Initial process of the nuclear explosion and cloud formation by the Hiroshima atomic bomb

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Introduction

The atomic bomb, named Little Boy exploded over the Hiroshima city at 0815 on August 6, 1945. According to the report of radiation dosimetry system DS02 (Young and Kerr 2005), the height of burst (HOB) and the energy yield of explosion are estimated to be 600 ± 20 m and 16 ± 2 kt TNT, respectively. Although the official information is not yet available about the detailed structure and composition of Little Boy, the amount of initially loaded uranium is reported to be 64.15 kg, the average ^{235}U enrichment of which is 80 % (Coster-Mullen 2008). Using equivalent values per yield of 1 kt TNT (Glasstone and Dolan 1977), the 16 kt TNT explosion can be converted to the total fission number of 2.32×10^{24} corresponding to ^{235}U mass of 910 g as well as the total released energy of 1.6×10^{13} cal. If a spherical ball is made from 64.15 kg of uranium with a density of 19.05 g cm^{-3}, its diameter will be 18 cm, something like a valley ball. The duration time of the fission chain reaction that continued in Little Boy is considered to be about 1 μsec.

The most outstanding feature of the atomic bomb explosion is that a huge amount of energy is released within a very short time in a very small space, which produces a core with extremely high temperature (> 10^7 °K) and pressure (> 10^6 atm). This core expands very rapidly transmitting its energy to the surrounding materials mainly by low energy X-ray. The whole bomb material is engulfed and vaporized by the expanding core, which is called fireball. According to the description in *The Effects of Nuclear Weapons*

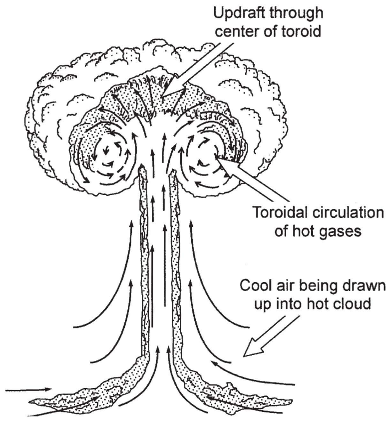

Fig. 1. Mushroom cloud formed after nuclear explosion in air at low altitude.

(Glasstone and Dolan 1977), at 0.1 msec after 20 kt explosion, the temperature of the fireball decreases to 300,000 °K with a radius of 40 feet (about 12 m). At this temperature, as the expansion velocity of the fireball decreases comparable to the local acoustic velocity, a shock wave appears at the fireball surface and its front moves ahead of the fireball expansion. At this stage, because of the opacity of shock wave heated air, the internal fireball is not visible through the shock wave front. Then, at 0.1 – 0.3 sec after the detonation, as the air becomes less opaque with the temperature decrease, the luminous inner fireball can be seen with the surface temperature of 6,000 – 7,000 °K. The fireball loses its luminousness in several seconds.

In case of the Hiroshima explosion, the shock wave blast was considered to arrive at the ground about 1 sec after the detonation, while the fireball began to ascend without touching the ground. As the fireball rose up, a strong upstream of air followed it like a chimney. Then so-called 'mushroom cloud' was formed. A simple scheme of mushroom cloud structure is drawn in Fig. 1. The formation process and radioactivity distribution of the Hiroshima atomic bomb are discussed in this paper.

Hydrodynamic simulation for Little Boy explosion

During the processes elaborating DS86/DS02, US working group carried out hydrodynamic simulation of Little Boy and Fatman (Nagasaki bomb) for the purpose determining the position of the rising fireball as well as air density disturbance by the explosion, using STLAMB code that was developed to simulate hydrodynamic processes for low altitude nuclear explosions. An example of air density contour plot obtained by STLAMB calculation in DS86 is shown in Fig. 2 for the Little Boy explosion (height of burst: 580 m, yield: 15 kt) (Roesch 1987). After the initial rapid growth up to a radius of about 260 m, the

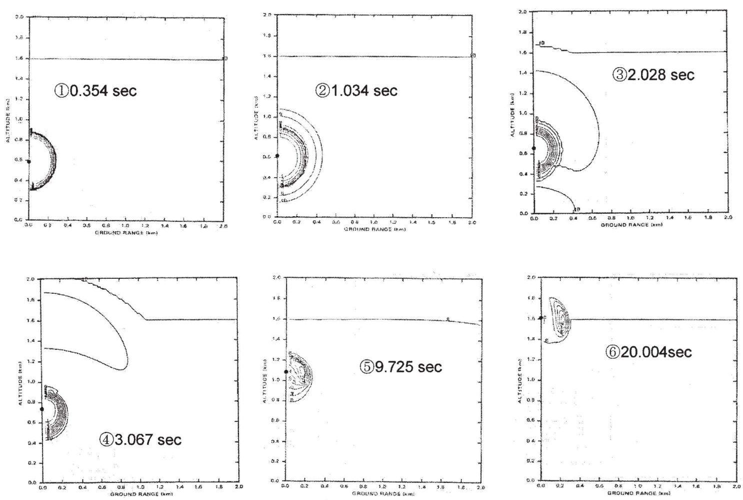

Fig. 2. STLAMB simulation of Little Boy explosion in DS86. Air density contour.

internal pressure of the fireball reached equilibrium with the ambient air at 0.35 sec after the detonation. At this moment the height of the fireball center did not move yet from HOB of 580 m. The air density of the fireball center was 2.26×10^{-5} g cm^{-3}, while 1.11×10^{-3} in the ambient air. The shock wave front already went ahead of the fireball, at 120 m from the fireball surface, but it can not be seen in Fig. 2. At 2.028 sec, the shock wave was already reflected at the ground surface. At 3.067 sec, the reflected wave passed through the fireball. The fireball began rising at a speed of 50-60 m sec^{-1}. It went up to 1100 m at 10 sec, and 1600 m at 20 sec. The shape of the fireball was changing from spherical to toroidal.

Similar STLAMB simulation was carried out during the process developing DS02. The author received the output lists of STLAMB calculation for Little Boy (HOB: 600 m, 16 kt) up to 3 min after the explosion (Egbert 2010). Two sets of STLAMB results were obtained: one (STLAMB-1) is up to 30 sec with 18 time intervals and another (STLAMB-2) is up to 3 min with 12 time intervals. From these data temporal change of the height of the fireball center is plotted in Fig. 3. At 3 min after the explosion, the fireball rises up to 7,000 m.

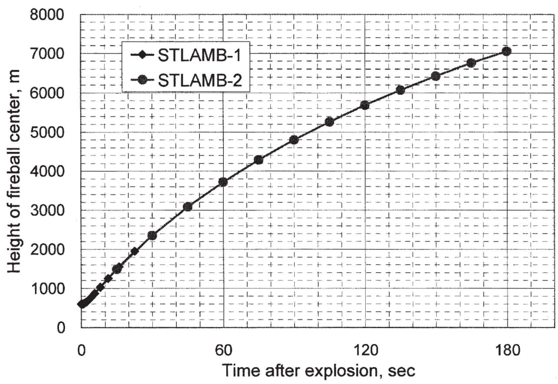

Fig. 3. Height of cloud center after the bombing

Comparison with observation in Nevada test site

A large report that compiled observation for all atmospheric nuclear tests in the Nevada test site was obtained through Internet (Hawthone 1979). From this report, seven tests comparable to the Little Boy explosion were chosen that were conducted by airdrop and exploded at the height where the fireball did not touch the ground. Rising pattern of the atomic bomb cloud for these seven tests were compared in Fig. 4 with the STLAMB simulation for Little Boy.

In Fig. 4, HOB values for Nevada tests are adjusted to be the same HOB (600 m) as Little Boy. The result of STLAMB simulation is similar to BJ Charlie（14kt）and BJ Dog（21kt）. By extrapolating the tendency of STLAMB simulation to the later period, it can be roughly said "The cloud height of Little Boy was about 8000 m at 4 min, and ascended about 12000 at 12 min".

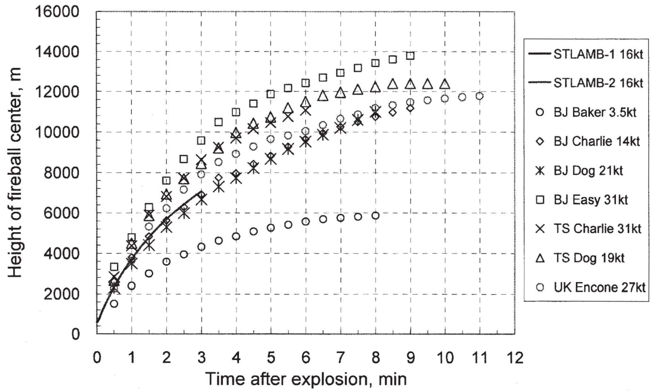

Fig.4 Comparison of cloud rising between STLAMB simulation and Nevada observations.

Size of the atomic bomb cloud

Values of the fireball radius obtained by STLAMB simulation are plotted in Fig. 5. RFB indicates horizontal radius of the cloud, while RFBM is considered to be vertical radius of spheroidal cloud or toroidal cloud. Several observations are also reported for Nevada tests about the cloud size increase. According to these observations, the horizontal diameter increased almost linearly with time up to 20 – 30 min after explosion. The horizontal width (cloud top – cloud bottom), however, seemed to saturate at a constant value after the cloud stopped to ascend.

Taking into account the results of STLAMB simulation (Fig. 5) as well as observations of nuclear tests in Nevada, an ideal case of the atomic bomb cloud formation with the same bomb parameters as Little Boy is plotted in Fig. 6 up to 20 min after the explosion. The cloud ascends until 12 min after the explosion up to the center height of 12 km. The horizontal radius increases linearly with the elapsed time

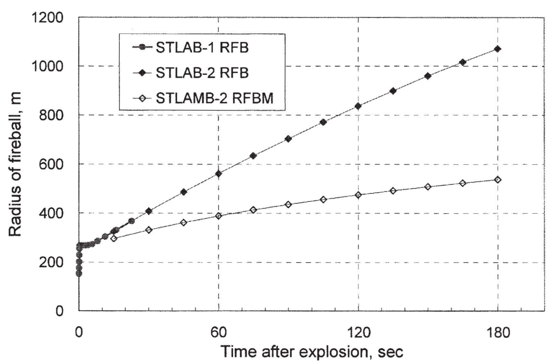

Fig. 5. Cloud radius by STLAMB simulation: RFB and RFBM.

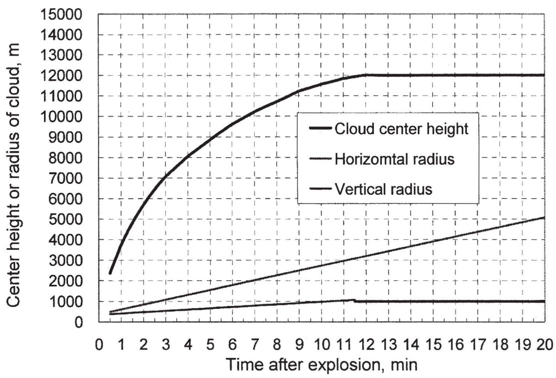

Fig.6 A-bomb cloud formation in case of the same parameters as Little Boy: HOB; 600 m, 16 kt.

and it becomes 5 km at 20 min, while the vertical radius (half value of the cloud thickness) saturates at 1 km at 12 min.

Temperature decrease and particle formation

As the fireball rise up, its temperature decreases by various mechanisms of thermal radiation, adiabatic expansion and mixing with cool air. With decrease of temperature, vaporized materials of the bomb components begin condensate and solidify, forming small particles that absorb and/or adsorb fission product nuclides. In order to consider the process of particle formation, time sequence for temperature decrease of the fireball is estimated based on STLABM simulation as well as literature data.

Although temperature data are not included in the output of STLAMB simulation, the air density at the fireball center is provided in the list. Considering that "pressure equilibrium" between the fireball and the ambient atmosphere is attained at 0.4 sec after explosion, the air density can be related with temperature

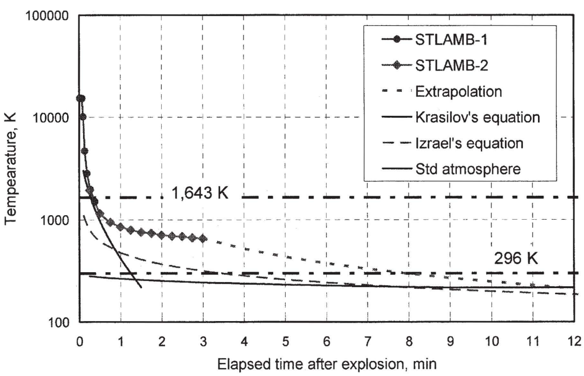

Fig. 7. Temperature change of the fireball/atomic bomb cloud.

based on the ideal gas equation of $PV = nRT$. For example, compared with air density of 1.16×10^{-3} g cm^{-3} in the ambient air of about 300 °K, air density of 2.26×10^{-5} g cm^{-3} at 1 sec corresponds to 15,400 °K. Temperature decrease obtained by this way from STLAMB calculation is plotted in Fig. 7 together with temperature curves proposed from Russian scientists. Black solid line is equation; $T(t) = 7500°K \exp\left(-\frac{1}{3}\sqrt{\frac{20}{q}t}\right)$ by Dr. Krasilov (2008), while red broken line is taken Izrael' s book (1995); $T(t) = 4000t^{-0.588}$ (t<40sec) or $2183t^{-0.374}$ (t>40 sec) for 20 kt air burst. Green dot line is extrapolation of STLAMB-2 up to the point of ambient temperature at 12 min using Izrael's equation of $T(t) = a \cdot t^{-b}$. Blue line indicates ambient air temperature at the height of the fireball (Fig. 6). Values of 1,643 and 296 °K are melting point of iron oxide (FeO) and dew point for the air of 27 °C and relative humidity of 80 %, respectively. STLAMB plot in Fig. 7 indicates that droplets of FeO begin to solidify at about 20 sec after the explosion.

Size distribution of particles in the atomic bomb cloud

According to *The Effects of Nuclear Weapons* (Glasstone and Dolan 1977), in case of air explosion by which no appreciable quantities of surface materials are taken up into the fireball, small particles with the range of 0.01 to 20 μm are formed from condensed residues of the bomb materials. Although it is difficult to say definitely how was the real situation in Hiroshima, the photo taken from the B28 bomber at 2 – 3 min after the bombing (Fig. 8) supports the idea that particles of dirt and dust raised by the bomb blast almost remained at low altitude and were not substantially sucked into the fireball or the cap part of mushroom cloud.

The process of particle formation from vaporized materials is discussed in detail by Storebo (1974) dividing the process into nucleation, condensation and coagulation. The size distribution of particles is

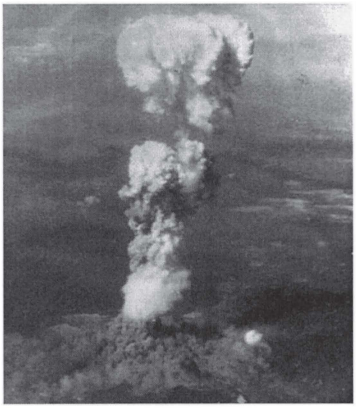

Fig. 8. Photo of the Hiroshima bomb cloud taken from the B29, Enola Gay at several min after the bombing.

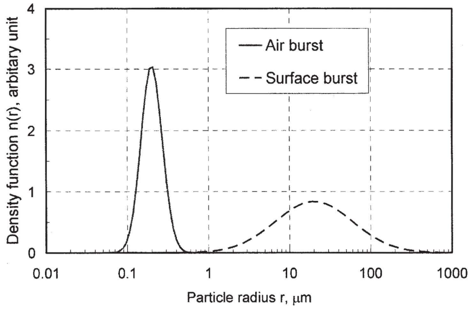

Fig. 9. Examples of particle-size distribution for air burst and surface burst. Air burst; mean 0.2 μm and GSD 1.35, Surface burst; mean 20 μm and GSD 3.

considered to follow a log-normal law;

$$\frac{dn(r)}{d\ln r}=\frac{1}{\sqrt{2\pi}\sigma}\exp\left(\frac{-(\ln r-\mu)^2}{2\sigma^2}\right)$$

Here, *n(r)*: particle density function for diameter, *r*,

μ, σ; geometric mean and geometric standard deviation, respectively.

In Storebo's paper (1974) μ and σ values are evaluated as parameters depending on the initial condition of vapour-to-air mass ratio in the fireball. Assuming that 4 ton of iron was vaporized by the Little Boy explosion and mixed with the spherical air mass of 260 m radius and 2.26×10^{-5} g cm^{-3} density, a value of 0.002 was obtained as a vapour-to-air mass ratio. Then, values of geometric mean and GSD (geometric standard deviation) were obtained to be 0.2 μm and 1.35, respectively. Histograms of log-normal particle-size distribution are shown in Fig. 9 together with a case for a surface explosion for which particle distribution were arbitrarily chosen as geometric mean of 20 μm and GSD of 3.

As an information to consider a possibility of local fallout by gravitational deposition on the ground,

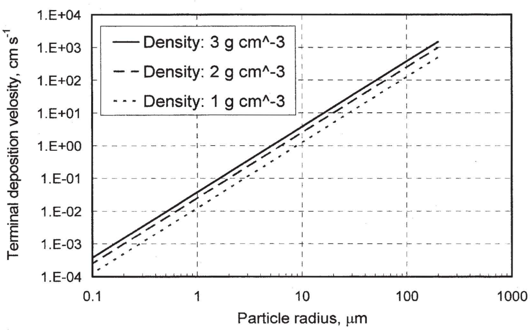

Fig. 10. Particle-size dependency of terminal descent velocity for particle density of 1, 2 and 3 g cm^{-3}.

terminal velocity of descending particles is calculated based on Stokes' equation;

$$V_t(D) = \frac{D^2 \rho g}{18\eta}$$

Here, $V_t(D)$; terminal velocity of particle with diameter, D,

ρ, g and η are density, gravitational acceleration and viscosity.

The results are shown in Fig. 10 as a function of particle radius for three values of particle density. Terminal velocity for particle radius more than 200 μm is not plotted in the figure because deviations from the simple Stokes's equation become significantly lower in this region than those based on Stokes's equation. As can be seen in Fig. 10, deposition velocity drastically changes with particle size. Considering that the fireball by Little Boy could rise up to about 10,000 m at 10 min after the explosion and the deposition velocity for the supposed particle-size distribution (Air burst in Fig. 9) would be less than 0.1 cm s^{-1}, the possibility of local fallout due to gravitational deposition, so-called 'dry deposition' can be excluded. The only realistic path of local fallout is considered to be deposition on the ground with rainfall, so-called 'wet deposition'. In case, however, particles more than 100 μm were somehow included in the atomic bomb cloud, they could descend to the ground by gravity after several hours after the explosion.

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