# Effects of nuclear weapons
# (Phys 8.S271)


## Jean Bele, Ph.D.

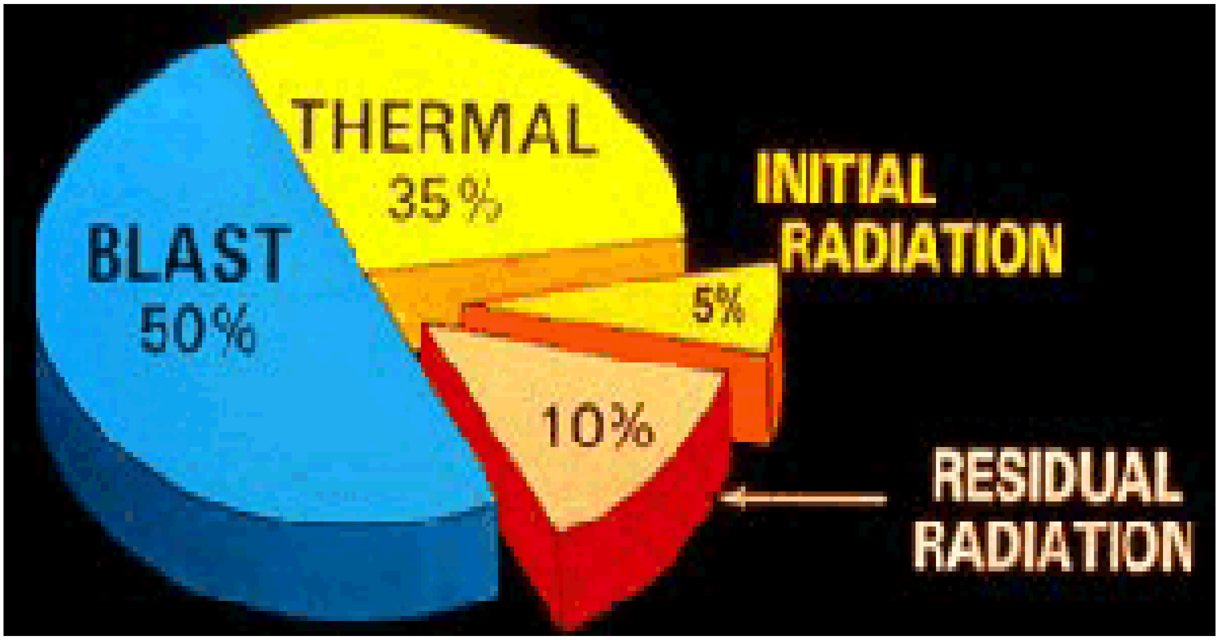

**Winter Term (2021-2022)**

**General Effects of Nuclear Explosions**

A nuclear detonation produces effects overwhelmingly more significant than those produced by a conventional explosive, even if the nuclear yield is relatively low.

It also produces an immediate large, hot nuclear fireball, thermal radiation, prompt nuclear radiation, air blast wave, residual nuclear radiation, electromagnetic pulse (EMP), interference with communications signals, and, if the fireball interacts with the terrain, ground shock.

**Typical Distribution of energy released during a nuclear explosion**




The "yield" of a nuclear weapon is a measure of the amount of explosive energy it can produce.

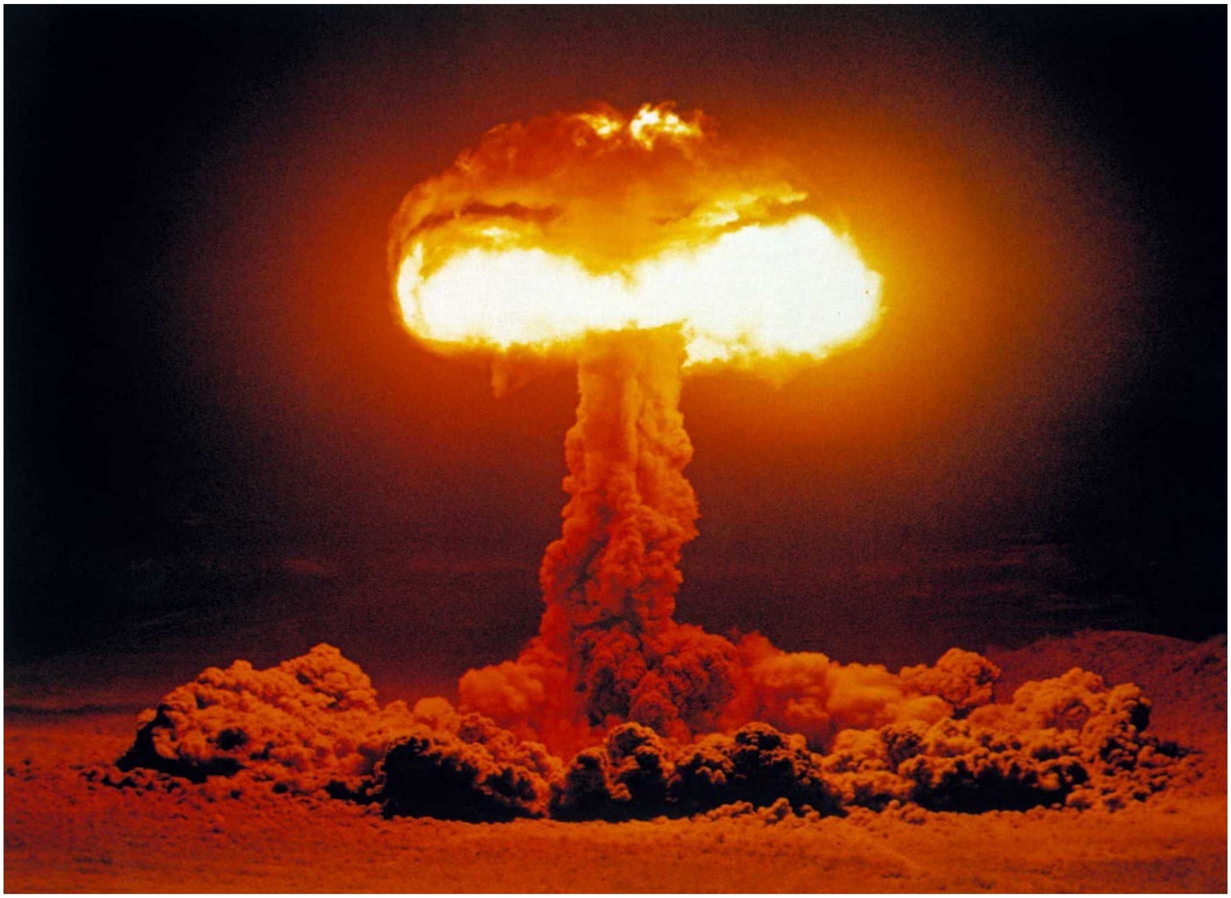
The equations below provide approximate scaling laws for relating the destructive radius of each effect with yield:

**Thermal Radius** = $Y^{0.41}$ * thermal constant
**Blast Radius** = $Y^{0.33}$ * blast constant
**Nuclear radiation Radius** = $Y^{0.19}$ * radiation constant

## Sequence of events:

| **Effect 1: FIREBALL (duration:8-10 seconds)** |
|---|

| **Fireball Physics** |
|---|
| Upon reaching criticality, a nuclear detonation releases a near instantaneous amount of energy in the form of fission fragments, x-rays, neutrons, and gamma rays. These particles interact with the surrounding environment including the weapons materials<br><br>Most of the energy released in a nuclear explosion is in the form of x-rays.<br><br>The fireball is heated to temperatures on the order of millions of degrees Kelvin. Expansion of the fireball can be segmented into three phases of growth:<br>burn out, diffusion, and hydrodynamic. |



**Burn out phase:**

This phase is the region where the fireball temperature is tens of millions of degrees as hot as the interior of the sun. Inside the fireball, the temperature and pressure cause a complete disintegration of molecules and atoms.

In this stage, the complete ionization of surrounding material continues until a burn out radius is reached. The rate at which the radiation front absorbs the x-ray radiation and re-emits approaches the speed of light in a vacuum for the yields in order of megaton. Initially x-rays and deep ultraviolet light escapes the fireball which heats the immediate air to similar temperatures. This forms the first optical peak.

The total amount of volume in the burn out phase of growth is material and yield dependent; the radius of that volume is on the order of meters for air, and on the order of centimeters for metals. Following the complete ionization of surrounding material, the fireball will eventually cool to a point in which only partial ionization is induced.

| **Diffusive growth phase:** |
| --- |
| During this phase, the volume of the fireball continues to expand, while the average temperature continues to decrease. Diffusion refers to the process by which molecules interact due to the kinetic energy of motion.<br><br>For a nuclear detonation, this diffusion process occurs near the fireball edge were the colder surrounding air and other materials interact with the nuclear fireball that is at a temperature high enough to continue to thermally radiate x-rays.<br><br>This diffusive fireball growth continues until the rate of expansion decreases below the local acoustic velocity of sound. |

-11-

RADIATION DIFFUSION—SHOCK WAVE TRANSITION ONE KILOTON

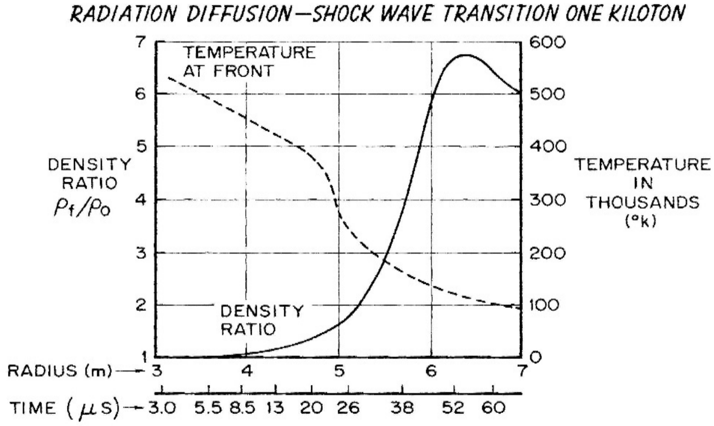
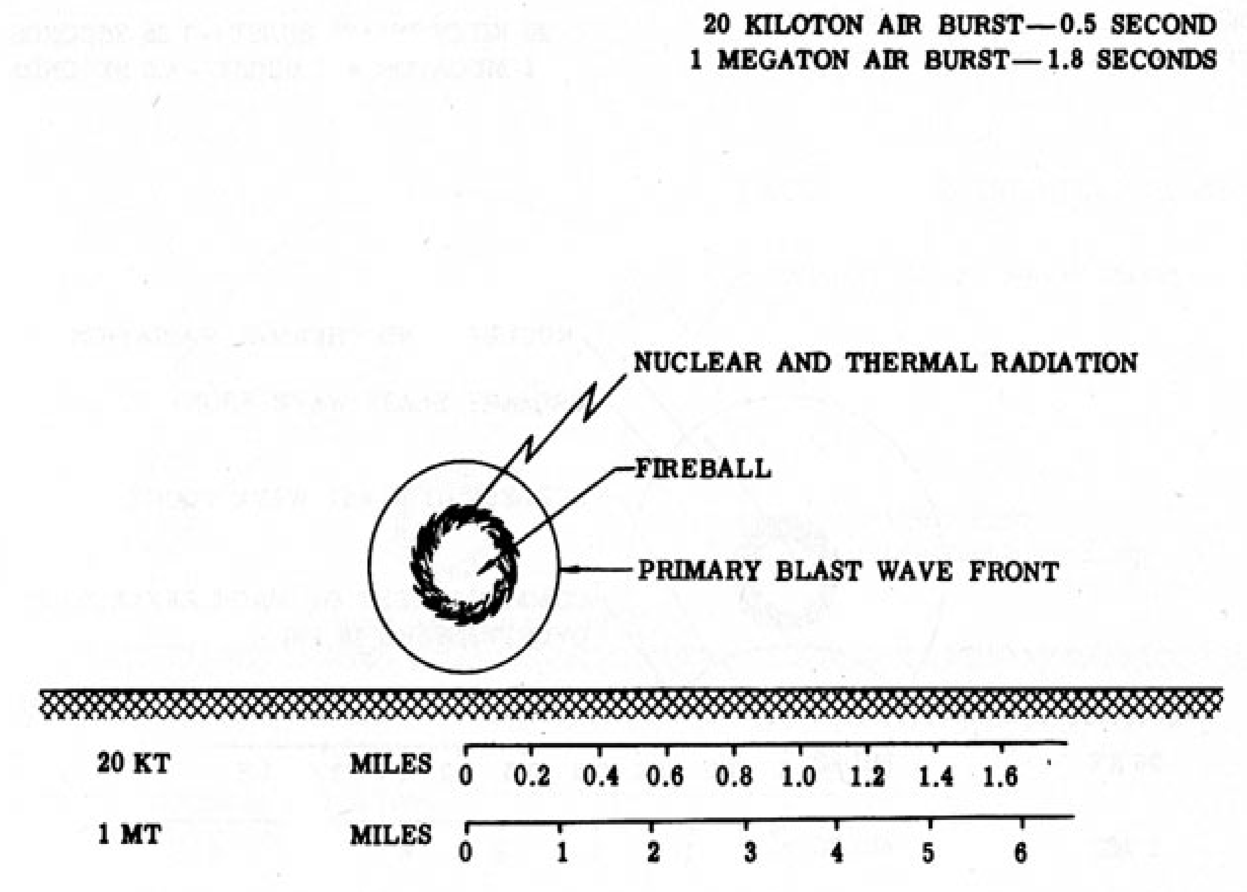



Fig. 6

| **Hydrodynamic separation phase** |
| --- |
| This is the phase were a shock wave advances ahead of the radiation front. During this time, the inner fireball continues to growth diffusively.<br><br>During hydrodynamic separation, the temperature at the surface of the shock front is greater than 100,000 K. The volume encompassing the shock front continues to advance and the temperature in the shock front decreases following a hydrodynamic growth model.<br><br>At this point the shock cools as it expands it becomes more transparent and creates the second peak (in<br>a phenomenon called breakaway).<br>For 1 Mt explosion : 440 ft in one millisecond, 5,700 ft in 10 seconds<br>after one minute: cooled, no longer visible radiation |

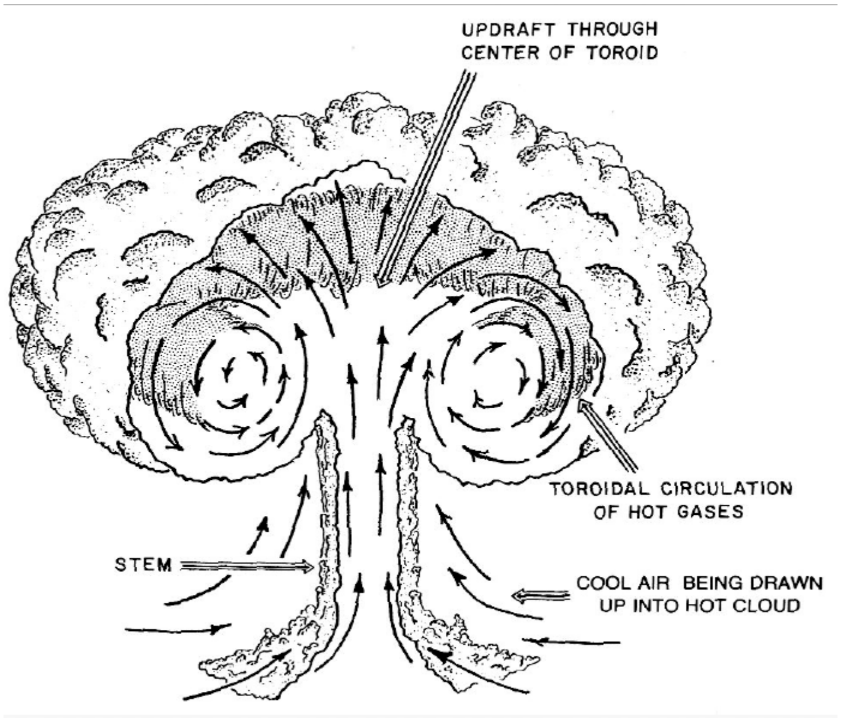


**Effect 2 : Mushroom Cloud (duration: 8-10 seconds )**

Vaporized matter condenses to a cloud containing weapon debris, fission products, and, in the case of a ground burst,radiated soil into its base to form the mushroom stem

Fireball becomes doughnut-shaped, violent internal circulatory motion  air is entrained from the bottom if dirt and debris sucked up from earth's surface.
As the fireball rises, it cools, losing its glow, and the vaporized material and water vapor condense and spread, forming the mushroom head.
The cloud consists chiefly of very small particles of radioactive fission products and weapon residues, water droplets, and larger particles of dirt and debris carried up by the afterwinds.

The eventual height reached by the radioactive cloud depends upon the heat energy of the weapon and upon the atmospheric conditions. If the cloud reaches the tropopause, about 6-8 miles above the Earth's surface, there is a tendency for it to spread out. But if sufficient energy remains in the radioactive cloud at this height, a portion of it will ascend into the more stable air of the stratosphere.




Toroidal circulation within the radioactive cloud from a nuclear explosion.

The color of the cloud is initially red or reddish brown, due to the presence of nitrous acid and oxides of nitrogen

As the fireball cools and condensation occurs, the color changes to white, mainly due to the water droplets as in an ordinary cloud. (The mushroom cloud forming at the Nevada Test Site.)

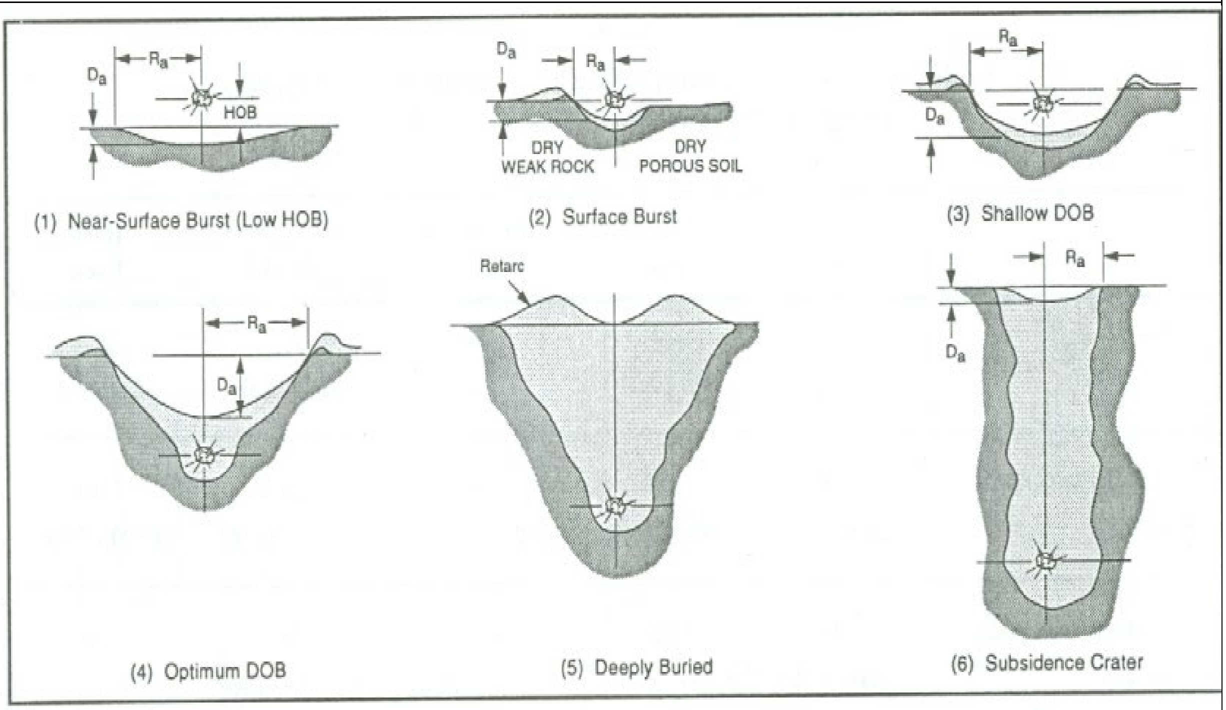
## Effect 3: Blast and Thermal Radiation

**Air blast** (duration:15 seconds) : Blast wave, rapid rise in pressure followed by extreme winds (more than 600 mph), **winds last up to 10 seconds**, then **reverse direction for 1-2 seconds**.


**Thermal Radiation**
Because of its extremely high temperature, it emits thermal (or heat) radiation capable of causing skin burns and starting fires in flammable material at a considerable distance.

## Cratering

- All explosives create craters when detonated at near the earth surface
- Explosives create a shock front that pushes interfering material out of the way




- Crater characteristics depend on where the detonation happened
- No crater if the HOB is greater than the radius of the fireball
  $R = 34\ W^{0.4}$ m
- Characteristics depend on yield and soil characteristics
- General scaling for depth and volume proportional to $W^{1/3}$
- Crater characteristics heavily parameterized and easily calculated.

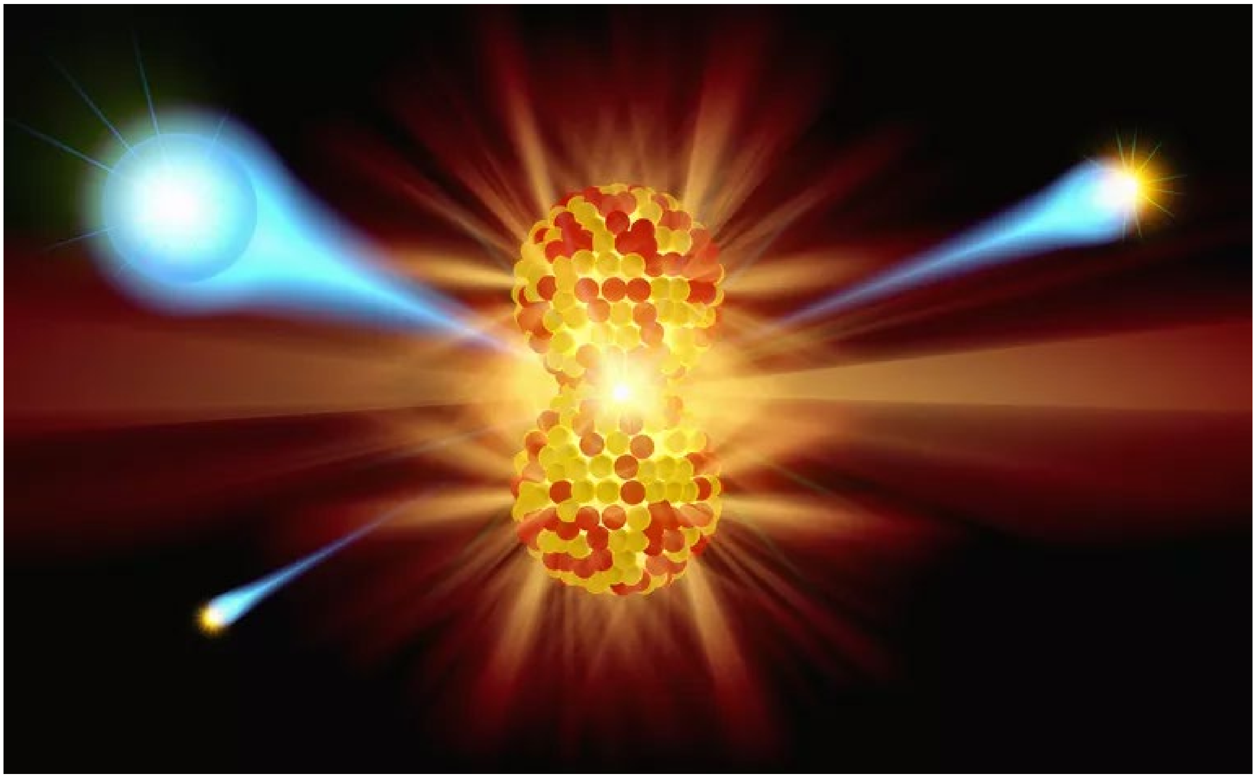
**In class simulation:** https://nuclearweaponsedproj.mit.edu/

**Effect 4: Initial (Prompt/Direct) Nuclear radiation**

**Initial radiation**
Occur during the first minute after an explosion

mostly neutrons and gammas (directly from the explosion or from fission products)

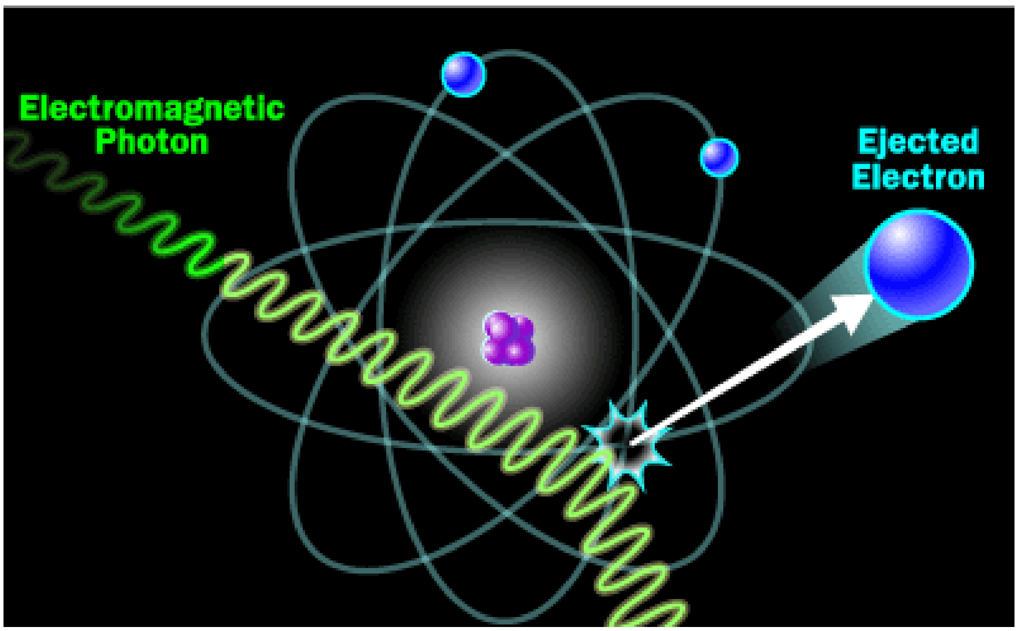
**Delayed nuclear radiation (duration:** (duration: continuous exposure to high radiation)
Origin: material lifted into the fireball right after the explosion
Mixed with radioactive residues of weapon (activated debris, fission products, ...)
Early and delayed fallout: Depending on height of burst, weather conditions.



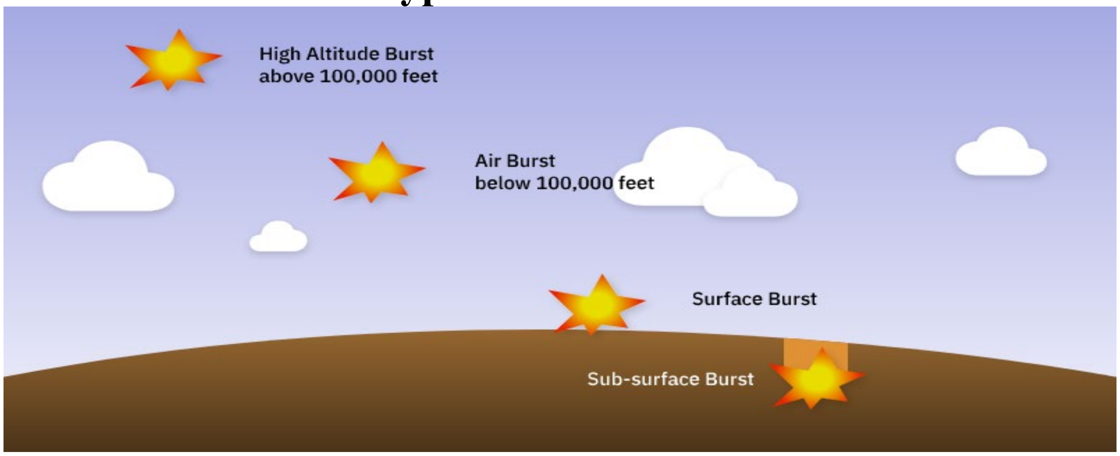
## Effect 5: Electromagnetic Pulse (EMP)

EMP is trigger by a nuclear weapon detonation in high altitude

Nuclear explosion above a country might severely damage its electric, electronic and telecommunications infrastructure



# Types of Nuclear Burst




**High Altitude Burst:**

- Initial soft x-rays generated by the detonation dissipate energy as heat in a much larger volume of air molecules. Less blast effects there is less to destroy.
- Large fireball with rapid expansion.
  The ionizing radiation travel for hundreds of miles before being absorbed. Can produce the ionization of the upper atmosphere (ionosphere).
- Generation of an intense electromagnetic pulse (EMP) which extends over a great distance

**Air Burst:** The fireball does not touch the ground. Detonation is below 100,000 feet. Typically, there is no local fallout from an air burst. The fission products are generally dispersed over a large area of the globe unless there is local rainfall resulting in localized fallout.

**Surface Burst:** Weapons detonated on or slightly above the surface of the earth so that the fireball touches the land or water surface.

- Ground absorbs a lot of energy, so range is reduced for most effects. Makes a crater.
- local fallout can be a hazard over a much larger downwind area. Very intense EMP in local area, due to asymmetry in ionizations.

**Sub-surface Burst:** Detonation occurs underground or under water. Depth determines destructive forces on the surface.

- If the burst does not penetrate the surface, the only effect will be from ground or water shock (Creates a base surge (tsunami-like) of radioactive mist. Overpressure limited near surface by destructive interference (surface cutoff).
- If the burst is shallow enough to penetrate the surface, blast, thermal, and initial nuclear radiation effects will be present, but will be less than for a surface burst of comparable yield. Local fallout will be very heavy if penetration occurs.

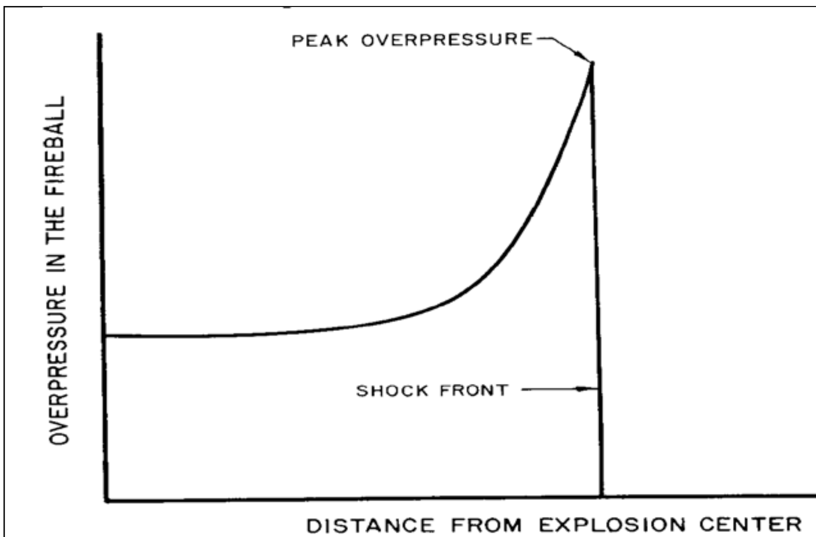
# The Blast Effects

**Formation of Blast Wave.**

As a result of the very high temperatures and pressures at the point of detonation,

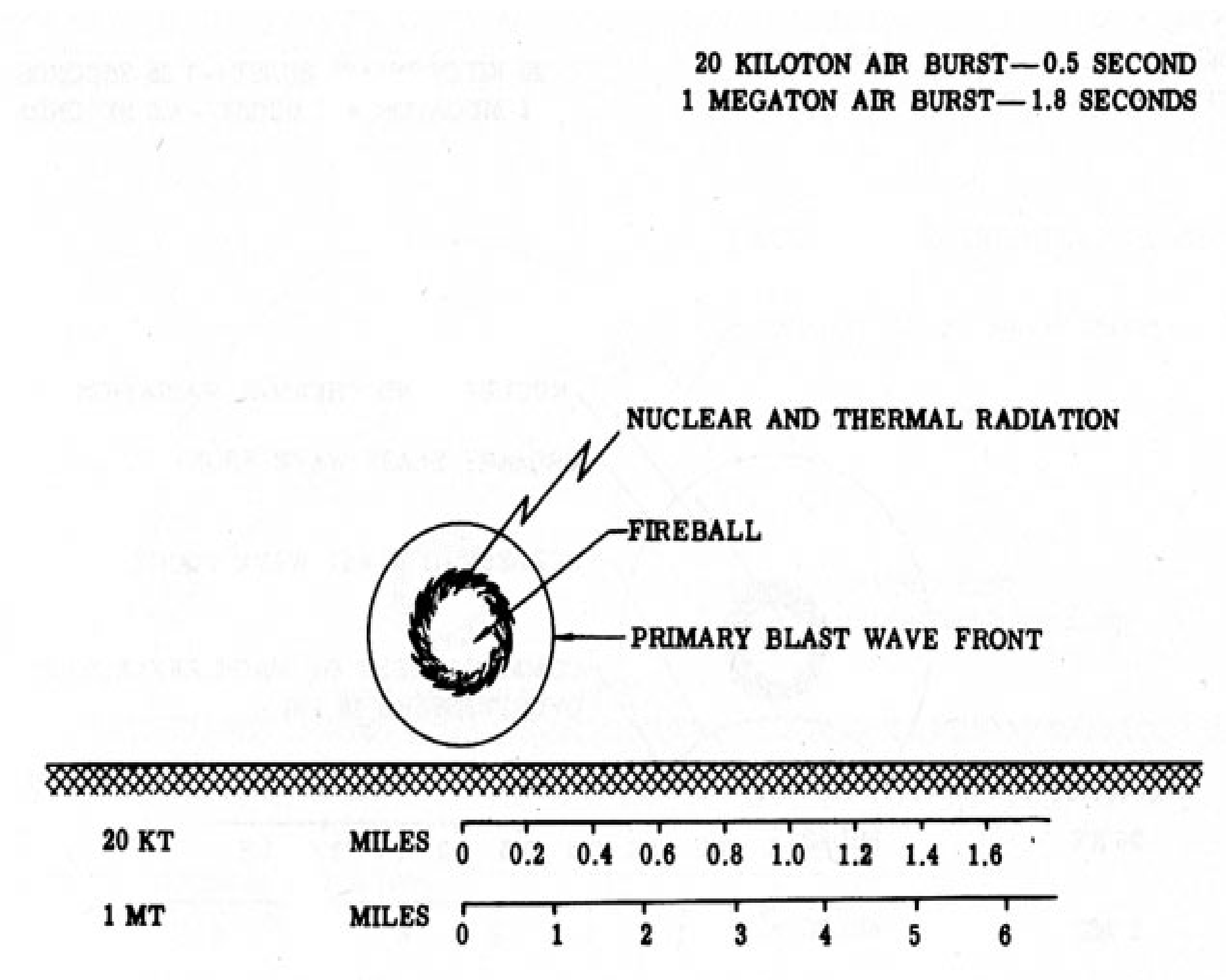
- the hot gaseous residues move outward radially from the center of the explosion with very high velocities.
- Most of this material is contained within a relatively thin, dense shell known as the hydrodynamic front. the front transfers energy to the atmosphere by impulse and generates an expanding shock wave.
- At first, this shock wave is behind the surface of the developing fireball. However, within a fraction of a second after detonation, the rate of expansion of the fireball decreases to such an extent that the shock catches up with and then begins to move ahead of the fireball.
- For a fraction of a second, the dense shock front will obscure the fireball, accounting for the characteristic double peak of light (see fireball).

### Development of blast wave




- Early stage of explosion, the variation of the pressure with distance from the center of the fireball at a given instant for an ideal rising shock front.
- Pressure at the shock front are two or three times as large as the already very high pressures in the interior of the fireball

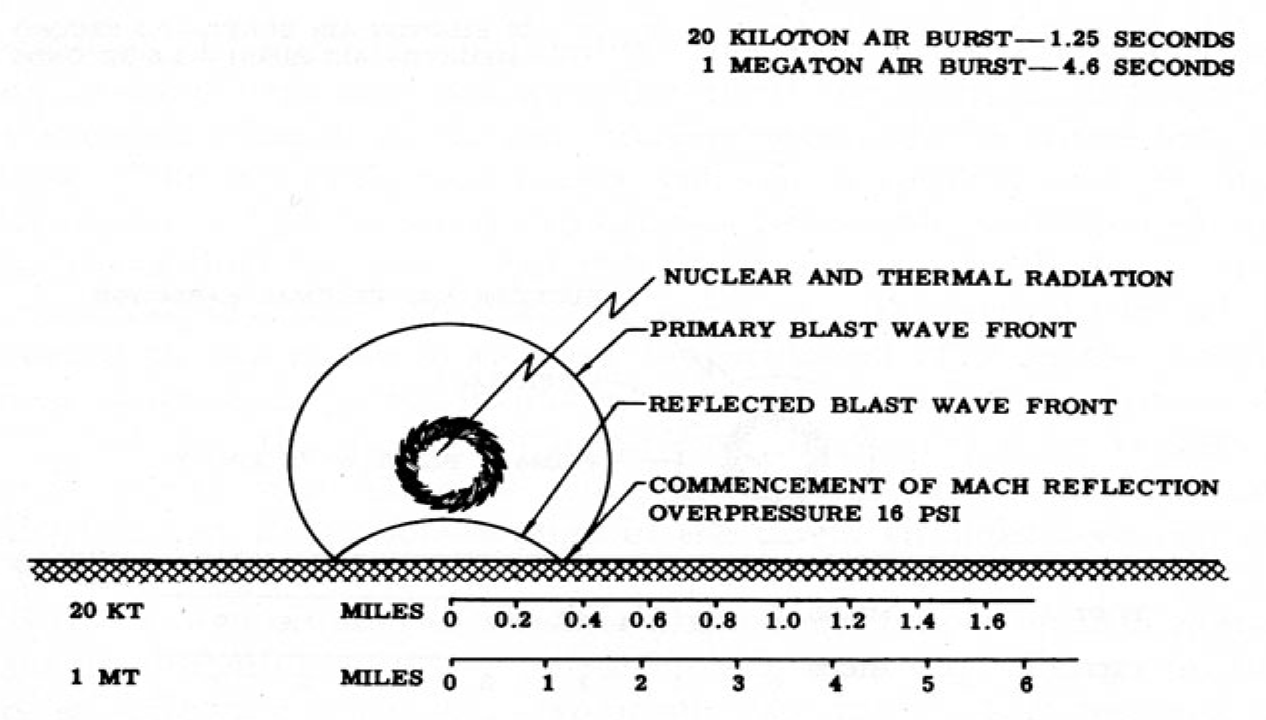
Figure 3.03(Glasstone). Variation of overpressure with distance in the fireball

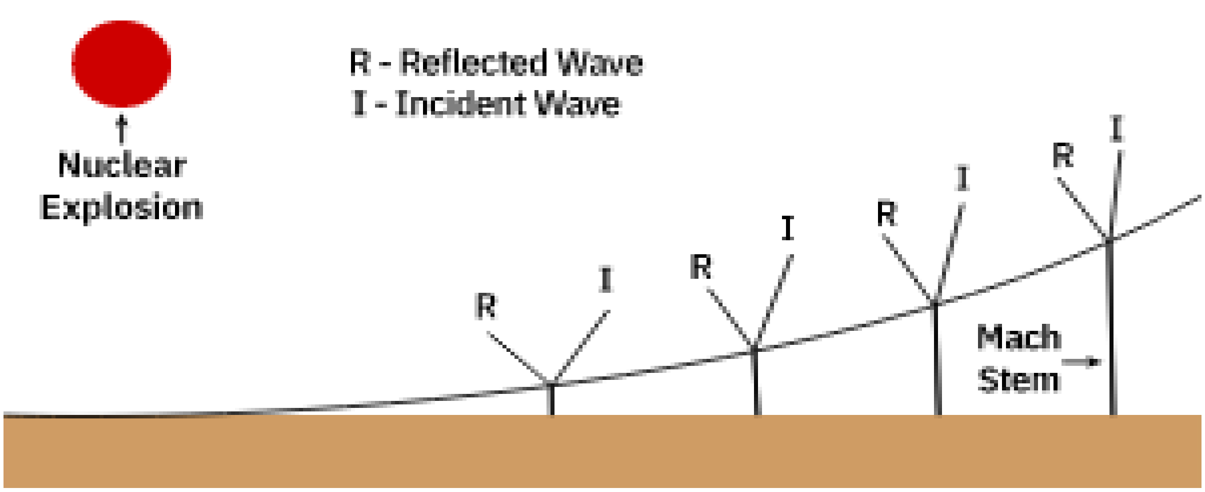



The blast wave front in the air is seen to be well ahead of the fireball, about 800 feet for the 20-kiloton explosion and roughly half a mile for the 1-megaton detonation.

## Waves characteristics (incidents and reflected waves)

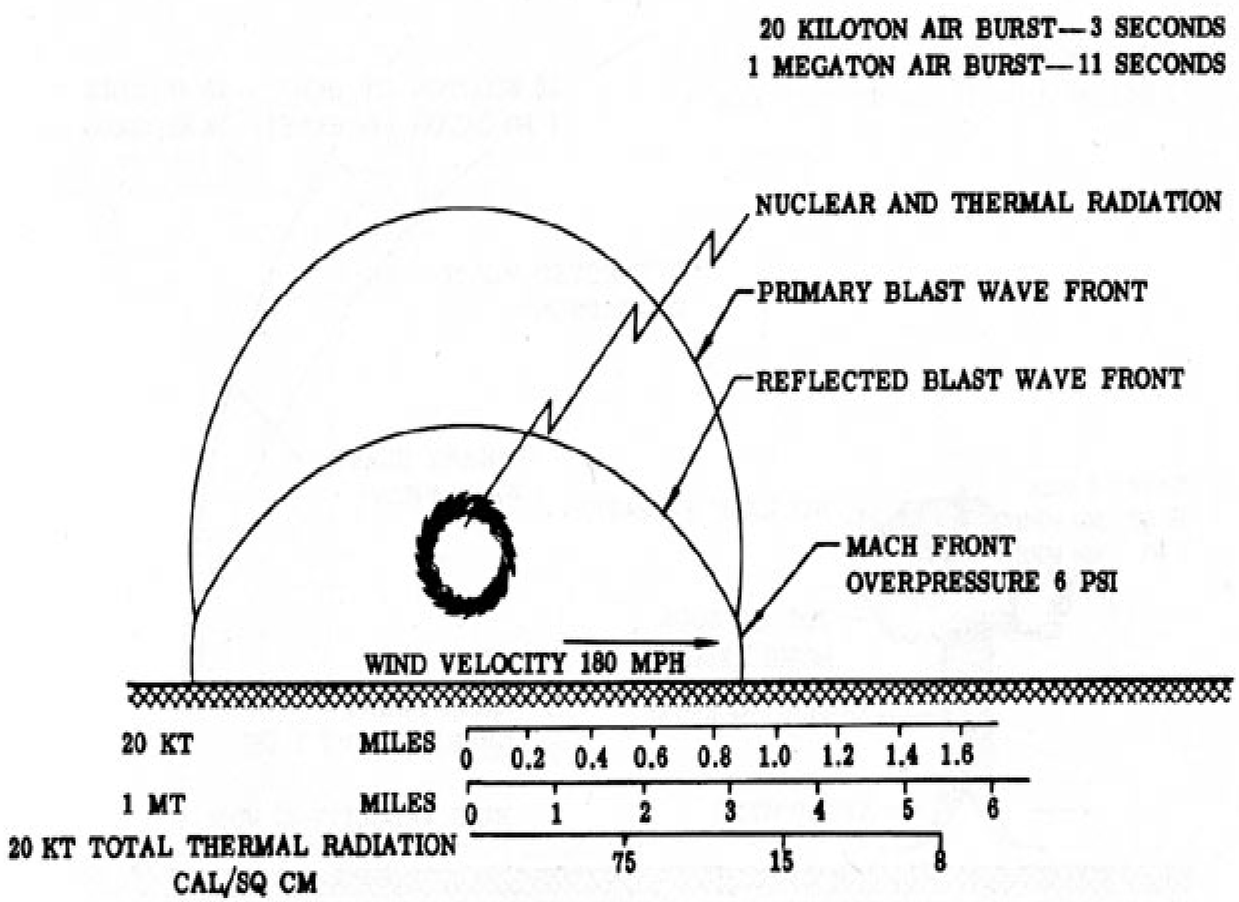
When the primary air blast wave from the explosion strikes the ground, another blast wave is produced by reflection. At a certain distance from ground zero, which depends upon the height of burst and the energy yield of the weapon



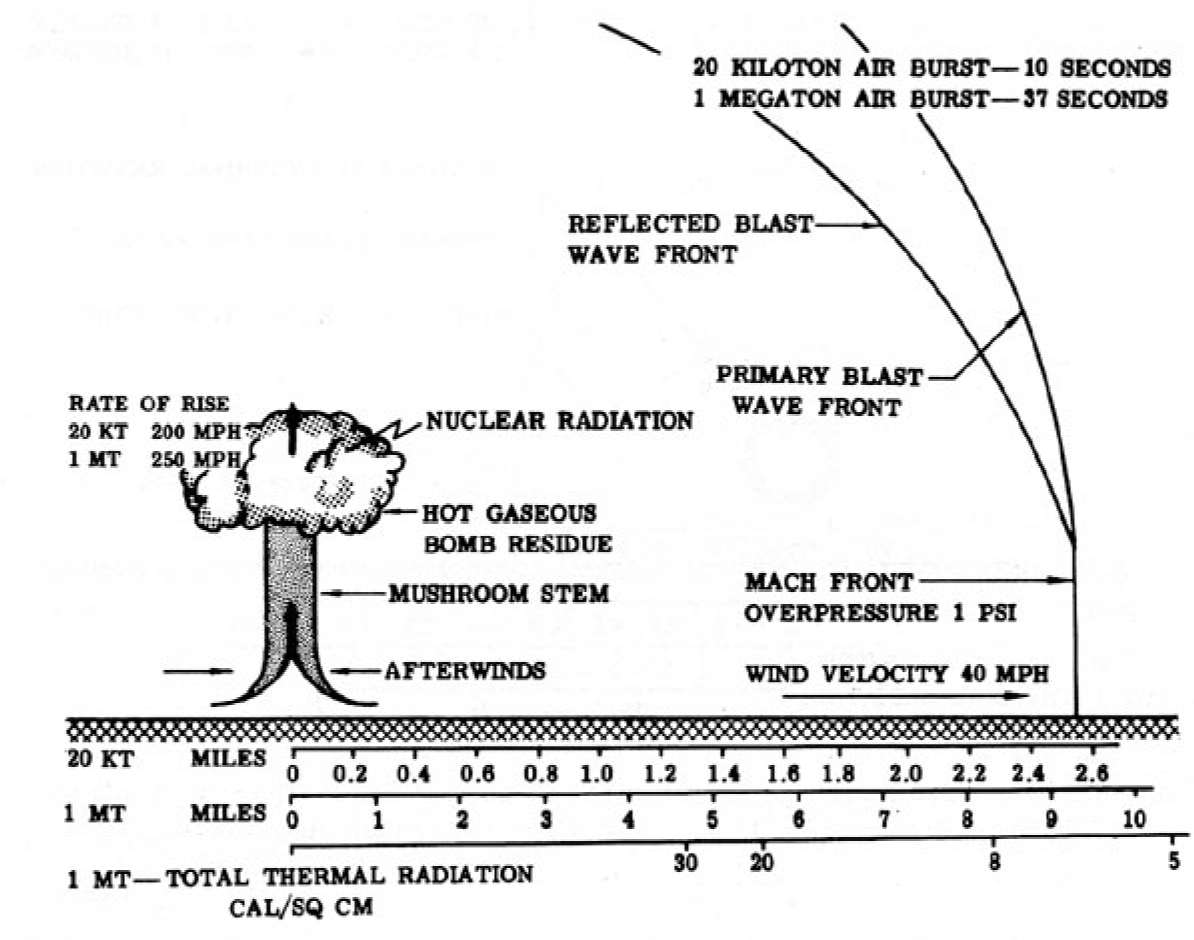
Nuclear radiations from the weapon residues in the rising fireball continue to reach the ground. But after 3 seconds from the detonation of a weapon, the fireball, although still very hot, has cooled to such an extent that the thermal radiation is no longer important.

The total accumulated amounts of thermal radiation, expressed in calories per square centimeter, received at various distances from ground zero can be calculated using the HOB and yield of the weapon. Appreciable amounts of thermal radiation are still coming from the fireball at different time based on the HOB. The thermal radiation emission is spread over a longer time interval than for an explosion of lower energy yield.



At 10 seconds after explosion one can calculate the high of the Mach front and the distance from ground zero the wind velocity behind the front will be 40 miles per hour. There will be slight damage to many structures, including doors and window frames ripped off, roofs cracked, and plaster damaged. Glass will be broken at overpressures down to 1/2 pound per square inch. Thermal radiation is no longer important, even for the higher burst, the total accumulated amounts of this radiation, at various distances, being indicated in the simulation. Nuclear radiation, however, can still reach the ground to an appreciable extent; this consists mainly of gamma rays from the fission products.

The fireball is no longer luminous, but it is still very hot, and it behaves like a hot-air balloon, rising at a rapid rate. As it ascends, it causes air to be drawn inward and upward. This produces strong air currents, called afterwinds. For moderately low air bursts, these winds will raise dirt and debris from the earth's surface to form the stem of what will eventually be the characteristic mushroom cloud.



## Expansion of the shock wave

### Changes in the blast wave with time

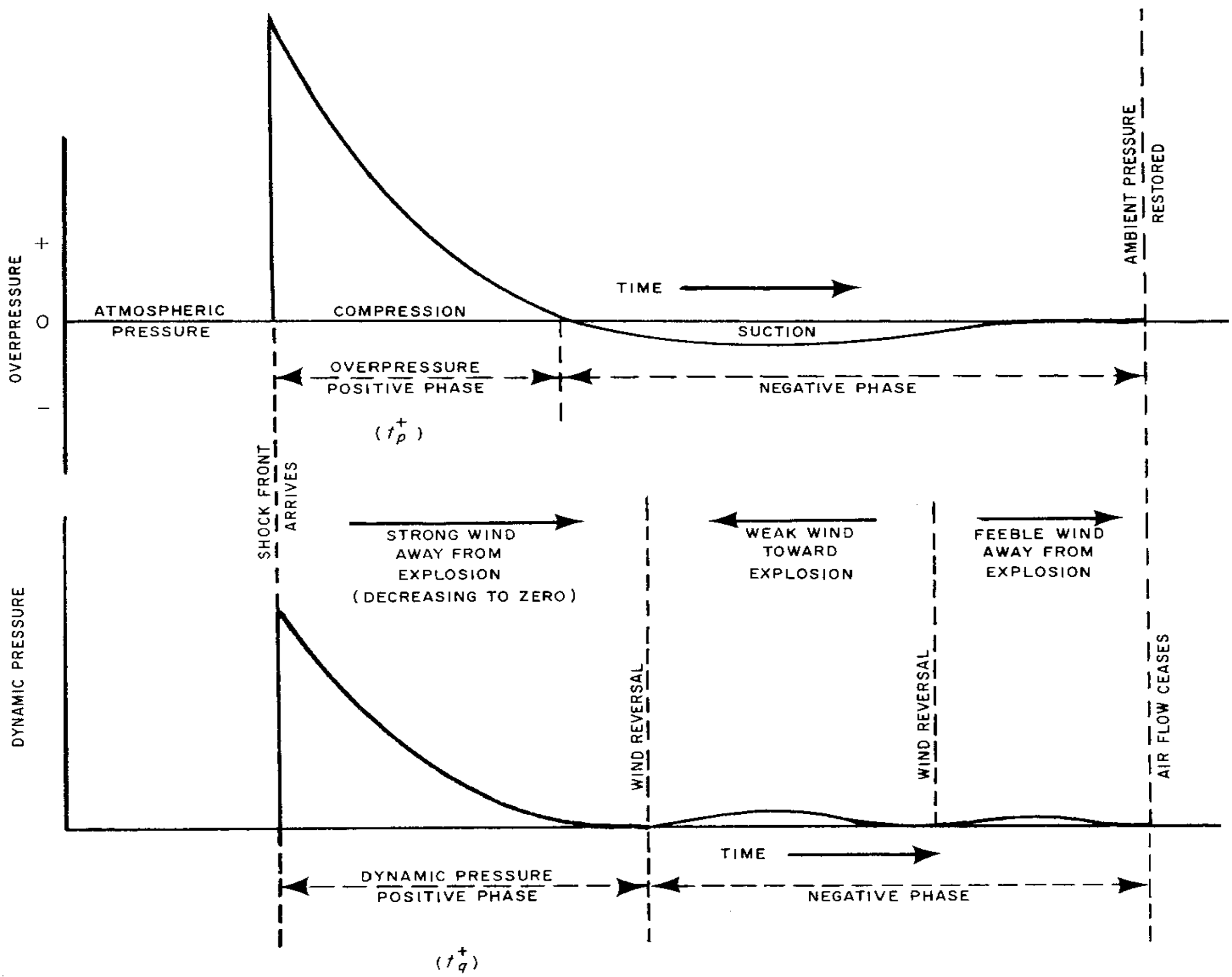



Figure 3.11. Variation of overpressure and dynamic pressure with time at a fixed location.

1. Shock hits
2. generates strong wind
3. Shock decreases
4. Underpressure
5. Wind direction changes
6. Normal air pressure
7. Wind calms down

**REFLECTION OF BLAST WAVE AT A SURFACE**

INCIDENT AND REFLECTED WAVES

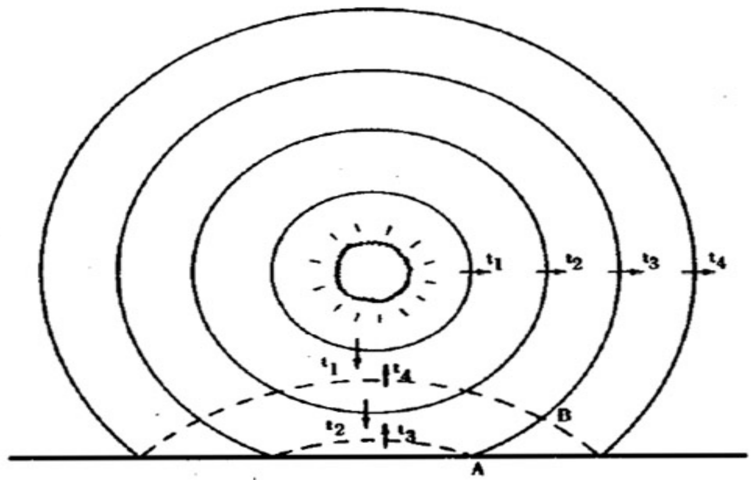



**Figure 3.17. Reflection of blast wave at the earth's surface in an air burst; $t_1$ to $t_4$ represent successive times.**

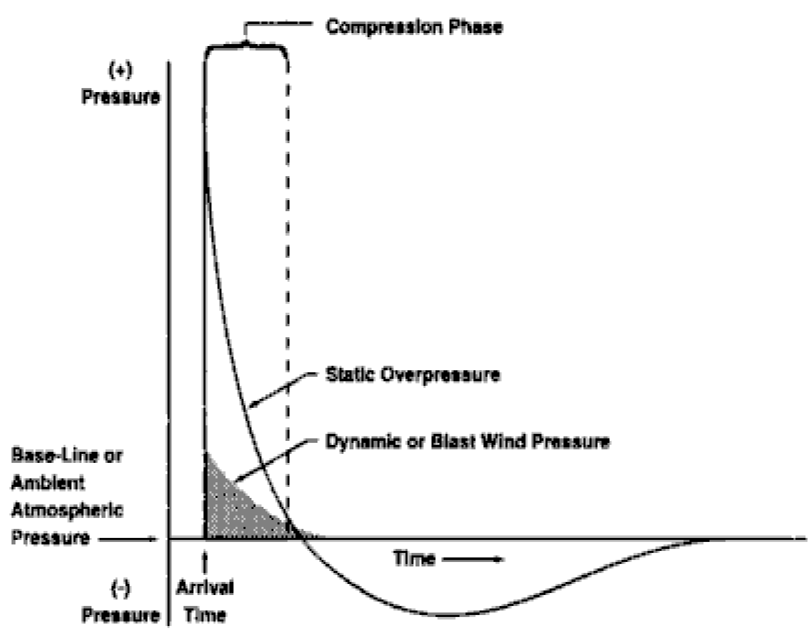



*Figure 3-II. Variations of Overpressure and Dynamic Pressure with Time*

- In general, the static overpressure rises very abruptly from normal atmospheric in the unaffected air in front of the blast wave to a sharp peak
- It then decreases behind the front. As the blast wave moves out from ground zero, the peak overpressure of the front diminishes while the decay of overpressure behind the front becomes more gradual. After traveling a sufficient distance from the fireball, the pressure behind the front actually drops below normal atmospheric pressure, the so-called negative phase of the blast wave.

- In passing through the atmosphere, the blast wave imparts its energy to the molecules of the surrounding air, setting them into motion in the direction of the advancing shock front. The motion of these air molecules is manifested as severe transient winds, known as "blast winds," which accompany the blast wave. The destructive force associated with these winds is proportional to the square of their velocity and is measured in terms of dynamic pressure. These winds constitute decay forces which produce a large number of missiles and tumbling of objects. These dynamic forces are highly destructive.
- Most of the material damage caused by a nuclear air burst is caused by a combination of the high static overpressures and the dynamic or blast wind pressures.

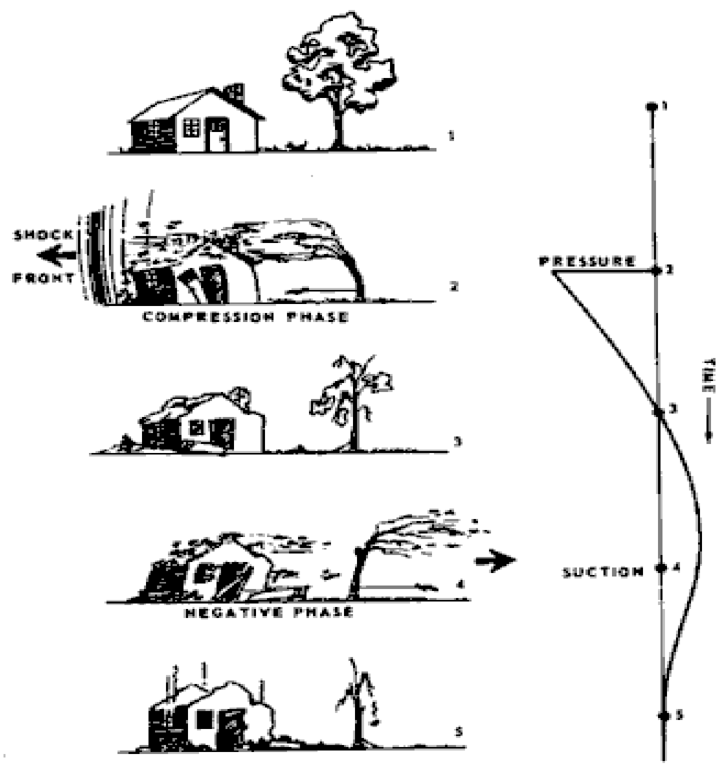



***Figure 3-III. Variations of Blast Effects Associated with Positive and Negative Phase Pressures with Time***

This photo sequence shows a wood-frame house exposed to a nuclear blast at the Nevada Test Site. The test was Upshot-Knothole Annie, a 16 Kt tower shot, on March 17, 1953. The house is 1,100 meters from ground zero.

The exposure to thermal radiation was 25 cal/cm$^2$, about one-quarter of that experienced at ground zero in Hiroshima.

The blast overpressure was 5 psi, and the blast wave created surface winds of 160 mph (257 kpm)

## Blast Damage and Injury

There are two basic types of blast forces which occur simultaneously in a nuclear detonation blast wave. These are: direct blast wave overpressure forces, measured in terms of atmospheres of overpressure; and indirect blast wind drag forces, measured best in terms of the velocities of the wind which cause them.

**Blast Loading.**

- When a blast wave strikes the surface of a hard target, such as a building, the reflected wave will reinforce the incident wave, and the face of the building will be subjected to overpressures 2 to 8 times that of the incident wave alone.
- The severity of this additional stress depends on many factors, including the peak overpressure of the incident blast wave, as well as the angle at which the wave strikes the building.
- As the shock front advances, it bends or diffracts around the building, and the pressure on the front wall decreases rapidly.
- However, during the brief interval in which the blast wave has not yet engulfed the entire structure, a considerable pressure gradient exists from front to rear that places a severe stress on the building.
- For small objects, this period of so-called diffraction loading is so small that no significant stress is encountered.
- For large buildings, however, the stress of diffraction loading will be considerable. Even after the shock front has passed across the building, the structure will still be subjected to a severe compression force and to severe drag forces from the transient winds.
- The actual overpressures required to produce severe damage to diffraction sensitive targets are quite low.

**Drag Loading.**

- All objects in the path of the blast wave, regardless of size or structure, will be subject to the dynamic pressure loading or drag forces of the blast winds. Drag loading is influenced to a moderate degree by the shape of the target.
- Round objects are relatively unaffected by the winds, while flat or recessed surfaces offer great resistance and hence are subjected to increased impact pressure and probability of damage.
- The effect of dynamic pressure is generally dependent on the peak value of dynamic pressure and its duration.
- While the dynamic pressure at the face of a building is generally less than the peak overpressure due to the blast wave and its reflection, the period of dynamic loading is much longer than that of diffraction loading, and hence the damage to frame-type buildings, bridges, and other structures will be considerable.
- Blast winds are the cause of most blast injuries. Because of the violence of the winds associated with even low values of overpressure, mechanical injuries due to missiles sent into motion by the winds or to violent bodily translation will far outnumber direct blast injuries due to actual compression of the organism.

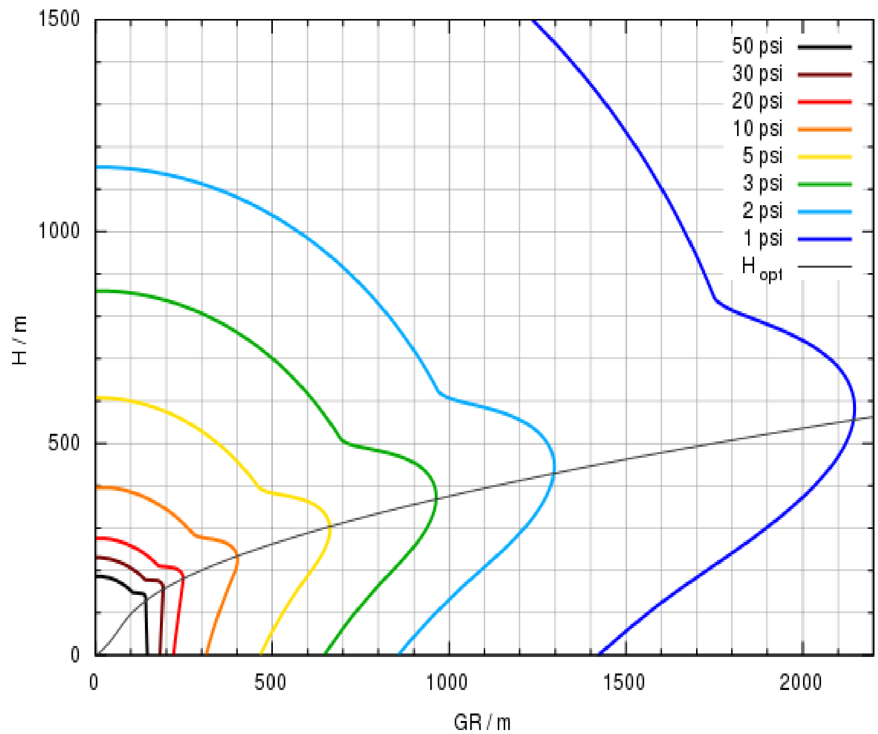
**Scaling constants for blast radius calculation**

Blast radius = $Y^{0.33}$ * blast constant

blast constant for 1 psi = 2.2
blast constant for 3 psi = 1.0
blast constant for 5 psi = 0.71
blast constant for 10 psi = 0.45
blast constant for 20 psi = 0.28

where Y is in kilotons and range is in km.

## Distance and altitude Effects




**Analysis of Attacks on Hiroshima and Nagasaki**

$$h = \sqrt[3]{Y} \; x \; h_1$$

**Calculated value of the Height of Burst (HOB) for 15 psi** **Real value**

| | | |
|---|---|---|
| **Hiroshima** | $\sqrt[3]{15x670}$ **ft ≈ 1650 ft** | **1640 ft** |
| **Nagasaki** | $\sqrt[3]{22x670}$ **ft ≈ 1880 ft** | **1900 ft** |

Height of Burst at Hiroshima and Nagasaki chosen to maximize area over which 15 psi or more occurs (1.1-1.3 miles in diameter) (2.5x times more area destroyed compared to surface burst)

Distance effects of airburst: **In class simulation and calculation:**
https://nuclearweaponsedproj.mit.edu

## The Thermal Effects

| **The thermal power of the fireball changes with time** |
|---|

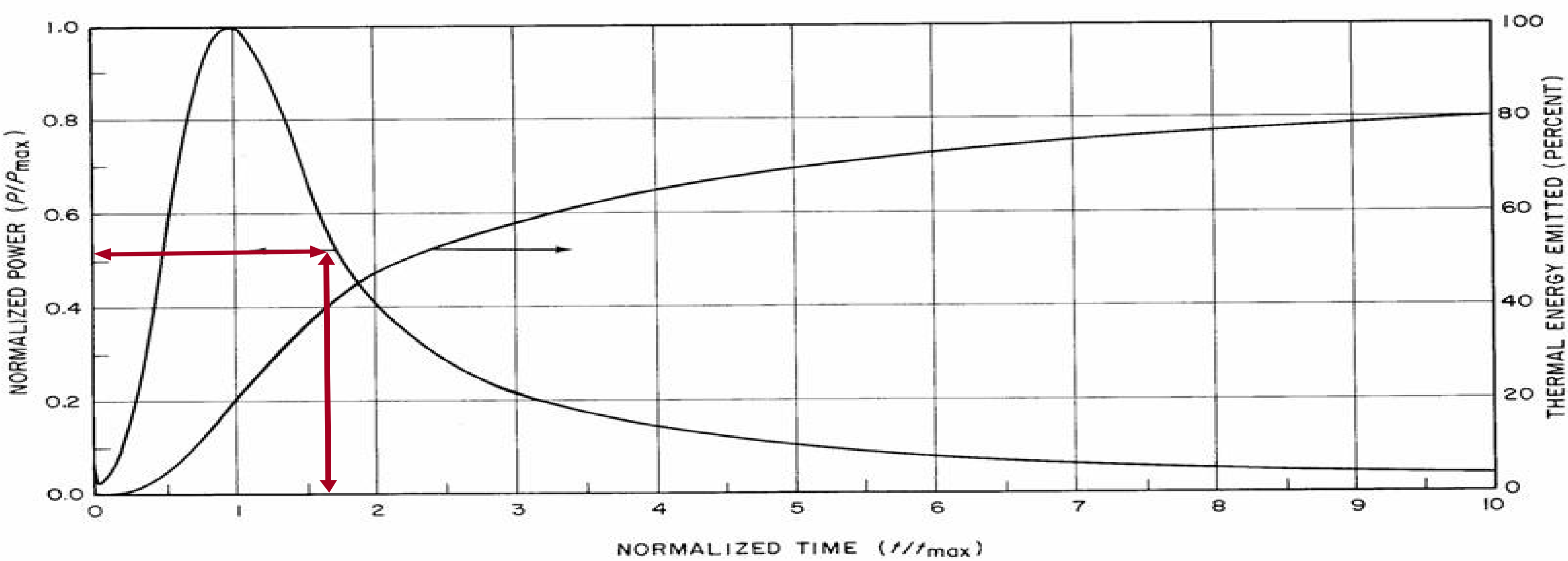
| **Thermal energy release should be expressed in terms of maximum power $P_{max}$ (scaled power) and in termsof scaled time $t_{max}$ which corresponds of time of the maximum thermal energy release from the fireball.** |
|---|

### The expansion of firestorms

Different scaling laws apply for calculating the heat and incinerating effects from bomb yield. Fire advances by wind driven heat propagation. In a uniform atmosphere without turbulent or convective processes the expansion would follow an exponential law with the radiation absorption parameter k. The heat exposure at distance d would be:

$$Q = \frac{Wthem}{4\pi.d^2} \cdot e^{-k.d}$$

For turbulent firestorms empirical approximations are used to describe transmittance of heat in terms of the transmittance factor $\tau$ (empirical factor for visibility) and $f$ the thermal heat fraction of total energy release ($f$˜ 0.35-0.42 depending on altitude).




$$Q = \frac{Wthem\,.\tau}{4\pi.d^2} = \frac{f.W\,.\tau}{4\pi.d^2} = 10^2\,.\,\frac{f.W.\tau}{4\pi.d^2}\ \text{cal/cm}^2$$

# Transmittance

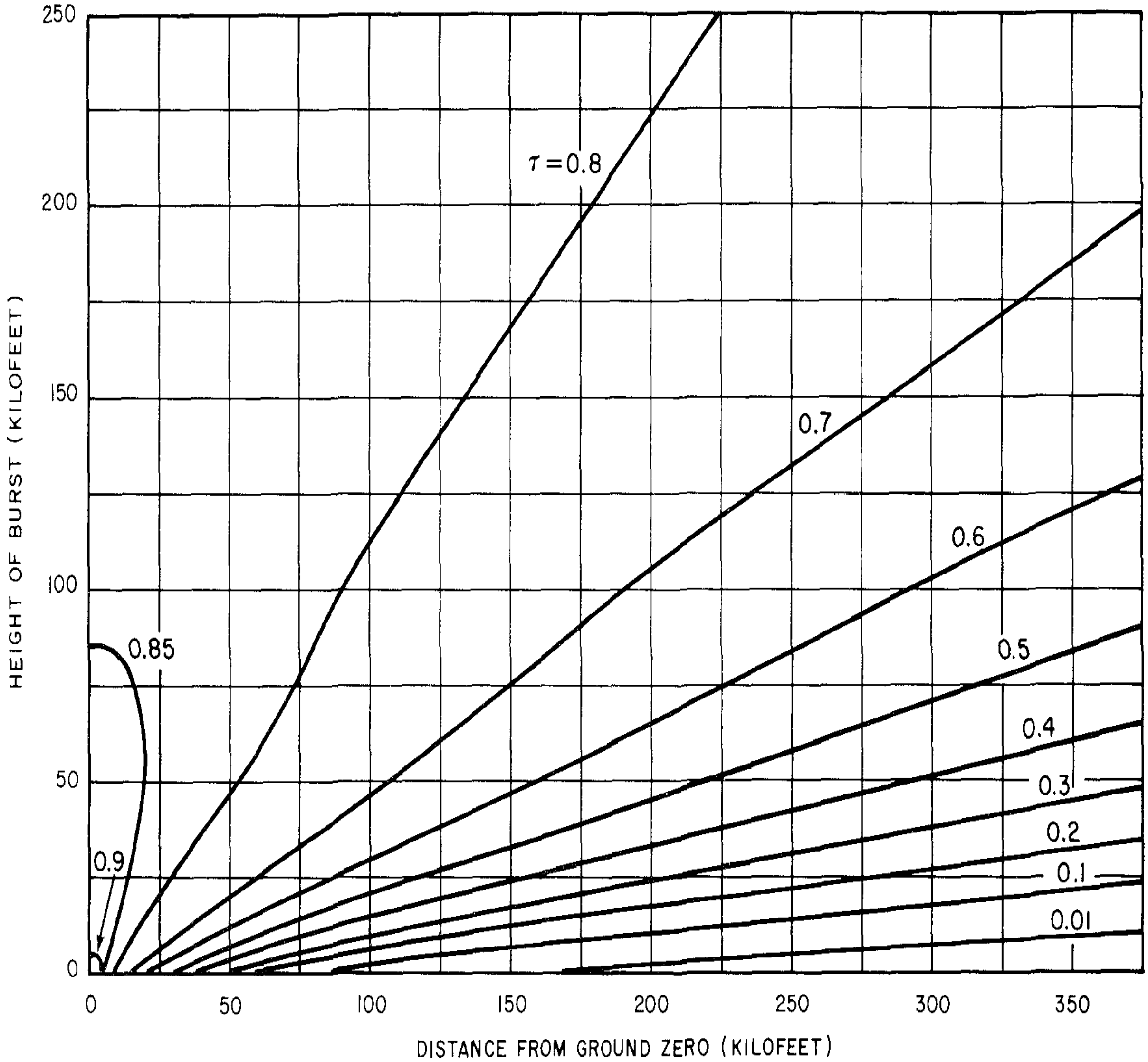
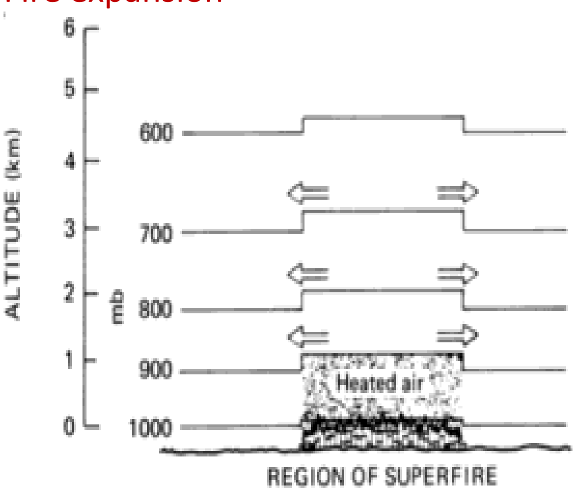


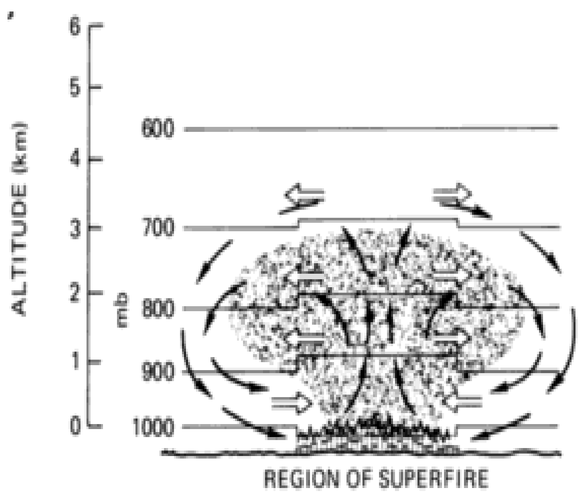

Figure 7.98. Transmittance, τ, to a target on the ground on a typical clear day (visibility = 12 miles).

## Ignition of combustibles

Ignition for combustibles $Q_T \cong 3.5\ W^{0.113}$ cal/cm$^2$

Fire expansion



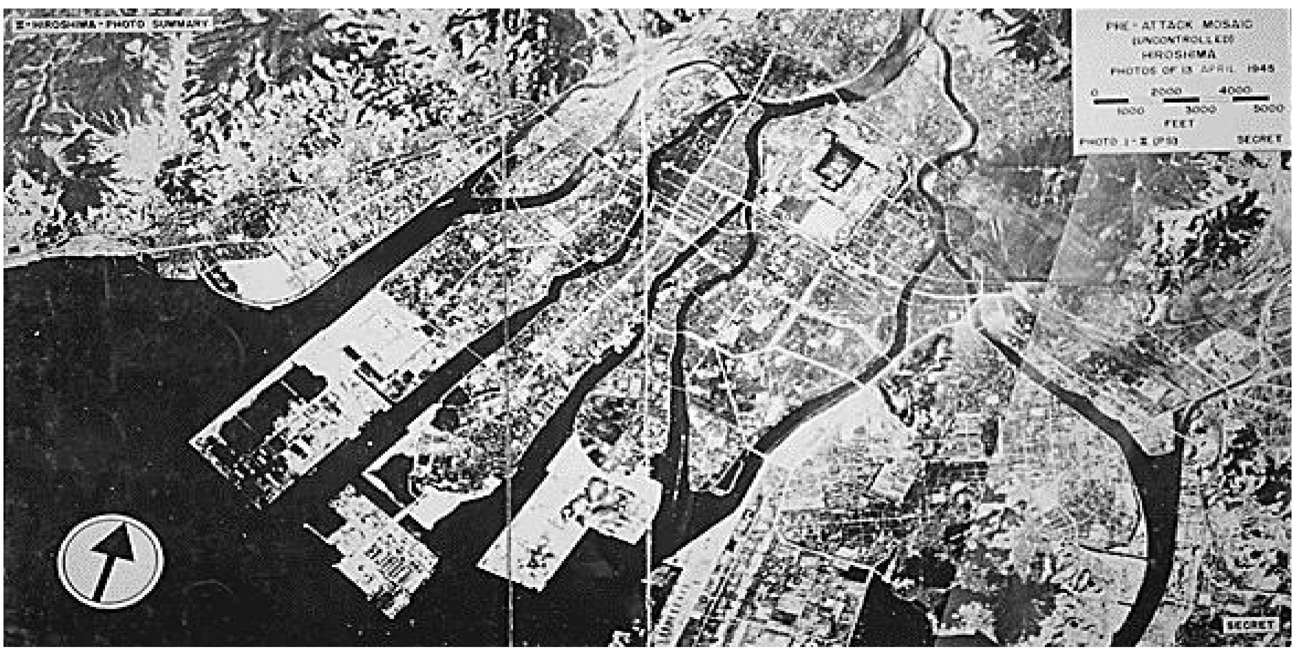

Fire expansion is driven by shock driven winds which develop rapidly turbulences due to temperature differences. Fire spreads with rapid speed, leaving no chance to escape.

## Thermal Injury

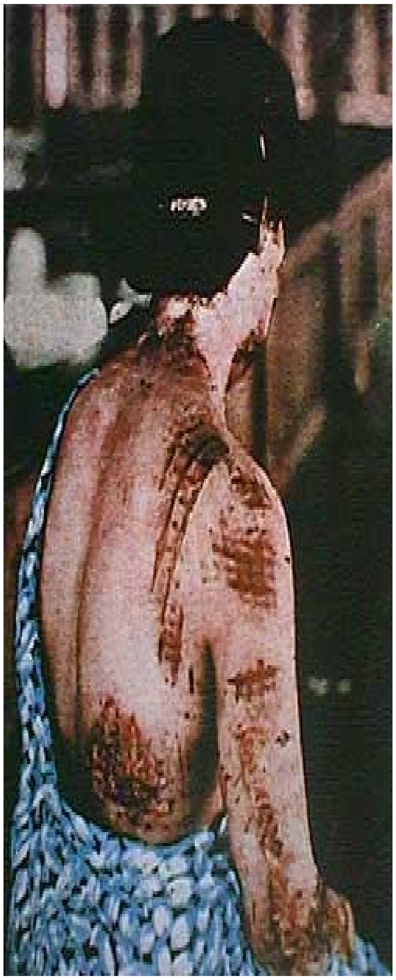
The result of very intense heating of skin is to cause burn injuries. The burns caused by the sudden intense thermal radiation from the fireball are called "flash burns". The more thermal radiation absorbed, the more serious the burn.

Scaling laws for calculation of burn effects for any yield:
thermal radius for 1st degree burn = $Y^{0.38} * 1.20$
thermal radius for 2nd degree burn = $Y^{0.40} * 0.87$
thermal radius for 3rd degree burn = $Y^{0.41} * 0.67$

**Hiroshima in flame**



## The **victims**



Peeled skin was dangling like seaweed from their arms. Red flesh exposed. People were staggering with vacant eyes. Extending their arms forward Like ghosts. Suddenly they fell, stumbling over Something. Never to get up again.

**In class Simulation and calculation**

https://nuclearweaponsedproj.mit.edu

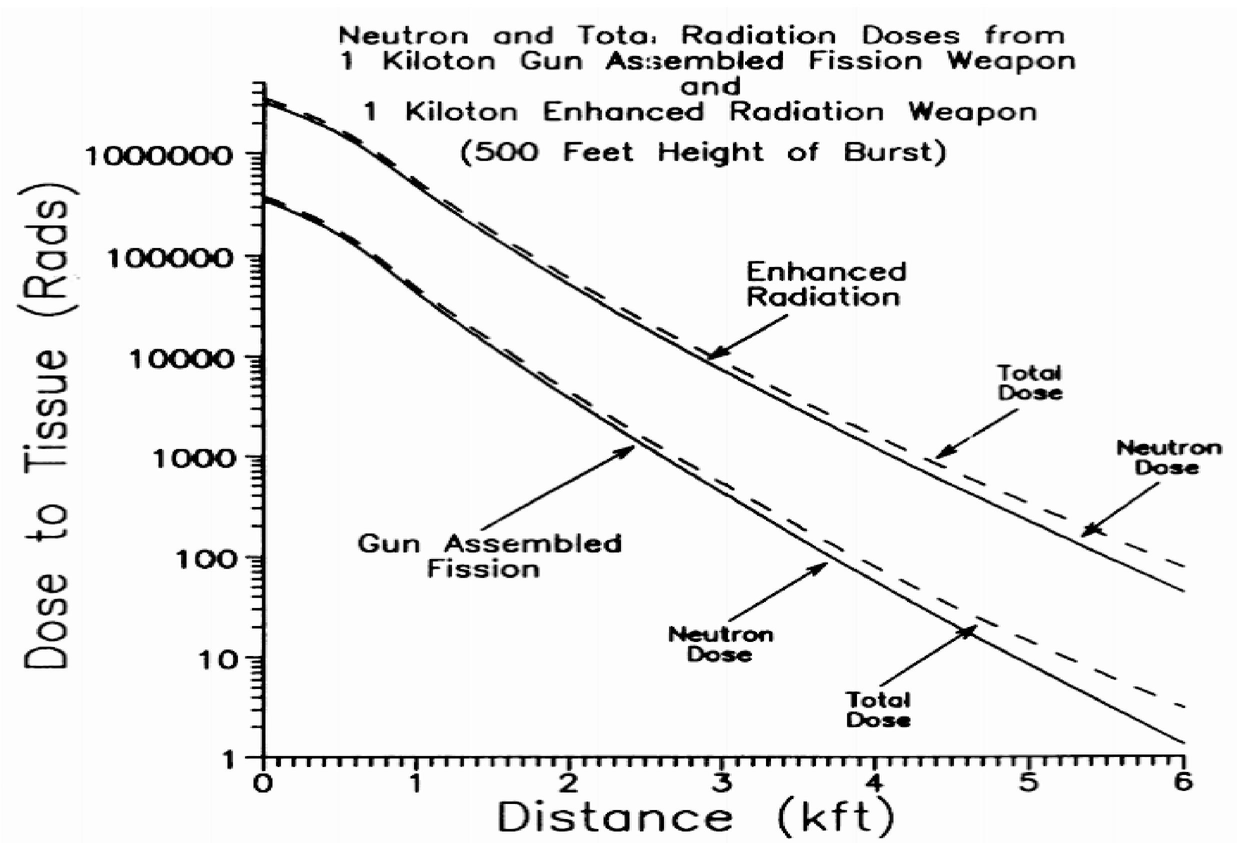
# The Nuclear Radiation Effects

**Sources of Nuclear Radiation**

- Initial or prompt nuclear radiation is that ionizing radiation emitted within the first minute after detonation and results almost entirely from the nuclear processes occurring at detonation.
- Residual radiation is defined as that radiation which is emitted later than 1 minute after detonation and arises principally from the decay of radioisotopes produced during the explosion.

## Initial Nuclear Radiation

Dose absorbed in the first minute after explosion

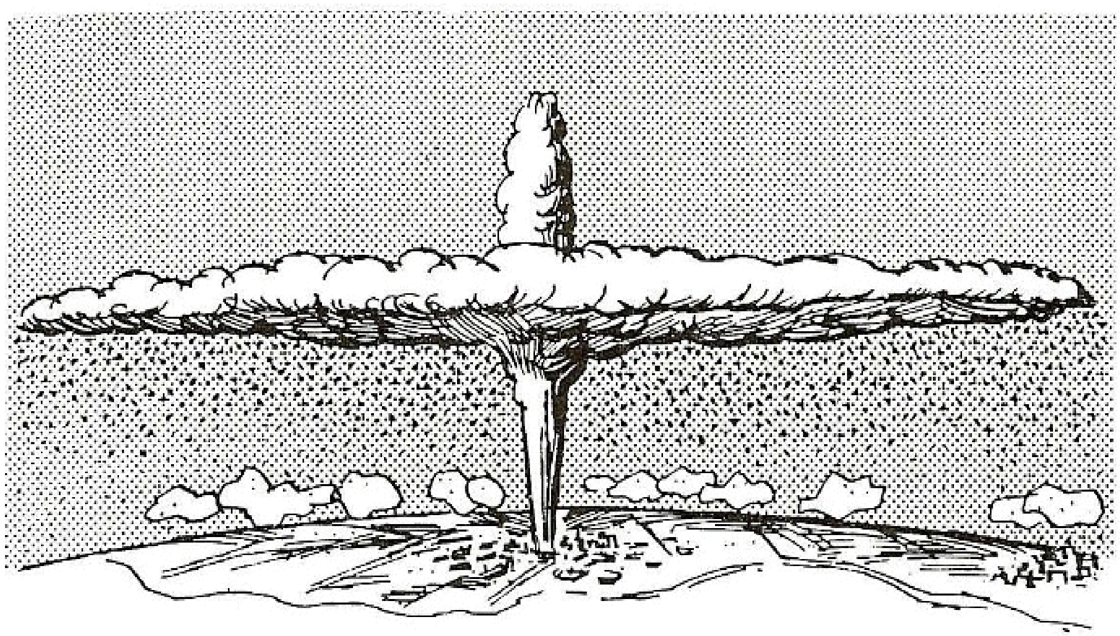


The following scaling law can be used to determine the lethal radius with yield:

Radiation radius = $Y^{0.19}$ * radiation radius constant
If Y is in kilotons, range is in meters, and the dose standard is 1000 rads then:
Radiation constant radius for dose standard 1000 = 700 m

**Radiative Fallout**

- Early fallout fraction for surface burst: 40-70% within one day
- Fallout pattern is difficult to predict
- Strongly depends on terrain and meteorological conditions
- Fission products and other radioactive debris condense onto solid and molten soil minerals (Particle size: 0.001-1 mm)



Radioactive Particles **fall out** of the Nuclear Cloud Many Miles From The Point Where The Explosion Took Place.

FIGURE 12.—General shape of a nuclear cloud and the fallout from it.

## Table 9.93

**SCALING RELATIONSHIPS FOR UNIT-TIME REFERENCE DOSE-RATE CONTOURS FOR A CONTACT SURFACE BURST WITH A YIELD OF *W* KILOTONS AND A 15 MPH WIND**

| Reference dose rate (rads/hr) | Downwind distance (statute miles) | Maximum width (statute miles) | Ground zero width (statute miles) |
|---|---|---|---|
| 3,000 | 0.95 $W^{0.45}$ | 0.0076 $W^{0.86}$ | 0.026 $W^{0.58}$ |
| 1,000 | 1.8 $W^{0.45}$ | 0.036 $W^{0.76}$ | 0.060 $W^{0.57}$ |
| 300 | 4.5 $W^{0.45}$ | 0.13 $W^{0.66}$ | 0.20 $W^{0.48}$ |
| 100 | 8.9 $W^{0.45}$ | 0.38 $W^{0.60}$ | 0.39 $W^{0.42}$ |
| 30 | 16 $W^{0.45}$ | 0.76 $W^{0.56}$ | 0.53 $W^{0.41}$ |
| 10 | 24 $W^{0.45}$ | 1.4 $W^{0.53}$ | 0.68 $W^{0.41}$ |
| 3 | 30 $W^{0.45}$ | 2.2 $W^{0.50}$ | 0.89 $W^{0.41}$ |
| 1 | 40 $W^{0.45}$ | 3.3 $W^{0.48}$ | 1.5 $W^{0.41}$ |

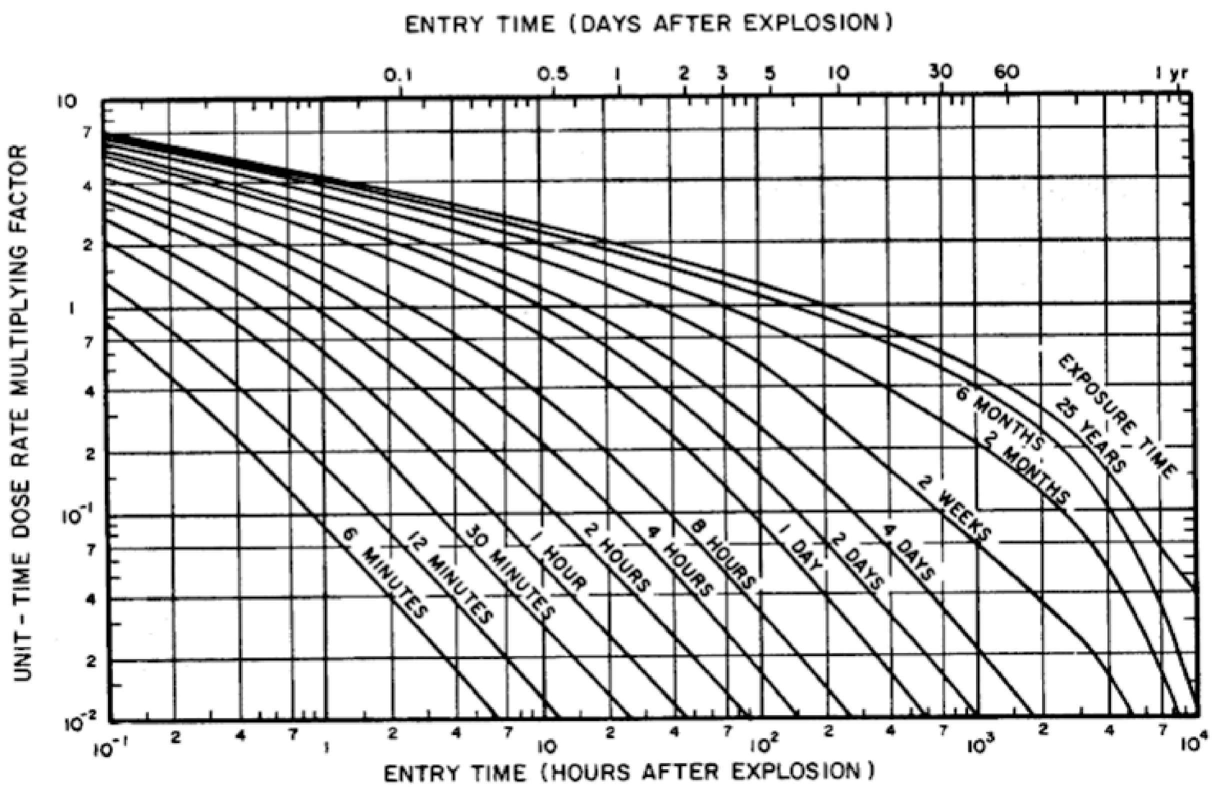



Figure 9.26. Curves for calculating accumulated radiation dose from early fallout based on unit-time reference dose rate.

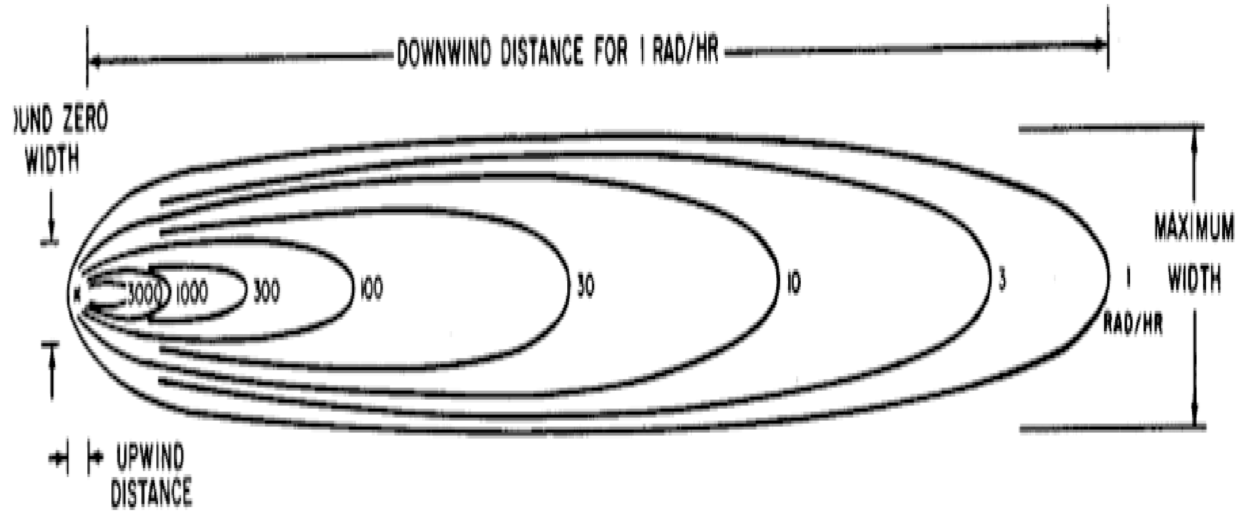
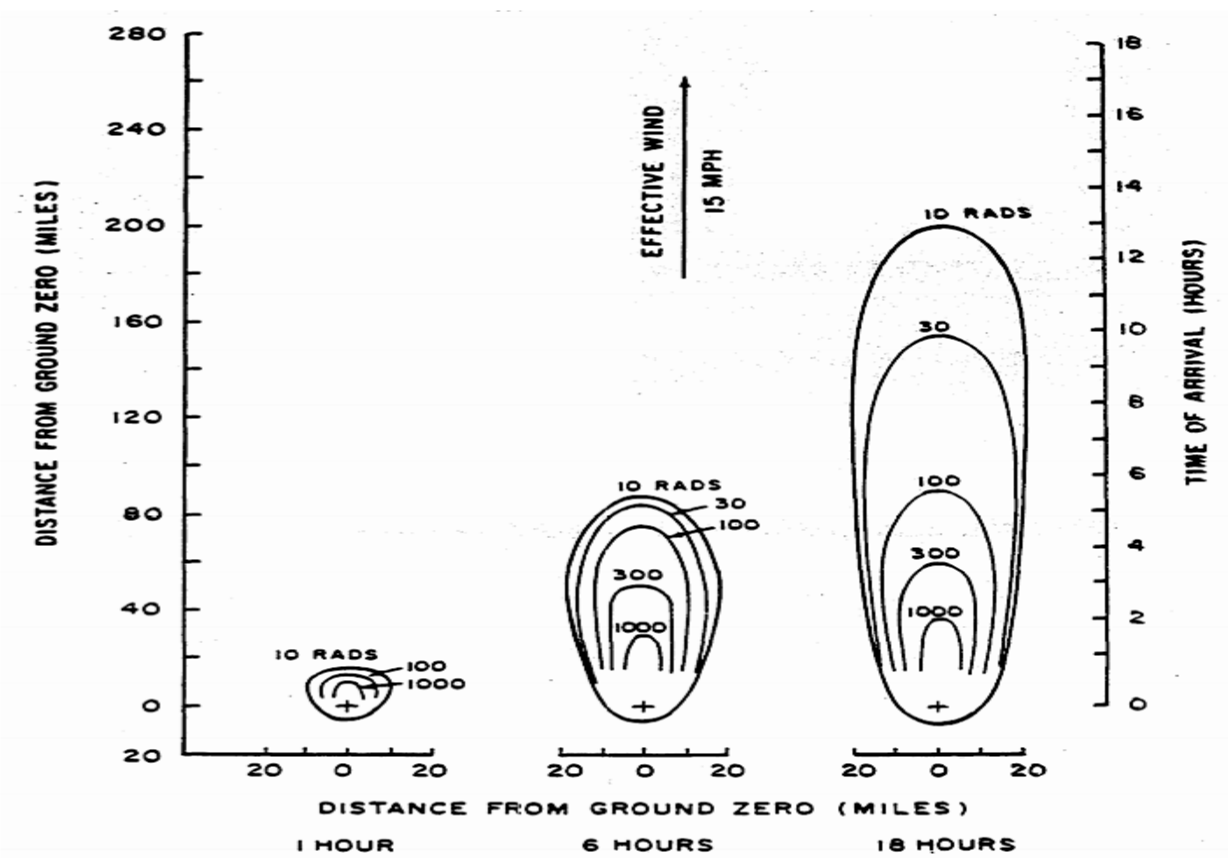
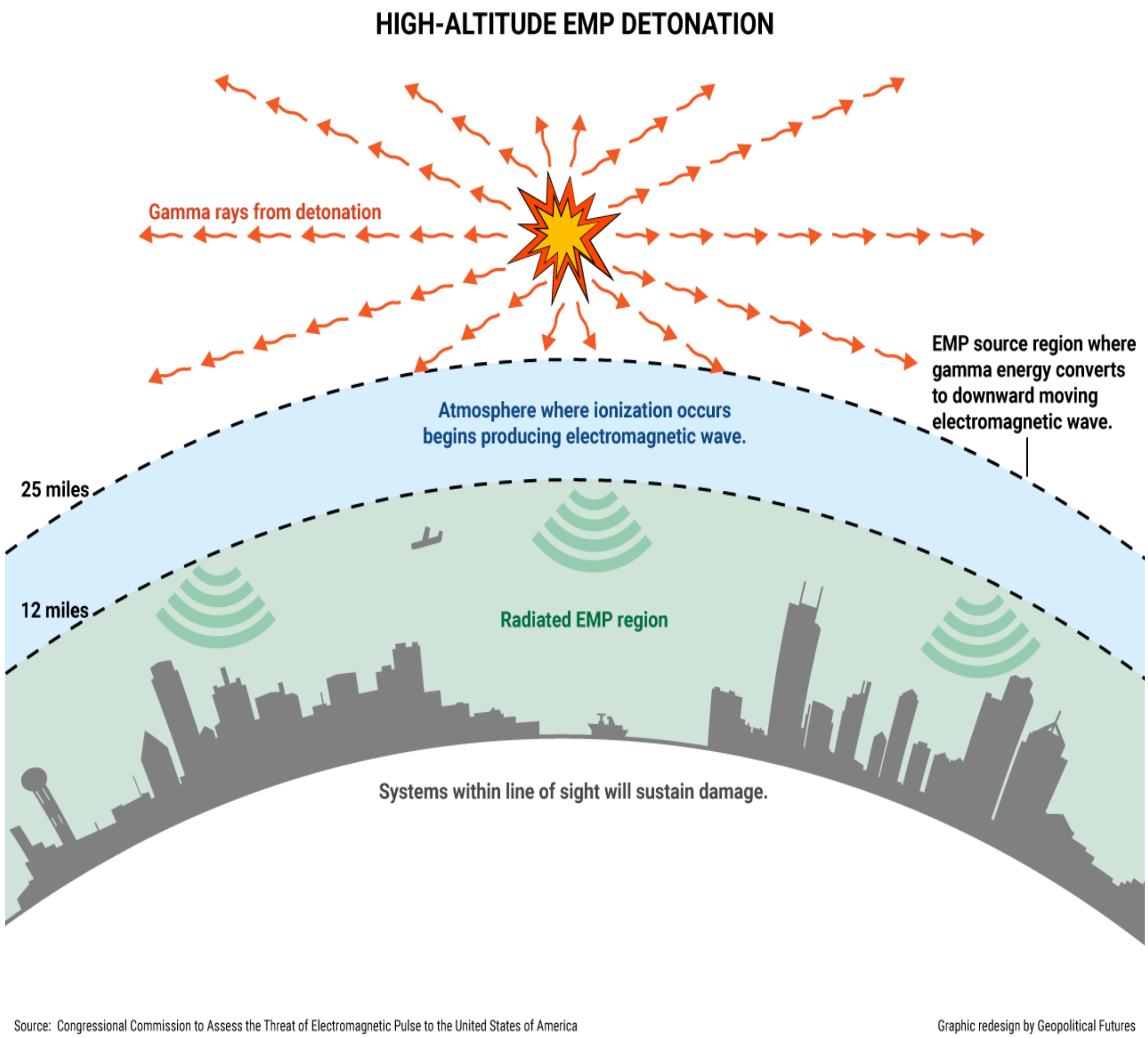



Figure 9.93. Illustration of idealized unit-time dose-rate pattern for early fallout from a surface burst. (The contour dimensions are indicated for a dose rate of 1 rad/hr.)



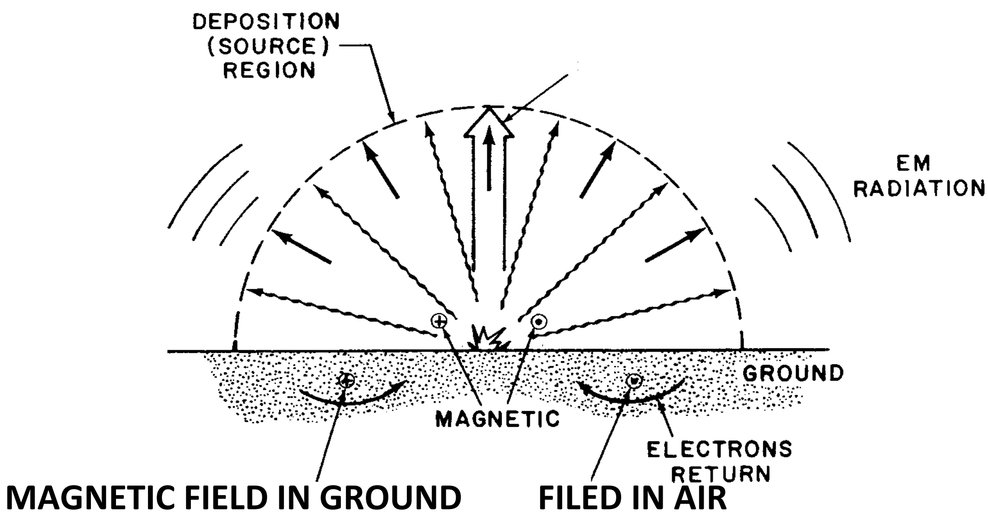
# Electromagnetic Pulse (EMP) Effects




The nuclear EMP is a time- varying electromagnetic radiation whichincreases very rapidly to a peak and then decays somewhat more slowly. The radiation has a very broad spectrum of frequencies, ranging from very low to several hundred megahertz but mainly in the radiofrequency (long wavelength) region

The instantaneous (or prompt) gamma rays emitted in the nuclear reactions and those produced by neutron interactions with weapon residues, or the surrounding medium (Fig. 8.14) are basically responsible for the processes that give rise to EMP from bursts in the lower atmosphere. The gamma rays interact with air molecules and atoms, mainly by the Compton effect, and produce an ionized region surrounding the burst point called the "deposition region."

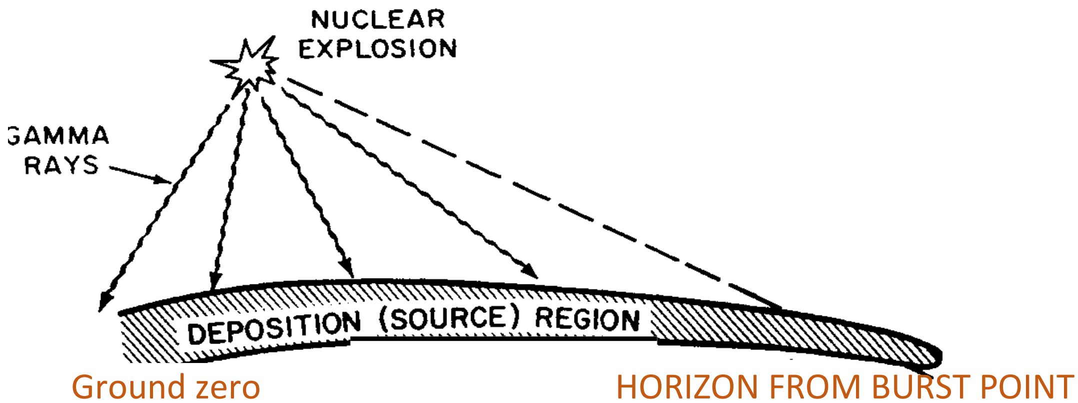
**EMP in surface burst**




**Schematic representation of the EMP in a surface burst.**

- In a surface burst, those gamma rays that travel in a generally downward direction are readily absorbed in the upperlayers of the ground and there is essentially no charge separation or electric field in this direction.
- The gamma rays moving outward and upward, however, produce ionization and charge separation in the air. Consequently, there is a net vertical electron current.
- As a result, the ionized deposition (source) region is stimulated to emit much of its energy as an electromagnetic pulse in the radiofrequency spectrum.

**EMP in High altitude burst**




(TANGENT POINT)

**Schematic representation of the EMP in a high-altitude burst. (The extent ofthe deposition region varies with the altitude and the yield of the explosion.)**

- If the nuclear burst is at an altitude above about 19 miles, the gamma rays moving in an upward direction will enter an atmosphere where the air density is so low that the rays travel great distances before being absorbed.
- The gamma rays emitted from the explosion in a generally downward direction will encounter a region where the atmospheric density is increasing. These gamma rayswill interact with the air molecules and atoms to form the deposition (or source)region for the EMP

## Class Discussion

**How is a nuclear bomb blast different from a nuclear power plant accident?**

**How you protect your community from nuclear radiation in case of nuclear attack? (Neutron and gamma ray)**

**How you protect your community from nuclear blast in case of nuclear attack?**

**How you protect your electronic device against EMP in case of nuclear attack?**