Questions

1. To what altitude raises the typical mushroom cloud?

2. What overpressure generates hurricane like winds?

3. Why is a nuclear burst at a certain altitude more damaging than the ground burst?
Thermal effects

Approximately 35 percent of the energy from a nuclear explosion is an intense burst of thermal radiation, i.e., heat. Thermal effects are mainly due to originated heat from blast which expands with wind velocity and incinerates everything within expansion radius. The thermal radiation from a nuclear explosion can directly ignite kindling materials. Ignitable materials outside the house, such as leaves, are not surrounded by enough combustible material to generate a self-sustaining fire. Fires more likely to spread are those caused by thermal radiation passing through windows to ignite beds and overstuffed furniture inside houses.
Total Radiation Emission from the Fireball

Emission of thermal radiation in two pulses in an air burst.
Thermal Energy Release

For a fireball with radius $r$ the heat emitting surface is:

$$ S = 4\pi \cdot r^2 $$

Total energy emitted per cm$^2$ and second is described by the Stefan Boltzmann law

$$ J = \sigma \cdot T^4; \quad \sigma = 1.36 \cdot 10^{-12} \text{ cal cm}^{-2} \text{s}^{-1} \text{deg}^{-4} $$

Total thermal energy emission from fireball is therefore:

$$ P = S \cdot J = 4\pi \cdot \sigma \cdot T^4 \cdot r^2 = 1.71 \cdot 10^{-7} \cdot T^4 \cdot r^2 \text{ cal/ sec} $$

With radius $r$ in units m and temperature $T$ in Kelvin
The thermal power of the fireball changes with time. Thermal energy release should be expressed in terms of maximum power $P_{\text{max}}$ (scaled power) and in terms of scaled time $t_{\text{max}}$ which corresponds to the time of maximum thermal energy release from the fireball.
For air bursts below 15,000 ft altitude the maximum power $P_{\text{max}}$ & the maximum time $t_{\text{max}}$ are related to the bomb yield $W$ (in kT)

$$P_{\text{max}} \approx 3.18 \cdot W^{0.56} \quad kT / \text{sec}$$

$$t_{\text{max}} \approx 0.0417 \cdot W^{0.44} \quad \text{sec}$$

e.g. for a 500 kT burst in 5000 ft altitude:

$$P_{\text{max}} \approx 3.18 \cdot 500^{0.56} = 103 \quad kT / \text{sec}$$

$$t_{\text{max}} \approx 0.0417 \cdot 500^{0.44} = 0.64 \text{sec}$$

According to the scaling laws expressed in the figure, total power and fraction of heat release can be calculated for any time; e.g. the total amount of thermal energy emitted at $t=1\text{sec}$ is:

$$\frac{t}{t_{\text{max}}} = \frac{1}{0.64} = 1.56; \quad \frac{P}{P_{\text{max}}} = 0.59 \quad (\text{see figure});$$

$$P = 0.59 \cdot P_{\text{max}} = 0.59 \cdot 103 = 60.8 \quad kT / \text{sec} = 60.8 \cdot 10^{12} \quad \text{cal / sec}$$

Fraction of thermal energy released at 1 s is $\sim 40\%$!
Fires can result from combustion of dry, flammable debris set loose by the blast or from electrical short circuits, broken gas lines, etc. These fires can combine to form as terrible firestorm similar to those accompanying large forest fires. The intense heat of the fire causes a strong updraft, producing strong inward drawn winds in which fan the flame, take away oxygen so it is difficult to breath, and destroy everything in their path (Chimney Effect).
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 $\kappa$. The heat exposure at distance $d$ would be:

$$Q = \frac{W_{\text{therm}}}{4\pi \cdot d^2} \cdot e^{-\kappa \cdot d}$$

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 ($f \approx 0.35$-$0.42$ depending on altitude).

$$Q = \frac{W_{\text{therm}} \cdot \tau}{4\pi \cdot d^2} = \frac{f \cdot W \cdot \tau}{4\pi \cdot d^2} = 10^{12} \cdot \frac{f \cdot W \cdot \tau}{4\pi \cdot d^2} \text{ cal/cm}^2$$

$$1kT = 4.18 \cdot 10^{12} \text{ J} = 10^{12} \text{ cal}$$
Simulation of nuclear explosion
Transmittance

\[ Q = 3.2 \cdot 10^{10} \cdot \frac{W \cdot \tau}{d^2} \text{ cal} / \text{cm}^2 \]

For distance up to 3km, \( \tau \approx 0.8-1 \)

\[ 1\text{ km} = 10^5 \text{ cm} \]

\[ f \approx 0.4 \]

Transmittance, \( \tau \), to a target on the ground on a typical clear day (visibility = 12 miles).
Effects of thermal radiation on materials

Heat exposure in bright sunlight: 2 cal/cm²

White paper ignites at ~ 5 cal/cm², (magnifying glass)
Fabric ignites at ~20-40 cal/cm² depending on color & material

1st degree burn ~ 3 cal/cm² (sunburn)
2nd degree burn ~5 cal/cm² (skin loss, no scars, >25% body ⇒ hospital)
3rd degree burn ~8 cal/cm² (destroy skin nerves, scarring, no cell regeneration; >50% ⇒ fatal)

In the case of bomb explosions, the released thermal radiation depends on the bomb yield W and also the heat exposure depends on bomb yield.
Ignition of combustibles ($W=10 \text{ kT}$)

\[ Q = 10^{12} \cdot \frac{f \cdot W \cdot \tau}{4\pi \cdot d^2} = \frac{8 \cdot 10^{10} \cdot f \cdot W \cdot \tau}{d \text{ [cm]}^2} = \frac{8 \cdot f \cdot W \cdot \tau}{d \text{ [km]}^2} \left[ \frac{\text{cal}}{\text{cm}^2} \right] \]

$f \approx 0.35$, $\tau \approx 1$ (for close distances)

Threshold ignition for combustibles $\geq 15 \text{ cal/cm}^2$

$\Rightarrow$ Ignition of clothes within radius of 2000 m.
Ignition conditions

\[ Q = \frac{3.07 \cdot f \cdot W \cdot \tau}{d^2 [\text{miles}]^2} \left[ \frac{\text{cal}}{\text{cm}^2} \right] = \frac{3.07 \cdot 0.35 \cdot 200 [kT] \cdot 0.8}{2.65^2} \approx 25 \left[ \frac{\text{cal}}{\text{cm}^2} \right] \]

Thermal effects on wood-frame house about \( \frac{3}{4} \) second later. No ignition of the wooden structure.

Thermal effects on wood-frame house 1 second after the explosion (~25 cal/cm\(^2\)). Ignition of paint.
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.
FIGURE 1  Velocity vectors at 15 minutes after the start of a 10-km radius fire.

FIGURE 2  Velocity vectors at 25 minutes after the start of a 10-km radius fire.

FIGURE 3  Stream lines in atmospheric circulation generated by a 10-km radius fire 40 minutes after ignition.

FIGURE 4  Stream lines in atmospheric circulation created by a 10-km radius fire 1 hour after ignition.
Hiroshima
Hiroshima Victims
Eyewitnesses

A bright flash and explosion at the same time; I could not see an inch ahead. Is it smoke or dust? It all happened in a moment Hiroshima was engulfed in a sea of flames. Those who got burns were fleeting here and there, crying in pain “Help!” With screams, a wave of people come rushing toward me.

Kojin-machi,
Burn wounds

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
Victims
Death rate anticipated for the case of more powerful bombs can be extrapolated using the scaling laws.