calculations, beginning with prompt neutrons and gamma rays generated in the fissile material of the bomb and ending in a neutron and a gamma dose estimated for each individual survivor."*
>
> *- DS02*

It is the purpose of this report to briefly outline the investigations performed to arrive at the dose estimates provided by the *Dosimetry System 2002*, to provide insight into the on going efforts of the RERF and their partners. It is by no means an in depth analysis of their work. It was written with the intent to provide a brief overview of the DS02 so as to enhance the learning experience for those planning to visit the RERF in the future.

Since studies of the atomic bombing in Hiroshima began, great amounts of research have been performed in an attempt to calculate the doses victims may have received. The most robust way of making this attempt is to perform a Monte Carlo simulation. In this case a Monte Carlo is a method of using a random (or pseudo-random) number generator and an elaborate series of codes to track individual particles as they explode from the bomb and into the environment. This is performed repeatedly so as to approximate all the particles in the bomb. The DS86 used the Monte Carlo method to approximate its dose estimates. Of course, throughout the entire process, calculations are checked with real world radiation measurements taken from numerous locations in Hiroshima.

The work done up to and including the DS86 provided significant information about the estimated doses to victims of the Hiroshima bomb (little boy). Although the approximation seemed to match well enough within a 1000 meter radius of the hypocenter, beyond this the measured and predicted results differed greatly. The DS86 underestimated the dose by a factor of five at a radius of 1000 meters and continues to diverge as the distance from the hypocenter increases. This has become known as the 'Hiroshima Neutron Discrepancy'. Resolving this issue was one of the major goals during the undertaking of the DS02.

On the surface the calculations may seem fairly simple: take a photon, for instance, pick a random direction, pick a random energy, and send it off and see what it hits. The real world is not so simple. In order to arrive at a reliable estimate of a victim's dose there are large number of steps that were taken. These can be categorized as follows:

- Bomb Parameters
- Radiation Transport Calculations
- Bomb Output Calculations
- Prompt Radiation Calculations
- Delayed Radiation Calculations
- Radiation Measurements
- Transmission Factors
- Survivor Dosimetry
- Survivor Shielding

The DS02 had the benefit of vastly more powerful computing capacity than was available for the DS86, however, even some of the calculations in the DS02 Monte Carlo take extensive amounts of time to complete. The entire system is composed of modules which pass their outputs on to the next module as inputs. Each module is responsible for estimating a small factor in the final outcome.

The first step is the most important because its output determines the inputs for the next step. As such, even subtle discrepancies can become magnified by the end of the entire process. Most of the improvements to the DS02 over the DS86 were a result of simply improving the resolution of the system. That is, improved energy resolution, spatial resolution, as well as great improvements in particle interaction data (ENDF) that had occurred since the DS86 all played important roles in making the DS02 the most impressive and scientifically substantial Dosimetry System to date.

**Bomb Parameters**

Even the quantification of the parameters of the bomb is a great exercise in scientific investigation. The yield (number of fissions in the bomb) is the first issue in determining the neutron and gamma-ray doses in Hiroshima. There are two extra factors in the Hiroshima bomb that really complicate the task further. The first is that the bomb is of asymmetrical geometry and thus a uniform radiation field cannot be assumed and secondly the design of the Hiroshima bomb has never since been tested, so there is no data to cross reference the calculation with, outside of Hiroshima itself.

Table 1. Bombing mission data (Malik 1985)

| **Parameter** | **Hiroshima** |
|---|---|
| Bomb Designation | L-11, Little Boy |
| Time of detonation | 0815, August 6, 1945 |
| Time of fall for bomb | 44.4 s |
| Indicated heading of bomber | 262 º |
| Wind speed and direction | 8 knots at 170 º |
| True heading of the bomber | 265 º |
| Indicated air speed | 322 km/h |
| True air speed | 528 km/h |
| Indicated altitude | 9.20 km |
| True altitude of bomber | 9.63 km |

*Bomb Orientation*

The asymmetrical geometry (cylindrical) creates a ‘blind spot’ or ‘shadow’ where the fluence is greatly reduced and it is because of this that it is important to know accurately the orientation and position of the bomb at the time of detonation. In Table 1, above, the initially known parameters are presented – these of course are not sufficient enough for accurate calculations. The epicenter is defined as the location of burst, and is extracted from two values, the height of the burst (HOB) and the coordinates of the hypocenter (position directly under the bomb). To determine the orientation of the bomb while it is in free fall, a large number of identical mockups (no explosives) of the original bomb were studied in free fall. It was found to fall with a tilt of 15 º.

*Bomb Design*

The bomb design consisted of a massive cylindrical steel housing for two subcritical components of highly enriched uranium. When the bomb is detonated by a radar controlled altimeter, explosives are ignited, sending the two components towards each other, creating a super critical mass, at this point neutron multiplication begins. The implications of using a radar controlled altimeter is that tall buildings could cause false altitude feedback, thus detonating the bomb at a higher position than expected. This issue, of course, is avoided in the method used above, but should provide at least a little insight into the sheer volume of complications involved in this study. It is also important to realize that the materials used in the bomb play a huge role in determining the parameters of the radiation that escapes the bomb, and thus the resulting doses.

*Yield and Height of Burst*

The height of the burst and the yield play opposite roles in determining the exposure directly under the bomb. So by estimating one variable accurately we can discern the other variable well too. Samples were collected in this area to aid in this calculation, as well, a three dimensional Monte Carlo calculation was done in Los Alamos National Laboratory (LANL). The radiation samples were re-measured using improved methods and the Monte Carlo was performed using an improved (increased energy resolution) database of cross section data (from the Evaluated Nuclear Data Files ENDF/B6.2). Since neither yield nor HOB is well known, the DS02 uses specially designed analytic interpolation tool to maximize the agreement between yield and the height of the burst, while at the same time minimizing the variance between them. The DS02 confidently estimates the yield at 16 kt (± 2 kt) at a height of 600 m, updated from the DS86 yield of 15.1 kt and a height of 580 m. It is important to realize that this is not an elaborate exercise in over-fitting a curve to data; the same methods described above were applied to Nagasaki data and the calculations resulted in impressive agreement. Since Nagasaki doesn't have the same complications (Neutron Discrepancy) it is often used to validate new approaches to estimating the parameters in Hiroshima.

Using the new ENDF/B6.2 data files, the DS02 Monte Carlo also provided a modified radiation spectrum. The improved cross section resolution contributed to a 31% increase in estimated gamma-ray leakage, while the estimated total neutrons remained unchanged. In the Hiroshima bomb, secondary and delayed gamma-rays constitute most of the gamma dose to survivors.

## Radiation Transport Calculations

Armed with new estimates of yield and HOB the DS02 can begin tracking radiation from the bomb. Of primary concern, from the bomb, are neutrons and gamma-rays, since bomb beta and alpha radiation will have too short of a range to be of serious concern.

*Neutrons*

The neutrons are categorized as either *prompt* or *delayed*. In the fraction of second that the bomb has been detonated, but is still in tact and sustaining the fission process, prompt neutrons are produced. Fission products create delayed neutrons during the fission process.

*Gamma Rays*

Prior to destruction the bomb emits gamma rays, after the explosion the fission products emit gamma rays, and also as the neutrons interact with their environment (the air, the ground, the bomb itself) they too create gamma rays.

*Source Term*

The Los Alamos National Laboratory was responsible for reconstructing the initial second of the detonation of the bomb. In this 'one second' of detonation a Monte Carlo simulation estimates the radiation as it escapes the boundary of the bomb. This 'source term', provides a description of the composition of the fissile debris from which is used to estimate the delayed radiation. In order to calibrate and benchmark this calculation, multiple tests were done including a Little Boy replica (LBR) operated as a critical assembly. The test revealed that the newly added detail in the ENDF Uranium cross sections brought the simulation closer to measured results. The LBR also suggested a 16 kt payload, reinforcing the reliability of the 16 kt estimate made above. Additional studies were carried out to 'thoroughly characterize' the source term by checking leakage through the steel case at the Los Alamos Neutron Scattering Center (LANSCE). It suggests that the gamma-ray leakage accounts for no more than 4% of the total gamma-ray radiation, the majority of the gamma-rays are then secondary and delayed.

*Prompt Radiation Transport*

Starting with the 'source term', the transport or 'air-over-ground' free-field calculations are preformed. At the Oak Ridge National Laboratory (ORNL) they take the 'source term' data from LANL and track the radiation that directly escapes the bomb. During this simulation, this 'prompt' radiation is allowed to be absorbed and can be re-emitted with a different direction, energy and/or composition, thus becoming 'secondary' radiation. The secondary radiation is also tracked.

*Delayed Radiation Transport*

The 'delayed' radiation calculations are carried out at a different location, the Science Applications International Corporation (SAIC). The delayed radiation originates from the fission fragments in the bomb's fireball. In Hiroshima delayed radiation accounts for approximately half the total dose, and are almost entirely due to gamma-rays. The fireball was modeled with STLAMB hydrodynamic code which calculates the location of the fission debris source within the fireball. This was the only part of DS02 detonation calculation not done with three-dimensional geometry as funding did not allow for it. This, of course, is where further improvements or validation can occur.

*Prompt & Delayed*

The collection of these calculations defines what is termed 'free-in-air' kerma. Kerma stands for 'Kinetic Energy Released in Material'. This data is eventually used to in conjunction with epicenter coordinates, yield data, shielding data and survivor locations in order to estimate doses to organs of the victims. The shielding data account for humidity, air density, surface composition, structures, terrain and the body of the victim.

This is implemented using the transport data above, and using discrete ordinates radiation transport (DORT). DORT only allows particles to scatter along a finite number of directions rather than in a continuous field. The entire geometry is divided into a 'fine space mesh' resulting in a numerical integration that provides solutions to the Boltzmann transport equation. ORNL DOORS 3.2 code was used for this DORT calculation.

The modeled environment was cylindrical in geometry and extended to an altitude of 2000 m and a radius of 3000 m. The collided and uncollided neutrons and gamma-rays are summed at the end of the simulation and DOORS 3.2 (now called VISTA) is used to combine prompt and delayed radiation as well as to account for shielding.

**Radiation Measurements**

The details of the methods used for radiation measurements in the DS02 is elaborate enough to warrant an entire summary unto itself. As such, this section will briefly outline these measurements.

When fast neutrons interact with surrounding material and via scattering, slow down and are termed 'thermal neutrons'. Thermal neutrons can be absorbed by an atom and thus activate the element that absorbs them, $^{36}Cl$, $^{60}Co$ and $^{152}Eu$, for instance. A measurement of the activity of these elements can indicate the neutron fluence through that sample. Much like all of the calculations prior to this, measurement of the sample and the extrapolation of the neutron dose is not trivial.

Fast Neutron Activation of $^{32}P$ in sulfur adhesives for insulating electric power poles. Quartz inclusion, high temperature and pre-dose thermoluminescence techniques were used in ceramic bricks and roof tiles. Activation in Cobalt ($^{60}Co$) and $^{152}Eu$ measurements were also made by looking at a variety of decay particles. For the DS02 alone, over 300 trace radiation measurements with existing techniques and over 150 with methods developed for A-bomb research have been made. Accelerator Mass Spectrometry (AMS) has been used to make $^{36}Cl$ measurements as well as $^{63}Ni$ measurements in Cu samples. While some of these techniques measure fast neutrons, most measure slow (thermal) neutrons.

**Transmission Factors**

To relate the radiation measurements in a sample to the free-in-air kerma calculations Transmission Factors (TFs) are required. In DS02 the transmission factor is defined as the ratio of the sample activation to the FIA activation at a height of one meter above ground at the same distance. Many parameters were taken into account in the use of the Transmission Factors including, sample height, shielding of the sample by both surrounding material and surrounding structures/objects, neutron energy cross sections, isotope(s) producing the measured isotope, and the composition of the material. Special care was taken to adjust the quartz TLD because new measurements were not performed. As a result the TFs for the TLDs depend on the accuracy of the assumption that the angle and energy distributions of the incident gamma-ray fluences are similar enough at the sample locations.

**Survivor Dosimetry**
Calculating the dose to the survivors is the purpose of the dosimetry system. The system tracks the energy deposited in 16 different tissues in survivors. Transmission Factors are not used, as were in the *in situ* samples, instead, an 'organ spectrum database' is used. The database consists of thousands of Monte Carlo transport histories connecting the energy-angle radiation fluences to the energy response in specific organs.

**Survivor Shielding**
The majority of shielding structures in Hiroshima at the time of the bomb were constructed primarily of wood. Survivors were assigned to an appropriate shielding category and the required transmission factor was applied. However, certain special cases were identified since this method was implemented in the DS86. However, the special cases were rectified in the DS02 by subdividing the shielding categories further.

Surprisingly the shielding provided by large terrain features such as Hijiyama Mountain was not included in DS86. In the DS02, these were accounted for, but seemed to have little overall effect on the TFs of the Hiroshima survivors.

**Uncertainty Analysis**
Perhaps one of the greatest additions to the dosimetry system in 2002 was the inclusion of uncertainty analysis. As with any rigorous calculations of this size, the scientific mind will always inquire about the accuracy and reliability of the estimates provided. This was one of the recommendations specifically offered by 'The Committee on Dosimetry for the Radiation Effects Research Foundation of the U.S. National Research Council". Analysis of the components that contribute to both systematic and random uncertainties are included in the DS02. As described above, DS02 software is modular and as such each module is responsible for providing the uncertainties associated with its calculations. The uncertainties of individual components in each module (computational element) are 'inferred' from input parameters, reaction cross sections, computational methods, computational statistics, any assumptions made and on expert judgment. Although it is nice to have each module conduct its own uncertainty analysis, this modular arrangement is also advantageous because it permits the separation of the uncertainties into the two types mentioned above (systematic and random). *Systematic* uncertainty describes the chance that a discrepancy would cause the does to all individuals to change in the same manner. On the other hand, the *random* uncertainty value relates to discrepancies that would affect each survivor 'more or less independently'. The DS02 uncertainty is assessed for the source, the free-field radiation, house-shielding and body-shielding modules of the system.

**Concluding Remarks**
It is easy to get caught up in finding all the little things that could have been done differently during this 50+ year long study, but it is important to remember the majority of the data these scientists are forced to work with are not generated in a controlled environment like a lab. They don't have the luxury of designing an experiment to remove as many variables as possible. They are forced to make due with the data and the technology they have available to them.

It is easy to state that a Monte Carlo simulation was performed to track all of the neutrons along their respective paths, but to perform that type of calculation takes a great deal of effort. For example, although the dose from the bomb itself is received within the first few seconds, the Monte Carlo calculation to estimate the emitted radiation required months of complicated preparation and many hours of computation on a 'massively parallel' computer.

As science continues to acquire new tools for probing the world around us, and as technology continues to grow to allow greater and greater amounts of computing power to process all of this new data we collect the results of this study will continue to improve and eventually converge on a definitive answer. The DS02 has made a giant leap towards its target.

**References**

[1] Kerr G. D., Young R. W., et al., Reassessment of the Atomic Bomb Radiation Dosimetry for Hiroshima and Nagasaki – Dosimetry System 2002 – DS02, Radiation Effects Research Foundation, 2002.