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The Light of the Atom Bomb

In brightness, a nuclear detonation is comparable to the sun.

Clay P. Butler

On 17 July 1945, the Albuquerque (N.M.) *Journal* carried an Associated Press dispatch describing an explosive blast which had occurred the preceding morning at the Alamogordo Base. Part of this front page news item read:

> So brilliant was the flash from the explosion, Miss Georgia Green of Socorro, blind University of New Mexico student, exclaimed, "What's that?"
>
> She was being driven to Albuquerque by her brother-in-law Joe Willis, Socorro theater operator.
>
> *BRIGHTENS SKY*
>
> The flash, "Lighted up the sky like the sun," Willis said. "The light lasted several minutes followed by a large crimson light in the southwest. We drove down the road several minutes before we heard the explosion."

These people were unaware that they were witnessing the light of the atom bomb, nor did the reporter know that his story would be the first report on the effects of atomic weapons. This was the Trinity Test, the culmination of the Manhattan Project.

This article is a brief description of the fireball produced by a nuclear detonation in the lower atmosphere of the earth, how its illuminance is calculated from thermal radiation measurements, and how it varies with weapon yield. The fraction of the total nuclear energy released as thermal radiation which arrives at a point in space depends on such local conditions as the height of burst above the ground, the state of the atmosphere, the terrain, and the cloud cover. Estimates of this fraction vary considerably; my calculations are based on the assumption that one-third of the total energy penetrates a clear atmosphere far enough to be measured (Fig. 1). At distances of a few miles, the radiant energy consists of ultraviolet, visible, and infrared wavelengths —all designated thermal radiation. Some idea of the amounts of energy involved are given in Table 1 in more familiar terms. The visible region—that is, that part of the radiation which can be seen as a brilliant flash—accounts for about one-half of the thermal radiation or one-sixth of the total weapon energy.

In high altitude nuclear bursts in the Pacific, the night sky was illuminated over millions of square miles with a brilliant flash of light lasting several seconds. Even though clouds covered the sky from horizon to horizon over the Hawaiian Islands the light of the fireball 800 miles away turned the black tropical night into day. The sequence of colors from green to red which filled the sky was awesome.

High altitude detonations not only initiate the light of the fireball itself, but also cause auroral displays, which cross the equator and are visible as far south as Samoa and the Cook Islands (*1*). In the nuclear test of 9 July 1962, over Johnston Island, an auroral line at 3914 angstroms was observed in the zenith airglow at China Lake, California. Normally this line cannot be seen; however, shortly after detonation its brightness showed a sharp rise (*2*). These displays of light are caused by the interaction of thermal x-rays with low-density air, which is quite distinct from the mechanism responsible for the light emitted by the fireball in the lower atmosphere.

As contrasted with conventional high explosives, in which temperatures of a few thousands of degrees and pressures of thousands of pounds per square inch are formed, a nuclear detonation creates temperatures and pressures comparable to those in the interior of the sun in a volume of space a few inches in diameter (*3*). Because the reaction is completed in microseconds, a violent explosion results. The series of events which follow the formation of this tiny star—how the gas expands into a glowing fireball, how the fission products form, and how these effects decay with time—comprise areas of physics, chemistry, and engineering known as the "effects of nuclear weapons." Such studies, starting with fireball phenomenology, are quite distinct from the work leading to the design and manufacture of nuclear explosives.

Shortly after the nuclear reaction has been completed, all fissionable products and remaining fissionable material, as well as the bomb casing, supports, and so forth, are in a gaseous state. As this gas expands, it forms first a symmetrical sphere whose rate of expansion is directly related to the yield of the weapon. The yield of a nuclear weapon is measured in a unit of energy called a kiloton, which is equivalent to 10^{12} gram calories. This is approximately equal to the energy released by 1000 tons of TNT. (A megaton is equal to 10^{15} gram calories.) During the first phase of growth, the edge of the fireball is very sharp and clearly defined, so that its diameter as a function of time can be readily measured from high-speed motion pictures which have been taken with cameras well beyond the region of severe blast damage. This period, when the radiation front is

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Table 1. Caloric equivalents between the total thermal energy radiated for different weapon yields and some familiar energy sources.

Weapon yield (tons equiv. TNT)	Thermal radiation (g cal)	Electric power (kw-hr)	Gasoline (gal)	Food* (time for human consumption)
1	3.3×10^{8}	380	11	120 days for 1 man
10^{3}	3.3×10^{11}	3.8×10^{5}†	11,000	1 year for 310 men
10^{6}	3.3×10^{14}	3.8×10^{8}‡	1.1×10^{7}§	1 day for 1.8×10^{8} people‖

* Recommended adult diet, 3×10^{6} gram calories per day. † Total output of the Niagara Falls Power Project for 30 minutes. ‡ Total output of Grand Coulee Dam for 8 days. § Total fuel for cars and trucks in the United States for 90 minutes. ‖ U.S. population assuming daily average at 2×10^{6} gram calories.

coincident with the shock wave, is marked by the most rapid rate of growth, and hence there are no line-of-sight distortions to confuse the image.

A curious change takes place in the luminance of the fireball when it has expanded to about half its final diameter (*4*). Quite suddenly it fades away to a faint glow that produces a distinct minimum in the radiant thermal intensity between what are referred to as the first and second thermal pulses. This phenomenon, known as breakaway, takes place when the isothermal sphere has expanded and cooled to the point where the shock wave advances ahead of the incandescent surface of the fireball. By this time, the air comprising the shock wave is at a temperature of approximately 2000°K which radiates feebly. When air is heated to this temperature it is no longer transparent, and consequently the fireball is hidden behind the shock front. As the shock wave continues to expand, the air temperature falls until the air no longer radiates. As the air becomes more and more transparent, the fireball reappears and seems to increase in brightness. The time when this minimum occurs varies with weapon yield from a few milliseconds for yields less than 100 kilotons to as long as ¼ second for megaton explosions. This minimum in thermal radiation output can be seen in many of the motion pictures which have been released, particularly if one is aware of its existence and is anticipating its appearance. When the distance between the observer and the point of detonation is several hundred miles, well below the horizon, the minimum can be seen easily in the sky glow.

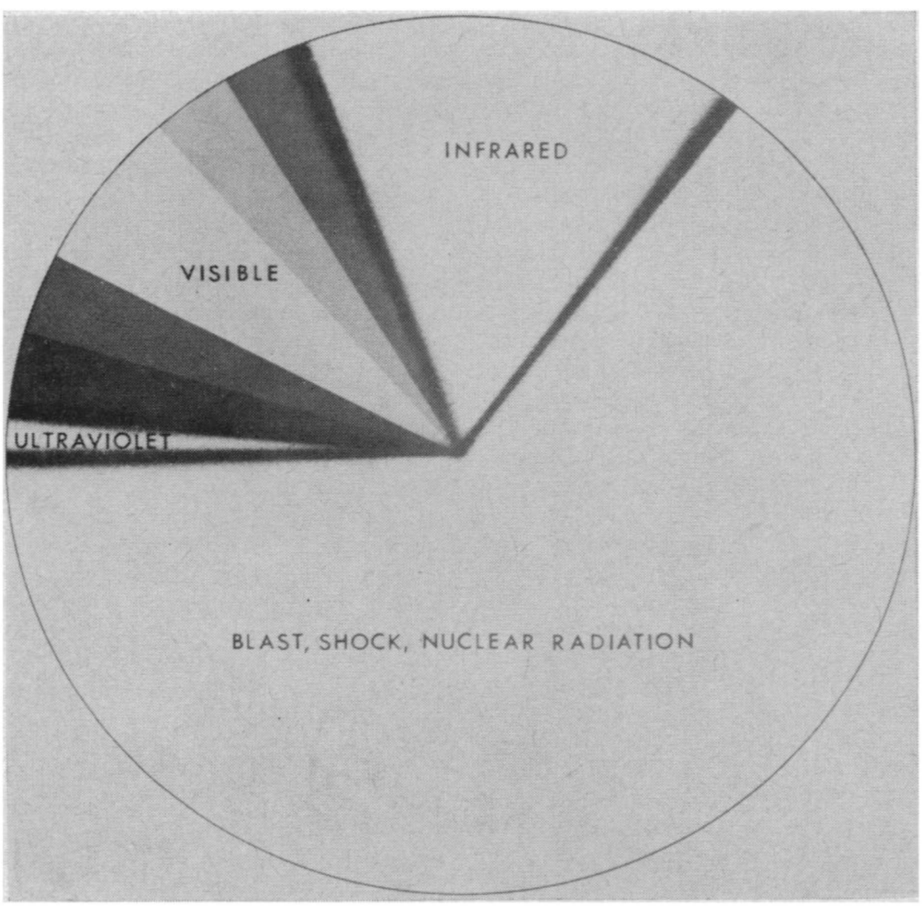


Fig. 1. Partition of energy for a nuclear explosion in air. Thermal radiation includes ultraviolet, visible, and infrared.

Nearly all the energy released is confined within the fireball up to the time of breakaway. Prior to this, less than 1 percent of the thermal radiation has been emitted, even though the shock wave and the radiation front are coincident and the effective temperature is very high. If the yield of a weapon and the radius of the fireball are known at breakaway time, then it is possible to make a simple estimation of the heat intensity of the air in the isothermal sphere.

For a 20-kiloton weapon detonated in air at sea level, the radius of the fireball at this time is about 380 feet. At normal temperatures and pressures, a sphere of this size would contain 8400 metric tons of air. Assuming that the specific heat of air for all temperatures could be considered to be 0.30 calorie per gram, it would require 2.5×10^{9} gram calories to raise this amount of air 1°C. Since the time is so short that we can neglect heat losses, it can be readily seen that if the yield is 2×10^{13} calories, then the temperature of the air comprising the fireball must be 8000°C just before the onset of the first minimum.

Following this brief decrease, the luminance increases to a maximum which occurs when the fireball has nearly reached its greatest diameter. By this time it no longer maintains the sharply defined rim which characterized the first pulse, but now appears diffuse in places, with uneven patches around the edge. This change is caused by the violent turbulence which occurs as the huge volume of hot air begins to rise. Its rate of rise for the larger weapons is some 300 feet per second, and during the time when it is emitting light it will have risen more than 3 miles from the point of detonation. After this, no significant amounts of thermal radiation will be emitted because the temperature has fallen to a few hundred degrees.

The thermal radiation of interest in the effects of nuclear weapons includes all wavelengths which will pass through the atmosphere. Since this radiation is emitted from the fireball, it can be described in terms of the power temperature of the fireball surface, corresponding to that temperature at which a black body having the same emitting area would radiate the same total power.

The two parameters required to make a power temperature calculation are total radiant power and radiating area of the source. The first is measured by mounting a blackened receiver at a known distance from the point of detonation with its surface exposed normally so that its field of view will include the entire fireball at all times. The rise in temperature of the receiver (a thin black disk of copper or silver) is due to the absorption of all the radiant energy reaching it, regardless of wavelength. Thermocouples translate this temperature into an electrical voltage which is then recorded on a high-speed oscillograph. The radiant power in calories per square centimeter per second can then be calculated from the heat content of the receiver, its time-temperature rise, and its projected area. This gives the total power received regardless of the dimensions of the source. The second measurement, the radiating area of the fireball, is taken from individual frames of high-speed motion picture film. The area measured by film, which is sensitive to a relatively narrow spectral region, may be slightly smaller than the true radiating area seen by the black receiver, but this inherent limitation in the technique is not large.

A further problem in arriving at a power temperature of the fireball lies in uncertainties in the absorption and scattering properties of the atmosphere. Before calculating the power radiated, it is always necessary to increase the measured flux at any distance by an amount corresponding to that lost to the atmosphere beween the fireball and the receiver. This loss of radiant energy in its passage through the atmosphere is highly selective in spectral regions where absorption of such gases as water vapor, carbon dioxide, and ozone occurs. Scattering of radiation due to particles of all kinds floating in the air changes the direction of propagation both into and out of a given area facing the bomb. When water vapor condenses to actual droplets, as in a cloud, scattering diffuses the radiation to such an extent that measurements of power temperatures cannot be made. Atmospheric transmission includes both effects, so that when the flux is corrected for this loss its only variation with distance is the inverse square law.

The power temperature of the fireball and the total radiant power per unit area of radiating surface are related by the Stefan-Boltzmann law. If the emissivity is unity, that is, if the fireball emits as a black body, then the power temperature will be its true temperature. However, spectral data have shown that there are some regions of the spectrum in which the fireball does not, in fact, behave as a perfect radiator. Therefore its real temperature may be somewhat higher than the power temperature. An instrument measuring the total flux cannot distinguish for the same irradiance between a surface with high temperature and low emissivity and a surface with lower temperature and high emissivity. An extreme example of this effect is the solar corona which shows an apparent temperature of 10^6 degrees Kelvin, yet its emissivity is so low that its contribution to the solar constant is negligible.

The maximum power temperature measured in this way varies from 6000° to 8000°K. These should be compared to the rough temperature calculations from the yield and from the heat capacity of the air within the fireball.

The visual range, often called the visibility, is defined as the distance at which a large dark object can be distinguished against the horizon in daylight. This is well known for a great many places and for a wide range of meteorological conditions; it can be used for estimating atmospheric trans-

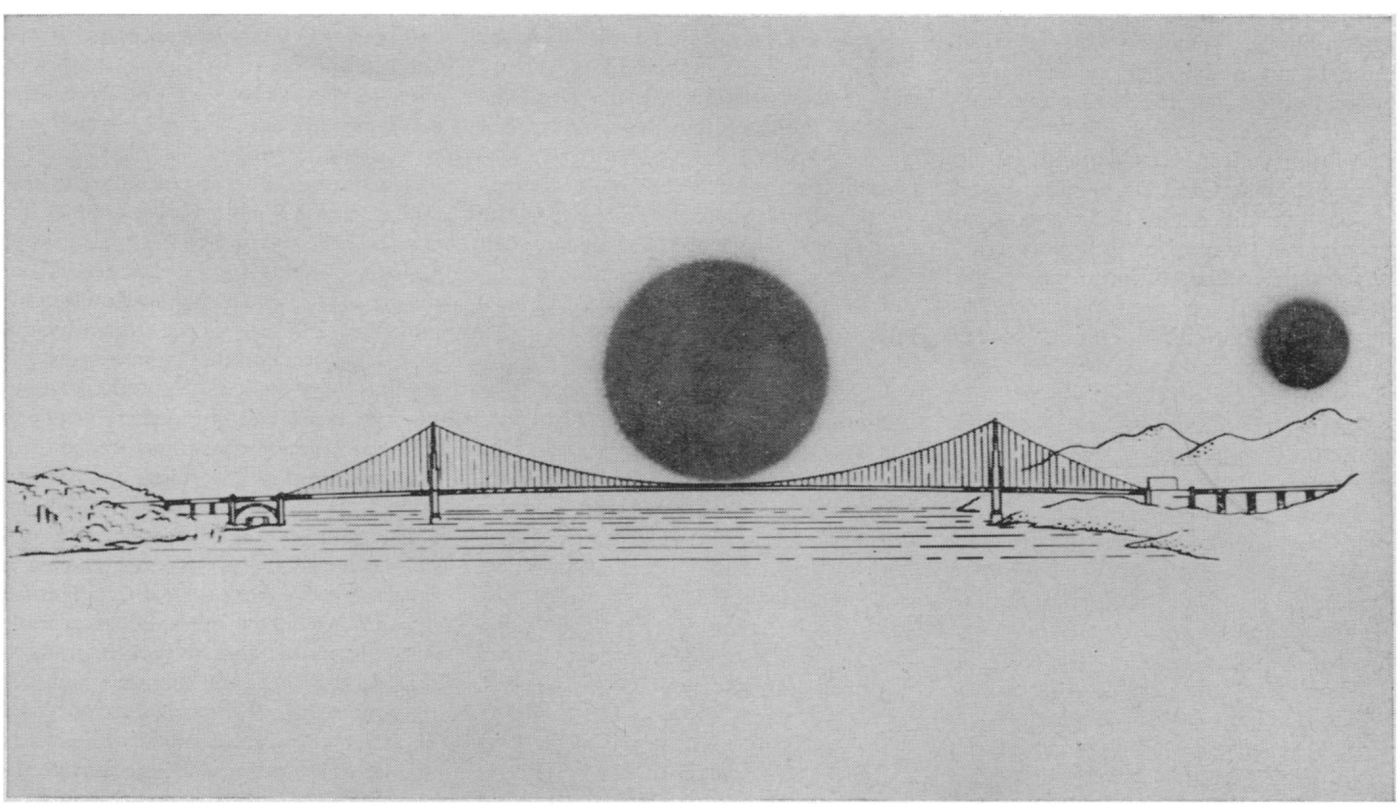


Fig. 2. Fireball of a 20-kiloton weapon detonated 4800 feet above the Golden Gate Bridge as viewed from a distance of 12 miles in the Berkeley Hills. Sun is seen to the right.

mission provided that the distances do not exceed about half the visual range. The reason for this restriction is that at very large distances the radiant energy falling on an exposed surface may consist of more multiple scattered radiation than that received in the direct line of sight. This can be illustrated by comparing direct sunlight with sky light. When the sun is low on the horizon, direct radiation is about half that from the sky, whereas when the sun is in the zenith, the direct solar radiation is several times the scattered sky light.

The primary reason for measuring thermal radiation from nuclear weapons is to evaluate the hazards associated with the heating of exposed objects. These hazards include cutaneous burns in humans, flash blindness, retinal burns, heating and subsequent weakening of wings and control surfaces of aircraft, and the ignition of kindling fuels such as those that helped produce the great fire storm at Hiroshima. Studies of these effects call for detailed information on the thermal radiation, including its spectral distribution, the irradiance history and the total energy as a function of distance, weather, and other factors. Rough scaling laws, which relate the diameter and power temperature of the fireball with the time and yield, make it possible to predict thermal radiation damage for a wide variety of conditions. These laws are based on the data accumulated during the period between 1948 and 1958 when the testing of nuclear weapons was most actively pursued in Nevada and at the Pacific Proving Grounds. While meteorological conditions at these two locations are not typical of most centers of population, sufficient information has been obtained on atmospheric transmission for visibilities comparable to those at the test sites, to allow for rough estimates of the irradiance and of the total energy for weapons less than 10 kilotons to more than 10 megatons, out to distances of 20 miles from the point of detonation. It should be noted that the scaling laws for the thermal output are independent of the type of nuclear reaction, that is, whether the device is a small fission or a very large fusion weapon.

The size of the fireball is illustrated in a familiar setting (Golden Gate Bridge) in the scaled drawing of the yield of a 20-kiloton weapon detonated at approximately one fireball radius above the center of the bridge (Fig. 2). This is an idealized sketch of the fireball at its maximum diameter. By the time this diameter has been reached, the rim is not as sharp and the shape is not as symmetrical as shown, because turbulence will have begun. At the side of the drawing is a scaled view of the setting sun as seen from Berkeley, California, about 12 miles from the bridge. It allows for a direct comparison between the radiating area of the sun and the fireball at this distance. The angular diameter of the sun is 30 minutes of arc, and its apparent diameter is 600 feet at the bridge at this distance.

The luminance of the fireball can be found from its temperature. The primary data from which power temperature calculations are made are shown in Fig. 3. This figure shows the standard thermal pulse of an air burst nuclear weapon, for any yield, at any unobstructed distance. Hence the coordinates are given in scaled units of power and time. When this curve is corrected for atmospheric transmission, the total radiant power at each time after detonation can be found. When the power value is combined with the radiating area of the fireball at corresponding times, its power temperature can be found. A few representative values of temperatures are given (*5*), but these calculated values may be in error by 1000 degrees or more, depending on the precision in extrapolating the observed irradiances back to the surface of the fireball. It is instructive to point out that the effective temperature of the solar photosphere lies between 5830°K and 7000°K (*6*), depending on the definition of the radiating temperature and the location of the radiating layer. This fact indicates an inherent difficulty in the concept that radiating bodies of hot gases have a unique temperature.

It is often convenient to express the light output of a source in terms of its luminous efficiency (number of lumens per watt of energy). This is a function of the power temperature of the source, taken here from the representative values at the scaled time units. When temperatures have been determined, both luminance and luminous efficiency can then be taken directly from handbook tables. It will be noticed that at the peak power output of the fireball, there is a slight drop in the luminous efficiency (Fig. 4). This occurs because the spectral sensitivity of the eye matches most closely the spectral distribution corresponding to a source temperature of 6000°K, an average value for the sun. As the temperature of the source increases to a maximum of about 7600°K, higher amounts of radiant energy fall in the blue region of the spectrum where the response of the eye decreases. (For comparison, a few common light sources are shown with their respective efficiencies.)

The question of how far the atom bomb can be seen depends upon such factors as weapon size, height of burst, atmospheric scattering, the adaption of the eye, the nature of the terrain, and the height of the horizon between the observer and the point of detonation. No effort was made during the years of weapon testing to determine the maximum distance at which the flash could be seen because the answer had little practical value. However, chance observers who happened to be looking in the right direction during the early morning hours have provided some interesting observations. The map in Fig. 5 (Nevada Proving Grounds) gives the maximum area in which people could have seen the flash, and is based on the greatest reported distance. This area has been illuminated only with weapons of less than 100 kilotons, and it is very unlikely that anyone along the eastern edge of this area saw any of the flashes. Most of the Nevada tests have been conducted about an hour before sunrise and by this time dawn has begun in Colorado and eastern Utah. From San Francisco to San Diego, however, the bright glow in the eastern sky could be seen easily by individuals watching the predawn horizon.

The illuminance at considerable distances can be approximated by comparing the maximum thermal output with that of the sun (as observed from sea level) and further assuming for purposes of estimating transmission, that the maximum temperature is 6000°K instead of 7600°K. Atmospheric transmission coefficients from solar constant measurements have been used to calculate the horizontal attenuation out to distances of 40 miles. These figures should be taken with caution, because the earth's atmosphere is far from homogeneous, especially over distances of a few miles. Furthermore, the sun, unlike the fireball, is not immersed in the atmosphere; therefore the transmission coefficients would not be expected to be identical. Regardless of these limitations, if the horizontal transmission is 97 percent per mile, then the illuminance values given in Fig. 6 would actually be found.

An interesting effect of the light from an atomic fireball is shown in the series of prints (cover photo) which were taken from motion picture film made during one of the Eniwetok tests in the Pacific. The device was detonated at night when the birds of the island were roosting in the trees and bushes located between the camera and the point of detonation. With the appearance of the light from the fireball, which at this distance was many times that of the noon day sun, the birds were suddenly awakened and took to the air. Because they were between the camera and the fireball, their silhouettes showed clearly on the film. The time required for them to fly above the tree tops was about the same as the time for the maximum delivery of the thermal radiation pulse. At this time, the intensity of thermal radiation was sufficient to ignite the tail and wing feathers of the black birds. As their feathers burned, they could no longer remain airborne; their trails were marked by curving puffs of smoke as they fell to the ground. These trails are visible in the last two prints of the series. In the motion pictures, it is possible to detect a few birds which remained airborne and continued on their way. These are the white-feathered ones. The differ-

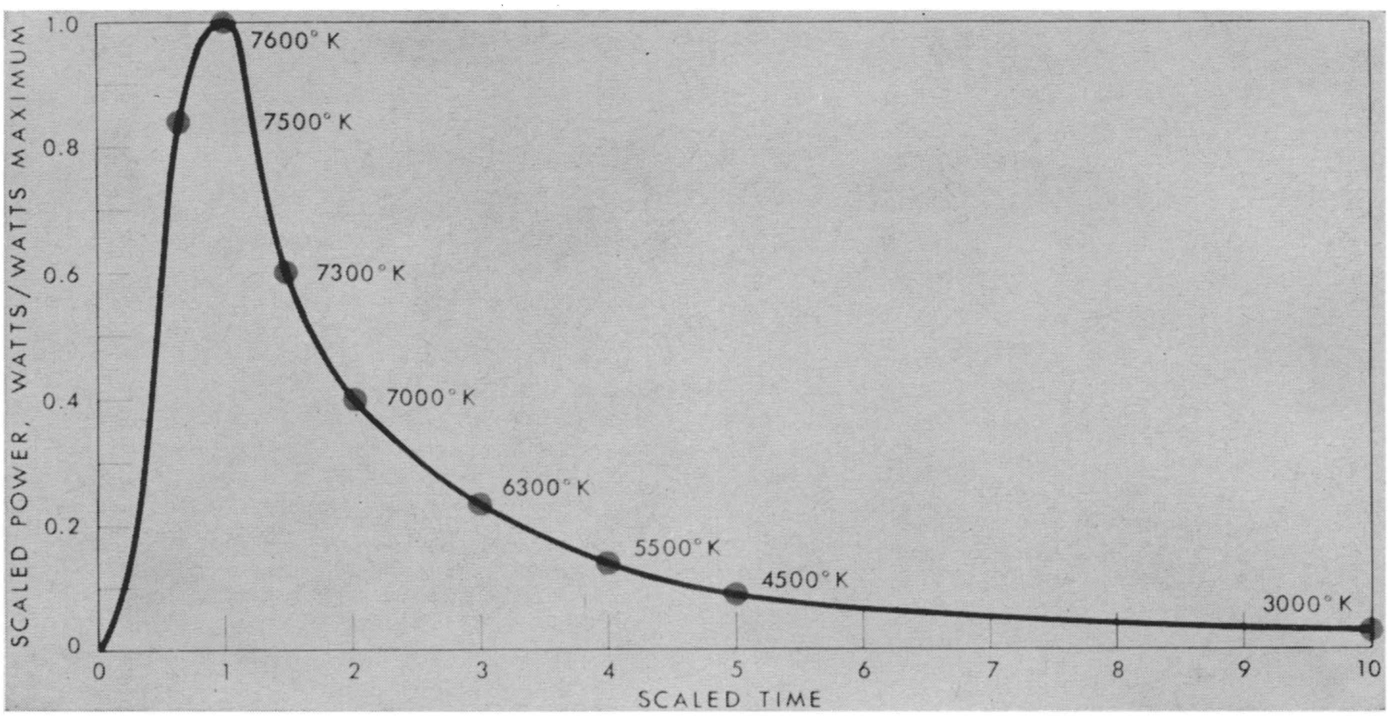


Fig. 3. Normalized thermal radiation pulse from any size nuclear weapon detonated in air. The scale factor for the abscissa varies from approximately 30 milliseconds to 3 seconds depending on the size of the weapon. The temperatures indicated on the graph refer to the surface of the fireball.

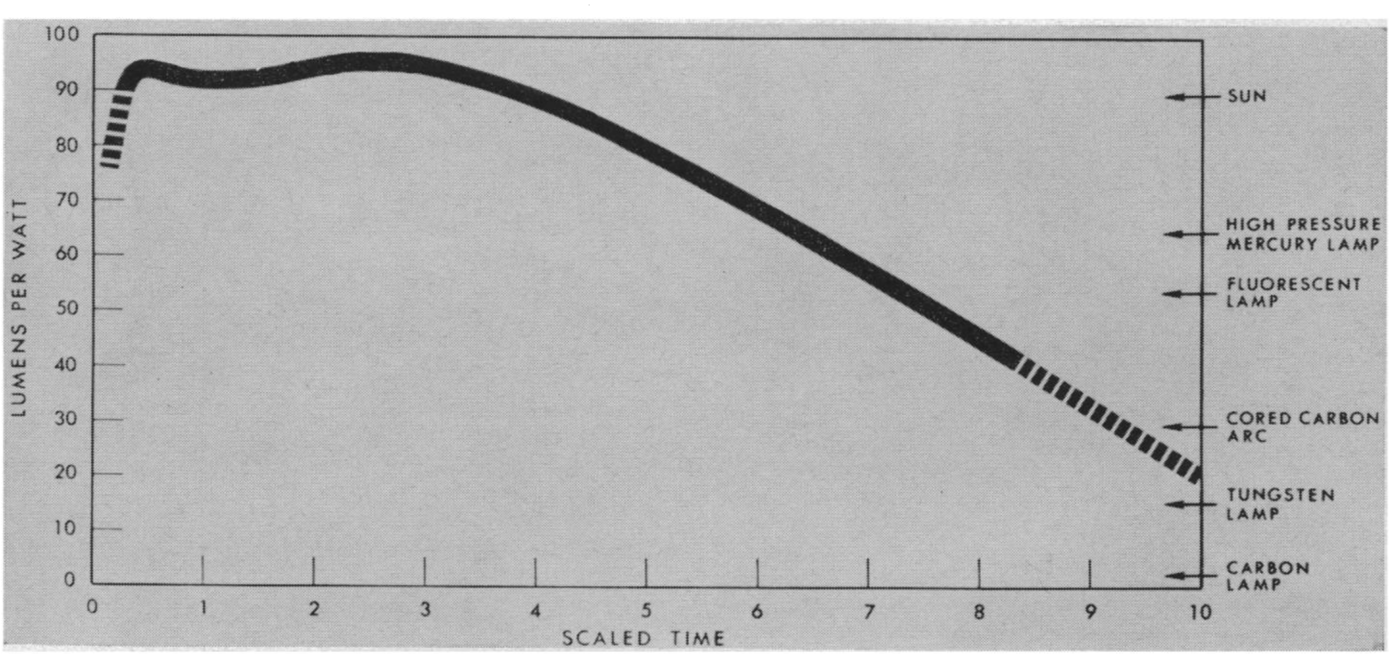
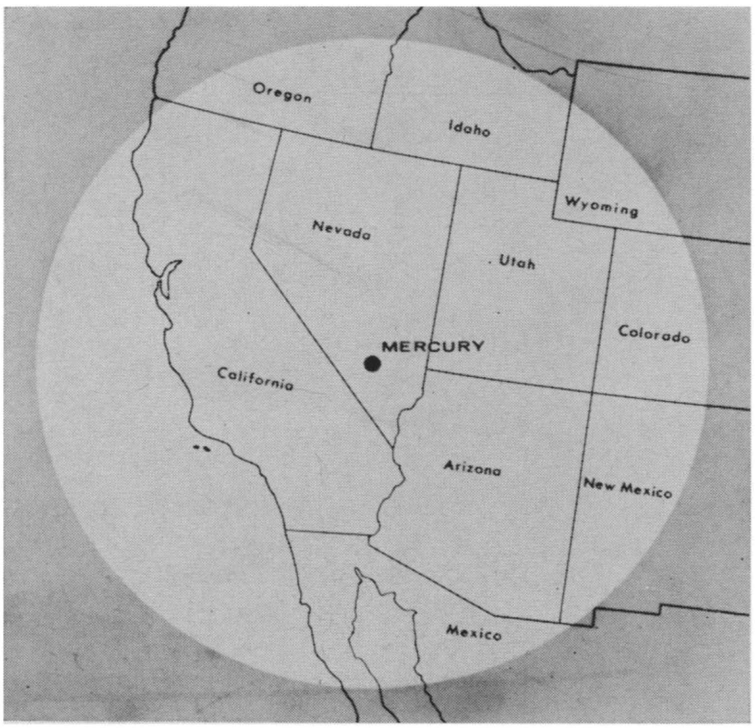


Fig. 4. Luminous efficiency of a nuclear fireball in air. Some other familiar light sources are shown for comparison.

ence in the thermal effects on these two classes of birds is due to the differences in the absorption of thermal radiation. As with sunlight, dark and especially black objects are heated more than white ones, and in this case the energy levels were just sufficient to ignite the feathers of the black terns and not the white ones.

Another way of relating the light of the atom bomb to familiar sights is to compare it with the light of the stars. Some stars are brighter than others, and this difference in luminance as seen with the unaided eye has been used since ancient times to classify each star and planet by its magnitude. These are familiar on star maps where the stars are shown with symbols from —1 to +6. The faintest star which can be seen by eye is about +6.



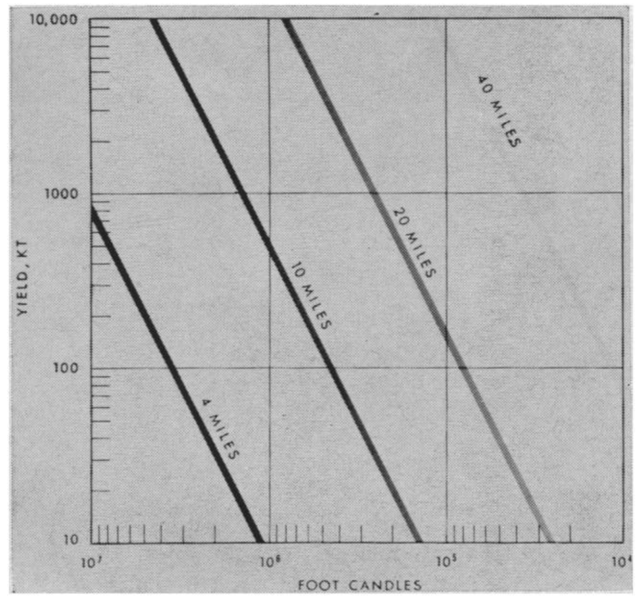


Fig. 5 (left). Map of area illuminated by atomic bombs detonated at the Nevada Proving Grounds. Fig. 6 (above). Maximum illuminance in foot candles for different size weapons at various distances.

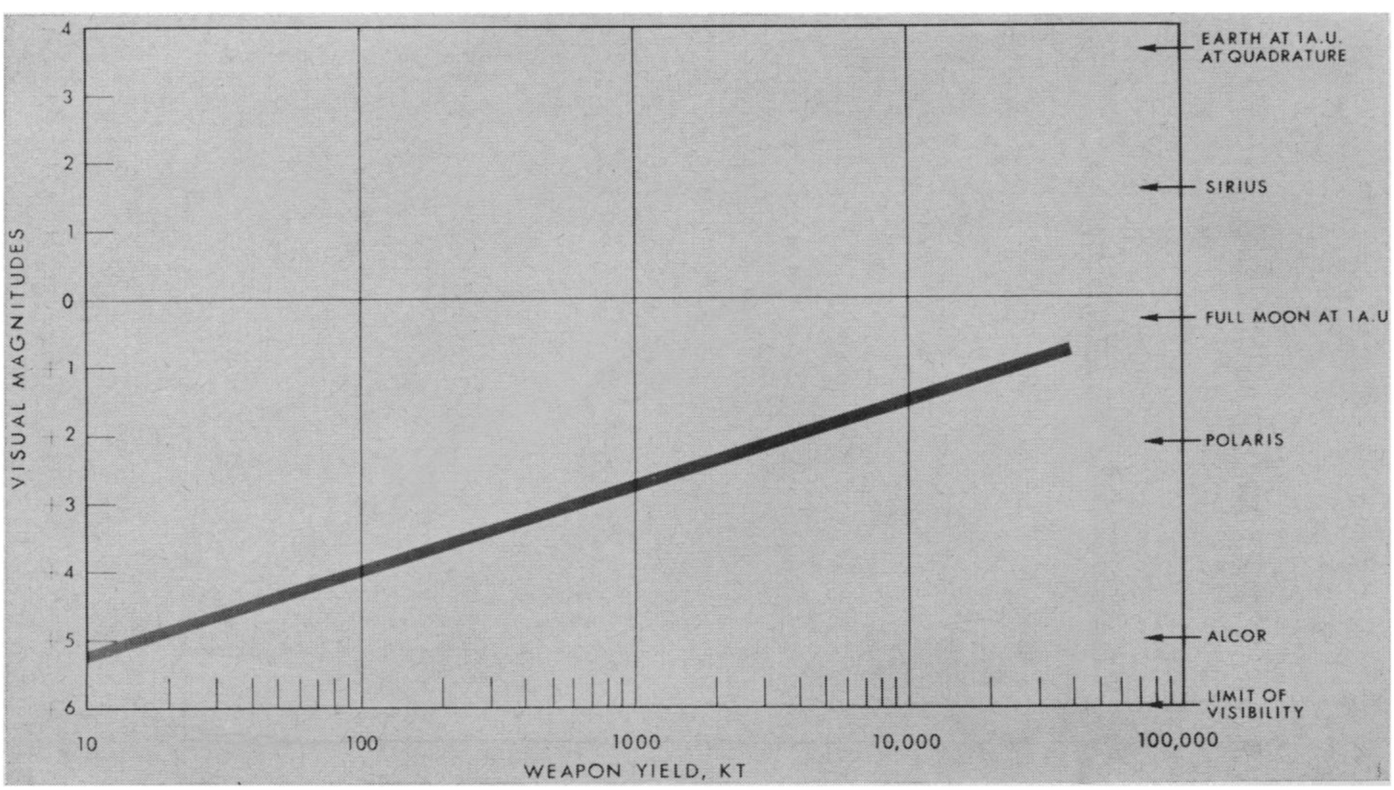


Fig. 7. Visual magnitudes of nuclear detonations in air as they would be observed at a distance of 1 astronomical unit (93,000,000 miles) from the Earth. Increased brightness corresponds to smaller numbers of the magnitude scale.

If we assume that the bomb is detonated at a distance of 1 astronomical unit, we can calculate the magnitude of each weapon size as seen from a distance of 93 million miles. This does not imply that we could see a bomb detonated in space at such a distance; I am concerned only with bombs exploded in air. But if we were at such a distance from the Earth, then the flash of light would have the magnitudes shown in Fig. 7. However, at a distance of 1 astronomical unit the Earth is never dark, and, as indicated on the graph, its magnitude at quadrature is nearly −4, or a little brighter than Venus as seen from the Earth. A 10-megaton weapon would be about 1/100 as bright as the visible quarter of the Earth. The problem of seeing a flash of light 1 percent greater than the background might be circumvented by using a telescope focused on the dark face of the earth, where the background would be quite dark.

It has been seriously suggested that the inhabitants of a planet belonging to one of the nearer stars could detect the light of the bomb with a super large telescope (*7*). It is reasoned that such a flash could not be explained on the basis of a falling meteorite or any other common geological phenomenon and hence would indicate the existence of intelligent life in the solar system. At a distance of 1 parsec, a little nearer than the nearest star, a 10-megaton weapon would have a magnitude of approximately +28, some one hundred times fainter than can be photographed with the 200-inch telescope at Palomar. It does not seem reasonable that such a faint pulse of light could be found above the background of the sun.

On the cosmic scale, the light of the atom bomb is quite weak, so faint in fact that we need not flatter ourselves that we will be noticed. On the local scale however, the light of the atom bomb exceeds all other man-made sources of light and is appropriately likened to a tiny star, indeed like a very small segment of the sun.

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Human Water Needs and Water Use in America

A permanent water shortage affecting our standard of living will occur before the year 2000.

Charles C. Bradley

The current rapid rise in population poses many problems, among them the question, Where are the limits, if any? More carefully stated for America, the question seems to be, how many people can we sustain at what standard of living?

My purpose in this article is to examine one vital resource, water—(i) to show the minimum amount necessary to sustain human life, (ii) to show the amount we are now using in the United States to maintain our standard of living, and (iii) to indicate from these figures when we may expect to find certain ceilings imposed on the crop of human beings in this country.

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While water economics is admittedly important in the complex problem of water supply, no discussion of this aspect of the problem is attempted in this article.

Water Needs of Man

The 2 quarts or so of water which a man needs daily for drinking is a requirement obvious to anyone. Less obvious is the equally vital but much larger volume of water needed to sustain a man's food chain from soil to stomach. This is the water necessary to raise the wheat for his daily bread and the vegetables that fill his salad bowl. This is also the still larger volume required to raise alfalfa to feed a steer from which a man may get his daily slice of meat. All this water represents a rather rigid requirement for human life, and it is water which is consumed, in the sense that it is removed from the hydrosphere and returned to the atmosphere.

An adult human has a daily food requirement of about 2½ pounds, dry weight. If he is strictly a vegetarian, an illustrative approximation of the water requirements for his food chain can be made by assuming man *can* "live by bread alone."

Wheat has a transpiration ratio of 500 (*1*); that is, ideally it takes 500 pounds of water circulating through the wheat plant from the soil to the air to bring 1 pound (dry weight) of wheat plant to maturity. If grain to be milled represents half the weight of the wheat plant, we can say that it takes 1000 pounds of water to make 1 pound of milling wheat, or (simplifying again) 1000 pounds of water to make 1 pound of bread. Therefore, it takes 2500 pounds of water, or approximately 300 gallons, to make 2½ pounds of bread. Three hundred gallons per day per person is, therefore, probably not far from the theoretical minimum water requirement to sustain human life.

The introduction of animal protein to a man's diet lengthens the food chain, thereby greatly increasing the water requirement. To illustrate, let us assume what might be called a