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VARIABILITIES IN THE NATURAL AND NUCLEAR ENDOATMOSPHERIC ENVIRONMENT

Ernest Bauer

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This document supplements a briefing on Uncertainties in the Prediction of High-Altitude Nuclear Effects. The intended audience consists of the SDS architects and engagement modelers who have to consider the nuclear (and other) environment but are under very severe constraints regarding computer running time so that very fast-running and thus simple models of atmospheric environment have been used. This material is a tutorial, intended to give the audience a physical feeling of the nature of the natural and nuclear endoenvironment (i.e., environments and heights of burst in the 0-100-km altitude range), pointing out the changes in nuclear phenomenology at different altitudes and the large variabilities in the natural atmosphere, including effects of turbulence, clouds, and rain. The factors to be considered for SDS modeling depend on the threat scenario under consideration, such as the number, altitude and yield of the nuclear bursts, and the nature of sensors under consideration (IR, UV/VIS, MMW; spectral and spatial resolution; sensitivity; active vs. passive sensors).

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ABSTRACT

This document supplements a briefing on Uncertainties in the Prediction of High-Altitude Nuclear Effects. The intended audience consists of the SDS architects and engagement modelers who have to consider the nuclear (and other) environment but are under very severe constraints regarding computer running time so that very fast-running and thus simple models of atmospheric environment have been used. This material is a tutorial, intended to give the audience a physical feeling of the nature of the natural and nuclear endoenvironment (i.e., environments and heights of burst in the 0-100-km altitude range), pointing out the changes in nuclear phenomenology at different altitudes and the large variabilities in the natural atmosphere, including effects of turbulence, clouds, and rain. The factors to be considered for SDS modeling depend on the threat scenario under consideration, such as the number, altitude and yield of the nuclear bursts, and the nature of sensors under consideration (IR, UV/VIS, MMW; spectral and spatial resolution; sensitivity; active vs. passive sensors).

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SUMMARY

This document supplements a briefing on Uncertainties in the Prediction of High-Altitude Nuclear Effects (Bauer, 1990). The intended audience consists of the SDS architects and engagement modelers who have to consider the nuclear (and other) environment but are under very severe constraints regarding computer running time so that very fast-running and simple models of atmospheric environments have been used. This material is tutorial in nature, intended to give the audience a physical feeling of the nuclear endoenvironment,[1] pointing out the large effects that natural variabilities in the unperturbed lower atmosphere can produce.

Table S-1 outlines the problems that are discussed here. We begin by reviewing the different nuclear phenomenology domains between sea level and 100-km altitude including nuclear-induced dust. Then we review ambient atmospheric variability in general, including effects of turbulence, clouds, and rain. All these phenomena can make significant differences in the environment for both sensing and survivability. The effects of atmospheric variability can be significant, especially for the very sensitive modern electro-optical surveillance systems. The factors to be considered for SDS modeling depend on the threat scenario under consideration, such as the number,[2] altitude, and yield of the nuclear bursts, and the nature of sensors under consideration (IR, UV/VIS, MMW; spectral and spatial resolution; sensitivity; active vs. passive sensors).

The environmental description in an engagement model may be severely constrained by computer capability, and the threat scenario will serve to define a computer model that makes an optimum tradeoff between the fidelity of the model and the running time it requires.

---

1 The notation regarding altitude ranges for nuclear bursts is nonstandard and confusing. Bursts below about 10 km are customarily described as low-altitude bursts, with the term "near-surface" frequently implying that dust is lofted and possibly a crater is produced. Bursts below 100 km are generally described as *endoatmospheric*, while those above 100 km are generally described as *exoatmospheric*. Note however that in Section 2.2 (see Table 3 and Figs. 4 through 6) we use the terms "low," "intermediate," and "high" to refer to bursts at 30, 70, and 150 km, respectively.

2 Nuclear multibursts are considered improbable in current (6/92) scenarios, and thus are not discussed here.

Table S-1. Summary of the Problems Discussed

- Atmospheric density decreases by a factor 10^6 in going from the surface to 100 km
- Significant changes in nuclear (and natural) phenomenology over this range in altitudes/densities
- In the endo-atmosphere the ambient density is relatively high, so that nuclear fireballs are confined to 1-10 km
  - Lots of data for near-surface bursts
  - Some data on bursts between 10 and 100 km
- Natural atmosphere varies significantly
  - Weather in troposphere (below ~ 10 km)
  - Clouds occur roughly half the time
  - Precipitation (rain or snow) occurs maybe 3% of the time
  - Wind and turbulence
  - Smoke

In contrast to the high-altitude environment, where the atmospheric density is so low that the effects of a single nuclear burst extend over hundreds or thousands of kilometers, below 100 km the ambient atmospheric density is relatively high, so that an individual nuclear fireball is confined to a region of 1-10 km in extent, while damage radii extend some tens of km.

Because the ambient atmospheric density varies by a factor of 10^6 between sea level and 100-km altitude, the nuclear phenomenology varies significantly with height. Further, while we have significant data on just two bursts above 100 km, there are test data on six bursts between 20 and 95 km and on perhaps 100 bursts below 10 km. Thus the data base for near-surface bursts is good, while for bursts at altitudes of 10-100 km there is significantly more test data than for bursts above 100 km.

Typically clouds are present half the time, it rains some 3-5 percent of the time, and tracer cloud-spreading rates (which reflect on underlying atmospheric turbulence) may vary by several orders of magnitude. It is important to be aware of these factors, so that the computer engagement model will appropriately balance the needs for model fidelity and computation time.

Figure S-1 provides a general orientation on how the different elements of phenomenology fit together as a function of altitude (or density, as parameterized by the gas-kinetic mean free path). This figure contains a great deal of information and is discussed in more detail in the text.

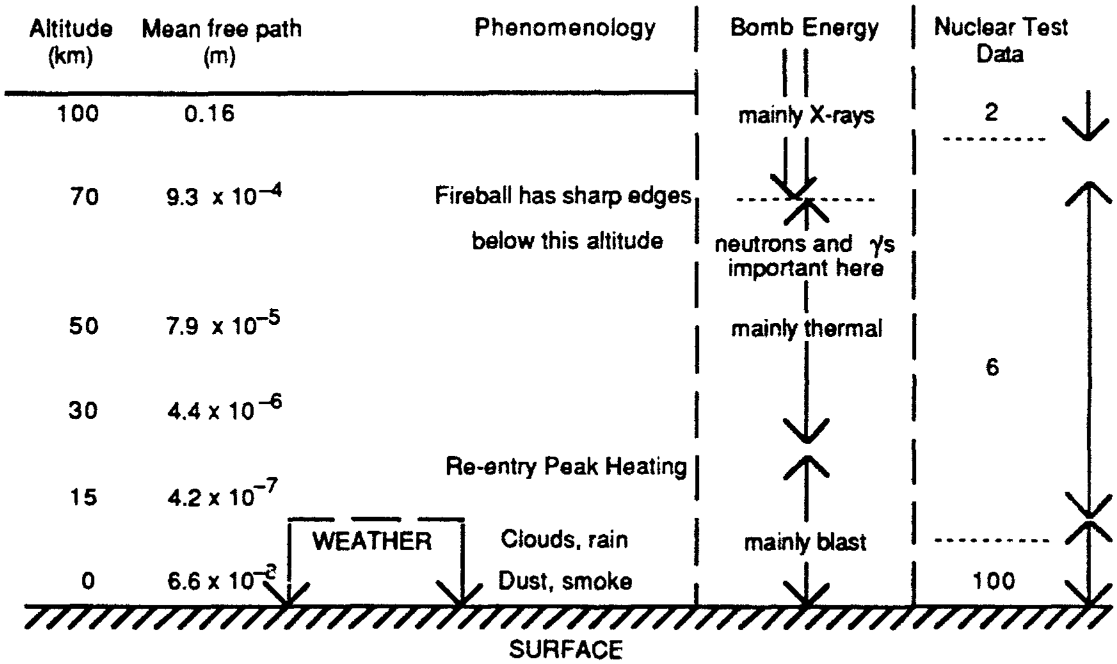

Figure S-1. Phenomenology in the Lowest 100 km of the Earth's Atmosphere

1.0 INTRODUCTION

This document supplements a briefing on Uncertainties in the Prediction of High-Altitude Nuclear Effects (Bauer, 1990). The intended audience consists of the SDS architects and engagement modelers who have to consider the nuclear (and other) environment but are under very severe constraints regarding computer running time so that very fast-running and thus simple models of atmospheric environments have to be used. Thus this material is intended to give the audience a physical feeling of the nature of the natural and nuclear endoenvironment (i.e., environments and heights of burst in the 0-100-km altitude range); it is noted that large atmospheric variabilities occur, so that the computer engagement model chosen will appropriately balance the needs for model fidelity and computation time.

In contrast to the high-altitude environment, where the atmospheric density is so low that the effects of a single nuclear burst extend over hundreds of kilometers, below 100 km the ambient atmospheric density is relatively high, so that an individual nuclear fireball is confined to 1-10 km and damage radii extend some tens of kilometers. However, electro-optical sensors viewing through the atmosphere are affected not just by nuclear fireballs but also by variable effects of the high-density lower ambient atmosphere, such as clouds, rain, smoke, or dust clouds.

Because the ambient atmospheric density varies by a factor of 10^6 between sea level and 100-km altitude, the nuclear phenomenology varies significantly with height. Further, while we have significant data on just two bursts above 100 km, there are test data on six bursts between 20 and 95 km and on perhaps 100 bursts below 10 km, so that the data base is very much better than in the exoatmospheric environment.

We begin by reviewing the different nuclear phenomenology domains between sea level and 100-km altitude and then discuss (nuclear-induced) dust, atmospheric variability in general, clouds, and rain.

Figure 1 sketches some variability in the lowest 100 km of the earth's atmosphere. It contains a great deal of information and requires detailed examination. Beginning at the left hand side, we give an altitude scale and show the gas-kinetic mean free path

$$l_{gk} = 1/\,n\,\sigma_{gk} \tag{1}$$

where n = particle number density which ranges from 2.5×10^{25} particles/m^3 at sea level to 1×10^{19} particles/m^3 at 100 km, and $\sigma_{gk} \sim 6 \times 10^{-15}$ cm^2 is the gas-kinetic mean collision cross-section of an air molecule. Thus l_{gk} varies from 0.07 μm at sea level to 20 cm at 100 km.

Re-entering missiles first interact with air molecules near 100 km, where the gas kinetic mean free path l_{gk} is of the order of missile dimensions. The *peak heating* of a typical high-performance ICBM occurs between 15 and 25 km.

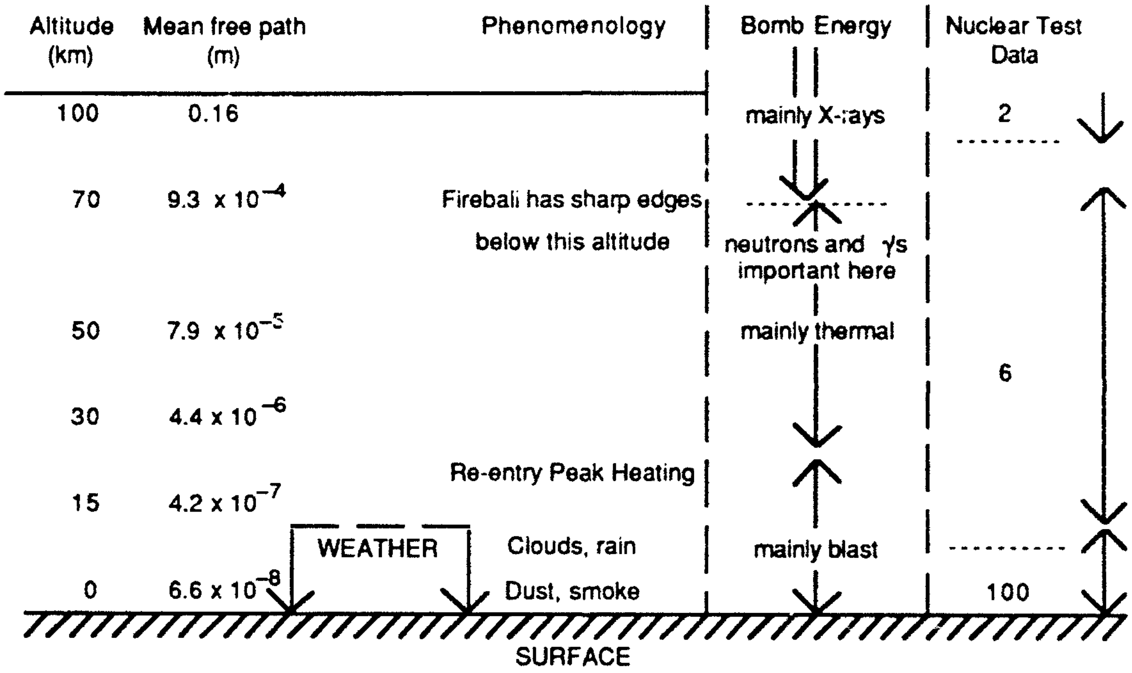

Figure 1. Phenomenology in the Lowest 100 km of the Earth's Atmosphere

The *weather* (i.e., clouds and rain) is confined to the troposphere, roughly the lowest 10 km of the atmosphere. Most dust and smoke and a large fraction of the blast effects are confined to this region, which contains approximately 75 percent of the mass of the earth's atmosphere.

A *nuclear fireball* for a high-yield burst is formed below 70-80 km; Table 1 shows that bomb X-rays (which account for roughly 75 percent of the bomb's energy) are typically transmitted in the atmosphere only above these altitudes since there isn't enough atmospheric mass at higher altitudes.

Table 1. Transmission of X-Rays, Neutrons, and Gamma Rays in the Atmosphere

Altitude (km)	Air Density (kg/m^3)	Transmission through 10-km horizontal path				
		X-rays			1 MeV neutrons	1 MeV gamma rays
		1 keV	3 keV	10 keV		
0	1.23	0	0	0	0	0
10	0.41	0	0	0	2×10^{-18}	4×10^{-11}
20	0.089	0	0	0	1×10^{-4}	5.5×10^{-3}
30	0.018	0	0	0	0.17	0.72
40	0.0040	0	0	6.1×10^{-6}	0.67	0.79
50	0.0010	0	0	0.0030	0.90	0.94
60	3.1×10^{-4}	0	1×10^{-23}	0.30	0.97	0.98
70	8.8×10^{-5}	0	3×10^{-7}	0.77	0.99	1.00
80	2.0×10^{-5}	0	0.03	0.93	1.00	1.00
90	3.2×10^{-6}	3×10^{-6}	0.58	0.99	1.00	1.00
100	5.0×10^{-7}	0.14	0.92	1.00	1.00	1.00
Extinction Coefficient is:		(4000 cm^2/g)	(170 cm^2/g)	(3.5 cm^2/g)	(0.0.7 cm^2/g)	(0.1 cm^2/g)

In Figure 1 we also show how the *bomb energy* is carried.[1] Above 80 km it is mainly transported by *X-rays*. Below 70 km most of the energy is carried as *thermal energy* of the fireball, while below ~ 20 km, where the air density is much greater than at higher altitudes, *blast and shock* become most important as a damage mechanism. Note that while neutrons and gamma rays account only for a small fraction of the bomb energy, yet they are important as a kill mechanism in the 50-70 km altitude range.

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1 For more detail, see Section 2.1.

Referring back to Figure 1, there are lots of test data for heights of burst (HOB) below ~ 10 km, some data from 20-90 km, and very few data above 95 km, so that with increasing altitude the phenomenology depends increasingly on analysis rather than on test data.

Table 1 shows the atmospheric transmission through a horizontal (constant density) 10-km path for 1, 3, and 10 keV X-rays, and for 1 MeV neutrons and gamma rays, at altitudes below 100 km. We see that X-rays are absorbed between 40 km (10 keV) and 90 km (1 keV), while the neutrons and gamma rays are absorbed between 20 and 30 km.

In an atmosphere at constant temperature T, the density $\rho(z)$ falls off with increasing altitude z as

$$\rho(z) = \rho(z_o) \exp - (z - z_o)/H \tag{2}$$

where the *atmospheric scale height* H is given by the expression $H = kT/Mg$. Representative values for H are 7 km at altitudes below 100 km where the temperature is ~ 200-250 K; above 200 km altitude, where T ~ 700-1500 K and the atomic oxygen is dissociated so that the effective molecular weight is typically 18 (rather than 29), H lies in the range 30 - 70 km.

In Section 2 we give a brief overview of the nuclear endo-atmospheric environment, pointing out the differences in phenomenology associated with the large difference in density (factor 10^6) between sea level and 100-km altitude. This is followed in Section 3 by a survey of variable aspects of the natural environment (mainly in the dense lower atmosphere), noting that clouds (which occur frequently) can totally obscure electro-optical sensors, as can rain, dust clouds, and smoke from fires.

2.0 NUCLEAR PHENOMENOLOGY BELOW 100 km

2.1 INTRODUCTION

There exist significant data on eight U.S. nuclear explosions between heights of burst of 20 and 400 km (two above 100 km, 6 between 20 and 95 km), as opposed to more than 100 between the surface and 5-10 km. Thus the low-altitude data base is very much better than that at high altitudes, and the warnings of uncertainty in the high-altitude data base given in Bauer, 1990, are not so critical here. However:

(a) As is pointed out in Figure 1 (above), the density falls off by a factor of 10^6 between the surface and 100 km, and thus there are significant variations in phenomenology throughout the region in which there is a significant atmosphere.

(b) Because all atmospheric nuclear tests were conducted in 1962 and earlier, the caveats about the lack of UV and LWIR data given in Bauer, 1990, still apply, but they tend not to be so serious because of the higher density of the atmosphere in which most of the UV and IR radiation are absorbed. Thus the atmosphere tends to radiate and absorb as a black body, so that the details of the radiating atomic and molecular species are normally not as critical as at higher altitudes where the spectral variation in atomic and molecular radiation is critical.

Much of the energy of a bomb is emitted initially as 1-10 keV X-radiation, which is absorbed in < 10 km of atmosphere at altitudes below 70-90 km (see Table 1). A fireball is produced at the relatively high densities corresponding to altitudes below 70-90 km by the energy emitted from the bomb--both X-ray energy (about 75 percent of the total energy) and bomb debris (20-25 percent of the total energy). The dimension of this fireball is of order 1 km for 1 Mt yield. At very low altitudes much of the fireball energy is dissipated by strong blast/shock effects, with the balance emitted as thermal radiation. If the burst is sufficiently close to the surface a large dust cloud is produced.

A small fraction of the energy of a bomb is emitted as nuclear radiation. The neutrons and gamma rays--while they may account for only 0.1-1 percent of the total energy of the detonation--can have very significant effects (especially on sensors, electronics, etc.) because they penetrate the atmosphere very effectively. As is indicated in

Table 1, 1 Mev neutrons are absorbed within a few kilometers in the atmosphere only below 30 km, and 1 Mev gamma rays are absorbed in the atmosphere only below 25 km.

For orientation, Table 2 gives a schematic partition of the energy yield from a nuclear weapon between X-rays, nuclear radiations, blast/shock, and thermal as a function of burst height. X-rays are absorbed below about 80 km while neutrons and gamma rays penetrate much farther down. Thermal energy is produced both from the fireball and from the absorption of bomb debris (which carries some 20-25 percent of the total bomb yield) at altitudes above ~ 80 km. Blast/shock is very important near sea level, but falls off as the pressure decreases with increasing altitude.

Table 2. Partition of Energy from a High-Yield Nuclear Explosion as a Function of Altitude[1]

Altitude (km)	Pressure ratio (p/p_o)	X-rays	Nuclear Radiation[2]	Thermal	Blast/Shock
> 80	< 1E-5	0.75	0.03	0.2	-
60	2E-4	0.2	0.03	0.6	0.15
40	3E-3	-	0.03	0.65	0.35
20	0.06	-	-	0.45	0.55
0	1.0	-	-	0.35	0.65

1 Some 25 percent of the energy of a bomb is carried as kinetic energy of the bomb debris which is absorbed much more readily than even soft X-rays, so that it is mostly absorbed above 80 km. In fact, the atmospheric effects of a high-altitude nuclear explosion are due largely to the absorption of this relatively small fraction of the energy, since most of the rest of the bomb's energy escapes, with the exception of the downward-traveling X-rays which are absorbed by the air below the detonation point.

2 The penetration refers only to the most penetrating nuclear radiations, neutrons and gamma rays, which make up a small fraction of the total energy yield. The partition fraction "0.03" may be an over-estimate for neutrons and gamma rays; there is also a significant contribution due to energetic beta particles which are confined by the earth's magnetic field.

Figure 2 demonstrates how the effects of the different components of the bomb output change with altitude, by showing the effects radius due to each individual component:

- Blast/shock predominates near the ground.
- Thermal effects predominate from 20 to 60 km, but remain significant above 100 km.
- In the 50-70 km altitude range neutrons (and also gamma rays) can be very important as a damage mechanism because electronics, optical focal planes, etc., are exceedingly sensitive to these nuclear radiations.

The hardness/vulnerability levels assumed are the following:

- 10 cal/cm^2 for X-rays
- 10^{13} neutrons/cm^2
- 50 cal/cm^2 for thermal (this is the incident fluence; if the surface reflectivity is 50 percent, then 25 cal/cm^2 goes into the material at this range).
- For blast/shock, we show the effective range for 1, 3, 10 psi, assuming the standard scaling, see, e.g., Glasstone and Dolan, 1977, p.100 ff.

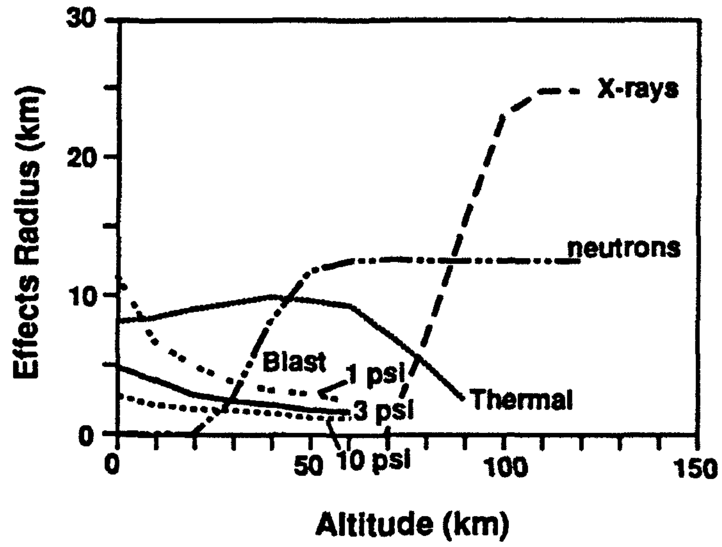

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Figure 2. Selected Effects Radii as a Function of Altitude for a 1 Mt Weapon

- Above about 70 km, the damage effect of soft X-rays normally predominate.[1]

The term "fireball" is used--conventionally but inconsistently--to refer to two distinct concepts:

- For altitudes below ~ 70 km, it is a visually defined volume in which essentially all the yield of the bomb is deposited. This volume of heated air is the source of the blast/shock wave and of the thermal radiation from the weapon.

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1 Above 100 km, the soft X-rays, which carry some 70-75 percent of the total bomb energy, are not absorbed in distances less than a few hundred kilometers. Thus exoatmospheric nuclear effects are produced mainly by the absorption of that 20-25 percent of the total yield that is carried by bomb debris as kinetic energy, which tends to be absorbed in the low-density air and is reradiated in the UV spectral range.

- The concept of a fireball is still useful for higher altitude bursts (for high yields, up to 150-200 km), but due to the lower ambient density and thus the longer mean free path for radiation, these higher altitude fireballs will have less well-defined edges, and contain a fraction of the total bomb yield that decreases with increasing altitude.

2.2 PHENOMENOLOGY FOR BURSTS BETWEEN 20 AND 80 km: THE "HIGH-ENDOATMOSPHERIC REGIME"

Reference to Figure 1 shows that the atmospheric density falls by a factor of 10^6 between mean sea level and 100 km. Much of the energy of a bomb is emitted as X-rays: at altitudes below 70 km they are absorbed within 1-10 km or less, giving rise to a *fireball*. At the lower altitudes (below ~ 40 km for a 1 Mt burst) this fireball is smaller than the local atmospheric scale height[2] $H = kT/Mg \sim 7$ km and thus rises as a buoyant bubble, entraining outside air during its rise. At higher altitudes (above ~ 70 km for a 1 Mt burst) the ambient density is much lower and there is less entrainment, so that the fireball rises more rapidly, "ballistically," and overshoots its final stabilization altitude.[3] Note that the upward speed of the fireball increases greatly with altitude.

An air parcel of radius R is said to rise *buoyantly* if $R << H$, and *ballistically* if $R >> H$. Buoyant rise, which occurs at relatively low altitudes, corresponds to relatively slow, adiabatic rise of the air parcel, which maintains a uniform pressure; ballistic rise, which takes place at lower densities, is relatively rapid with pressure varying in the parcel. (See, e.g., Sowle, 1977, pp. 480 ff and 505 ff.)

Table 3 indicates how the scale of phenomena changes with increasing altitude, and Figures 3 through 6 illustrate disturbed environments for three different modeling regimes as determined by burst altitude. Note both that the *scale* of the disturbed region increases as one goes up in altitude (and down in density) and the *phenomenology* changes.

Regarding the *phenomenology in the different altitude regimes*, Figure 3 for a near-surface burst[4] comes from Glasstone, 1964, pp. 89-90. Note that while the fireball does not touch the ground (definition of an air burst), yet the afterwinds can sweep up a relatively small amount of dust.[5]

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2 Which is defined in Eq.(2), Section 1.

3 At intermediate altitudes (40-70 km for 1 Mt) the behavior is intermediate between the "buoyant" and "ballistic" limits.

4 This discussion of the physics is very useful, but some of the numbers are slightly inconsistent with current models.

5 Cf. Figure 7b below; for both of these examples, the SHOB ("scaled height of burst") is 6,500 ft/Mt$^{1/3}$.

Table 3. How the Scale of a Nuclear Detonation Changes with Altitude

Altitude Regime	Near-Surface	Low	Intermediate	High
Altitude (km)	2	30	70	150
Ambient density (kg/m^3)	1.0	1.8×10^{-2}	8.8×10^{-5}	1.8×10^{-9}
Gas-kinetic mean free path (m)	8.1×10^{-8}	4.4×10^{-6}	9.3×10^{-4}	41
Fireball size (km, for a 100 kt weapon)				
at t = 1 sec	0.4	1.5	5	~50
at t = 30 sec	0.75	3	30	~200
See Figure:	4	5	6	7

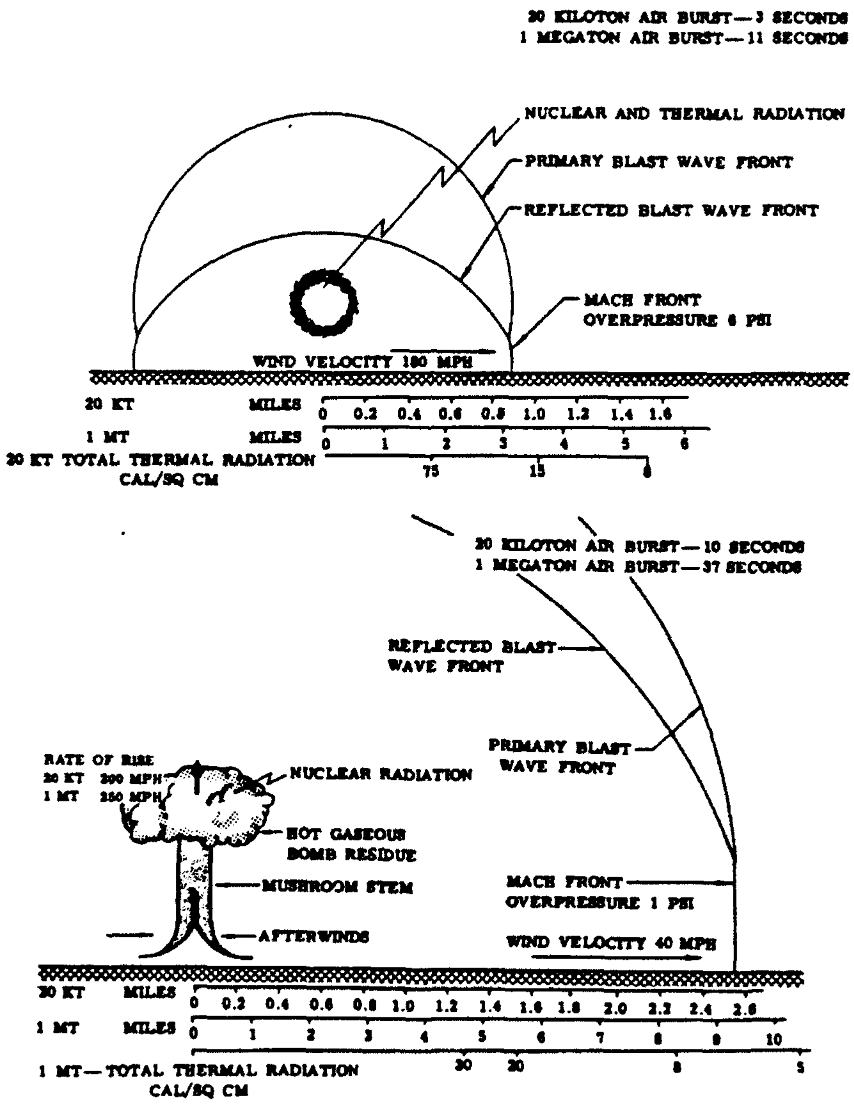

Figure 3. Chronological Development of a Near-Surface Burst (20 kt @ 0.5 km, 1 Mt @ 2 km) (Source: Glasstone, 1964)

The description for the higher altitude bursts and Figures 4 through 6 comes from J. Jordano (private communication):

> Fig. 4 shows potential IR emission features from a burst below about 50 km altitude. In this altitude regime, the hot fireball expands to pressure equilibrium with the ambient air, then rises buoyantly as an underdense bubble, with the subsequent vortex flow generating a torus (donut) shaped region. The different features result from different kinds of emission processes which have different wavelength dependencies, and their relative importance depends in general on the sensor band. The "plasma" emission region is one of high ionization and is thus also the primary disturbed region of interest to RF systems. The debris cloud is the vaporized weapon material. The molecular aura is a warm shell (1000-2000 K) surrounding the main fireball where thermoluminescent emissions are dominant. The "near" and "far" wake are turbulent regions, with mixing of hot fireball air and ambient cool air, where chemiluminescent emissions[6] are dominant. The near wake is air that eventually gets swept up into the fireball; the far wake is air that sweeps across the fireball surface but gets left behind as the fireball rises.

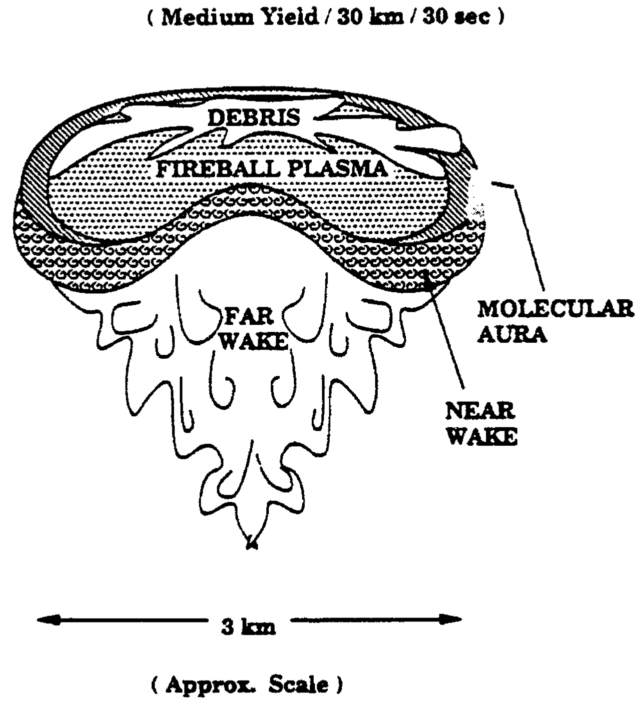

Figure 4. Potentially Important Emission Features in the Low-Altitude Regime (Source: J. Jordano, PRI)

6 Sufficiently energetic chemical reactions leave some of their product molecules in excited states which can radiate. If the molecules are formed in electronically excited states, the radiation is mainly in the visible and UV; this is called *chemiluminescence*. If they are only vibrationally excited, they radiate in the IR--this is called *vibraluminescence*.

Fig. 5 shows IR emission features from an intermediate altitude burst, say 50-100 km altitude. In this regime the fireball is much larger than at lower altitudes because of the lower air density. The fireball is bigger than the atmospheric scale height, i.e., it senses the vertical atmospheric gradient, and its expansion in the upward direction is much more rapid than in the downward direction. This net upward acceleration results in very rapid ("ballistic") rise of the fireball to altitudes of several hundred km. In contrast to the low altitude fireballs which are underdense, the intermediate altitude fireball is overdense compared to the ambient air. The upward expansion also launches a strong shock wave which actually accelerates and gets stronger as it moves into decreasing air densities. Also in the intermediate altitude regime, the reduced air densities allow some forms of weapon energy to escape from the fireball region. In addition to the plasma, debris, and molecular aura regions that we saw in the low altitude regime, prompt X-rays from the initial burst form the X-ray patch, and delayed beta radiations from the radioactive fission debris form the beta tube (which parallels the geomagnetic field lines, ie has different direction at different geomagnetic latitudes). These are regions of potential chemiluminescence or vibraluminescence.

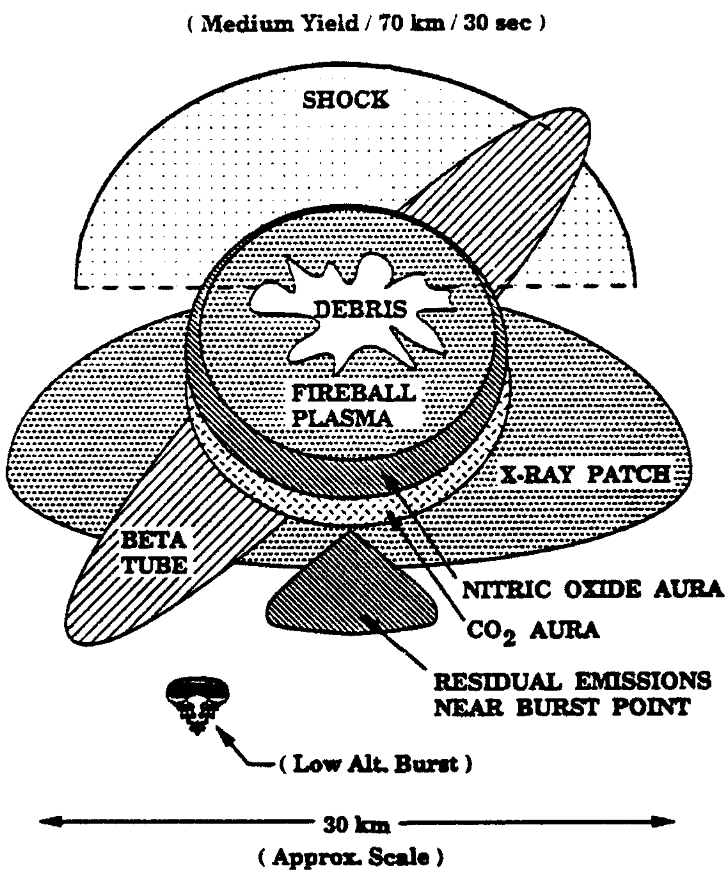

Figure 5. Potentially Important Emission Features in the Intermediate-Altitude Regime (Source: J. Jordano, PRI)

Fig. 6 shows IR emission features from a high altitude burst, say above 100 km altitude. Note again the vast increase in spatial extent and in anisotropy. At these altitudes, nearly all the burst X-ray energy--about 75 percent of the total yield--escapes the burst region, so that there is no longer a well-defined fireball. The softer X-rays form a patch near 100 km altitude where vibraluminescent emissions will dominate. The fireball and aura regions are formed by UV photon energy generated by the interaction of the expanding weapon debris shock and the surrounding air. The early-time dynamics for this region are similar to the intermediate altitude fireball of Fig. 5, with rapid rise leading to an overdense fireball region. Due to slower deionization chemistry at the lower densities (higher altitudes) where the ions are atomic rather than molecular,[7] the fireball plasma remains highly ionized so that later time dynamics (after about half a minute) is influenced by the earth's magnetic field, and the fireball evolves into a "geomagnetic plume." Due to the large spatial extent of the disturbance at high altitude, it is quite likely that disturbances from several nuclear bursts will overlap, so that it is critical that a high altitude model include interactive multiburst effects. The primary interaction is through atmospheric heave,[8] where the increased air densities from earlier bursts create an environment for later bursts that corresponds to lower effective detonation altitudes. Thus the phenomena from a 300 km burst in a severely heaved environment might look much like a 150 km burst in an undisturbed atmosphere.

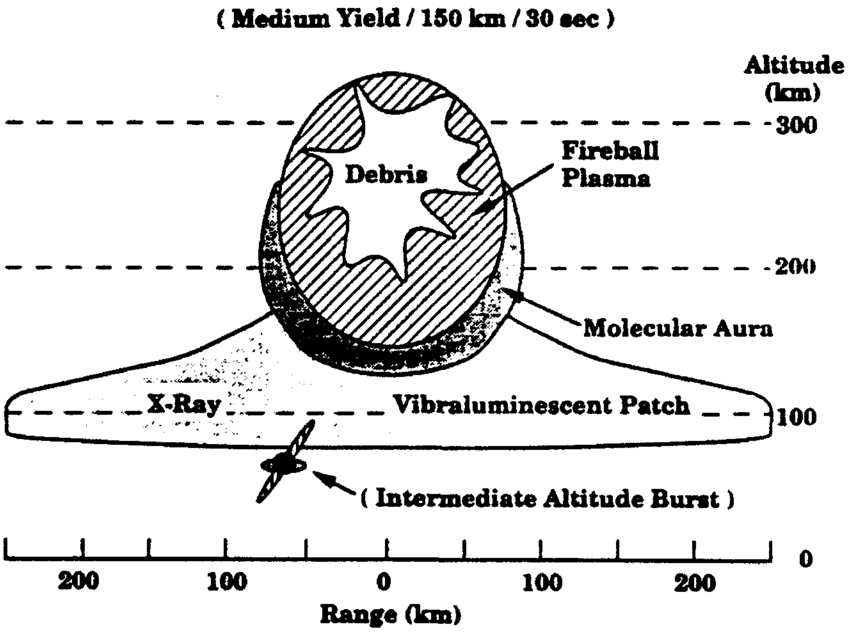

Figure 6. Potentially Important Emission Features in the High-Altitude Regime (Source: J. Jordano, PRI)

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7 Molecular air ions recombine with electrons by the very rapid process of *dissociative recombination* while atomic air ions recombine by *collisional-radiative recombination*, which is 10^4 to 10^6 times slower.

8 When significant energy is deposited in the upper atmosphere by high-altitude nuclear explosions, large regions of the atmosphere move upward relatively slowly, generally adiabatically. Heave is significant above about 200 km where the ambient air density is very low ($\rho/\rho_0 \sim 3 \times 10^{-10}$).

2.3 DUST FROM NEAR-SURFACE BURSTS

When a bomb is detonated so close to the surface that the explosion interacts with the ground, there are a number of effects:

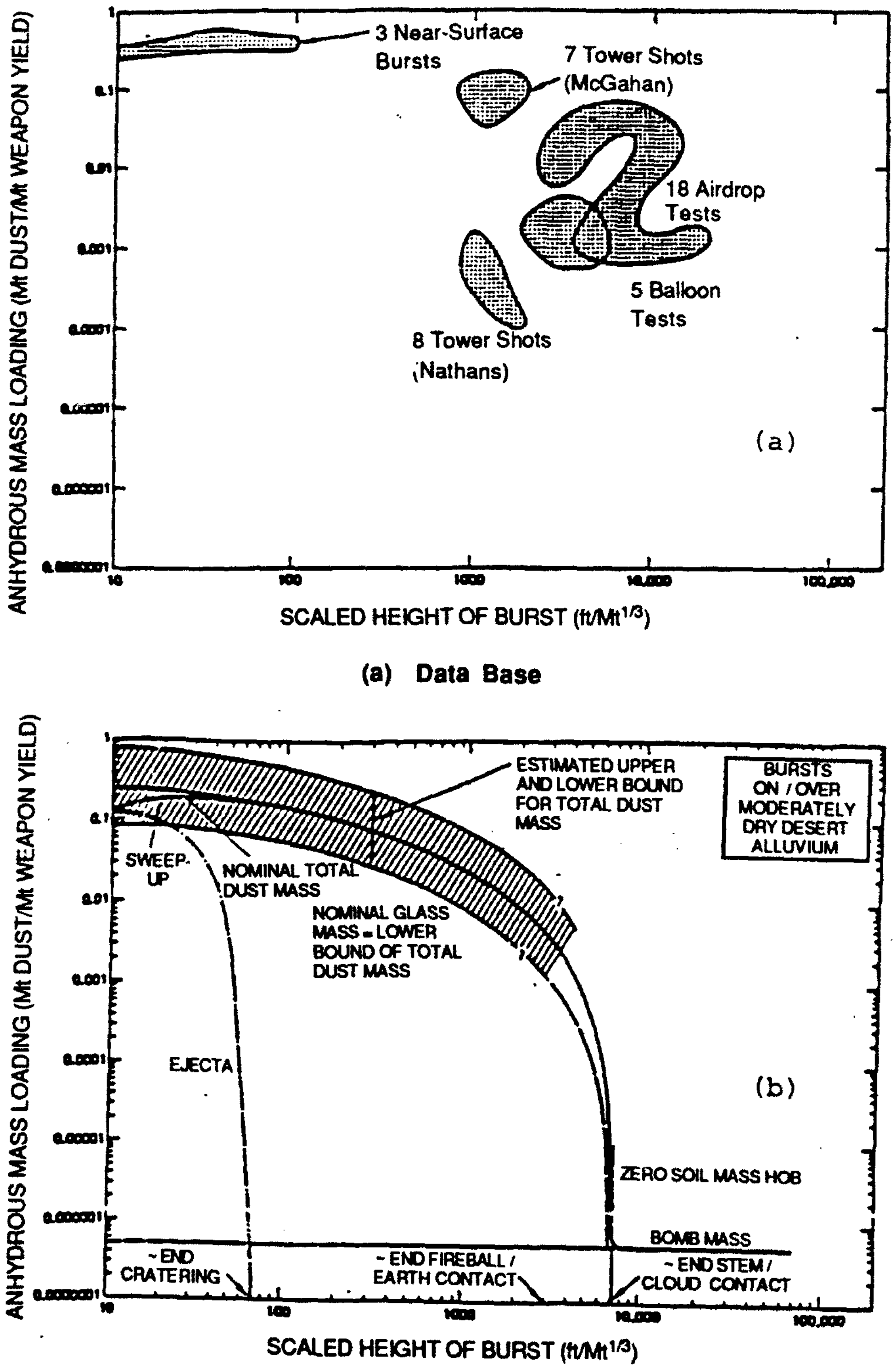
1. To first order, a surface burst, defined as corresponding to a detonation so close to the surface that the fireball touches the ground, is equivalent to a free air burst of twice the yield because the shock wave is reflected from the surface--cf., e.g., Brode, 1987.

2. A crater will be formed and a large fraction of the energy can go to produce this crater and to send a shock wave through the ground. Because the earth density is larger than the air density by a factor ~ 1000, the crater radius will be significantly smaller than the fireball radius; for a near-surface 1 Mt burst the radius of the crater is on the order of 200 meters. This ground shock due to a surface burst will lead to structural damage. As the height of burst decreases so that the interaction of the explosion with the ground becomes stronger, more of the energy goes to produce a crater and to send a shock through the ground. For a discussion of ground and subsurface bursts, see Glasstone and Dolan, 1977, Ch. 6, and also Frederickson, 1991, which is reproduced here as Appendix B.

3. A--possibly large--dust cloud will be sent into the atmosphere. Figure 7 shows the anticipated mass of dust that is lofted for a given yield as a function of the "scaled height of burst"--which scales with yield Y as $Y^{1/3}$. Figure 7a shows the data base, and Figure 7b a currently accepted model. There is a significant possible variation in dust raised, depending on geology, soil moisture, and ground cover.

Most of the dust particles are quite small--mainly less than a few micrometers in effective radius (R)--but the particle size distribution will again show significant variation, depending on the local geology, hydrology, and conceivably on the scaled height of burst (SHOB - ft/Mt$^{1/3}$) of the nuclear bursts. Figure 8 compares the model for dust raised by a nuclear detonation as described in the NORSE code with the ambient tropospheric aerosols (from Jursa, 1985, p.18-14). The dust particles kicked up by an explosion are naturally much larger than the ambient tropospheric aerosols, which have a much longer atmospheric mean residence time. Some representative numerical values (cf., e.g., Bauer, 1983) follow:

Radius (μm)	Fall speed (cm/sec)	Time to fall 5 km
0.1	10^{-3}	> 10 years
1.0	10^{-2}	~ 6 months
10	4	2 days



(a) Data Base

(b) Model

Figure 7. Dust Mass Lofted Into the Stabilized Cloud by a Near-Surface Nuclear Explosion. (Source: Rausch, et al., 1988)

Thus small particles of radius 0.1-1 μm will remain suspended in the atmosphere for almost a year, while particles of radius 10-20 μm will remain in suspension for a period of days--still very long compared to the time for a single engagement.

There are very few larger particles (> 1-10 μm), but they are particularly important for public health because a large fraction of the radioactivity (which is produced mainly by fission and by neutron activation) condenses on their surface. These large particles drift in the wind and are eventually deposited as radioactive fallout, which produces a serious long-term health hazard for people (see Glasstone and Dolan, 1977, Ch. 9 and 12).

The curve labeled "NORSE" in Figure 8 is the current model used in this code. Its analytic description is the following:[9]

$$P(R) = \begin{cases} \dfrac{\exp - (1/2) \left[\ln(R/R_m)/ \ln S\right]^2}{(2\pi)^{1/2} R \ln S} & \text{for } R < R_1 \\ \\ C R^{-p} & \text{for } R > R_1 \end{cases}$$

where $R_m = 0.25$ μm, $S = 3$, $R_1 = 5$ μm, $p = 4$ and C is chosen so that P(R) is continuous at $R = R_1$.

$$P(R) = (1/n_{tot})\, dn/dR$$

and

$$\int_0^\infty P(R)\, dR = 1 \quad .$$

Note that

1. There are really no data below $R_{thres} \sim 0.5\text{-}1$ μm because during the last U.S. atmospheric nuclear tests (before 1962) there were no adequate sensors for smaller particles.

2. The data base on atmospheric dust loading is quite limited and the results show a great amount of variability.

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[9] J. Thompson, PRi, private communication, January 1991.

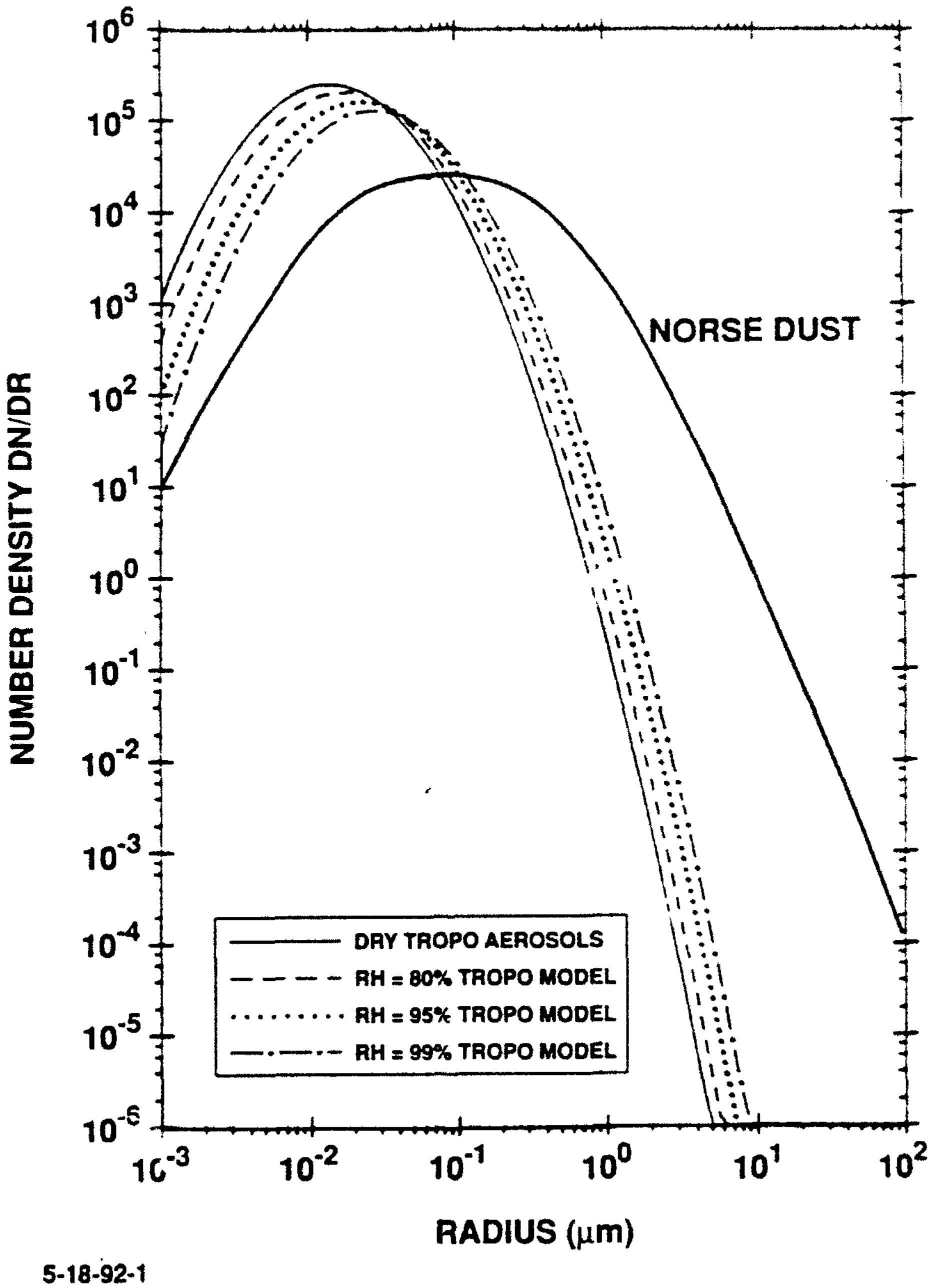

Figure 8. Dust Particle Size Distribution
(Sources: *Tropospheric Aerosols*, Jursa, 1985, p. 18-14, "NORSE Model," J. Thompson, Visidyne, private communication)

One question to be asked about nuclear-induced dust is how high in the atmosphere it is lofted. It is hard to provide a general answer, but an upper bound is provided by Figure 9, which shows some typical data on nuclear cloud rise as function of weapon yield for low air bursts, i.e., bursts whose fireball does not touch the ground. Reference to Figure 7b shows that the scaled height of burst (SHOB) is greater than 3,000 ft/Mt$^{1/3}$, or 1,000 m/Mt$^{1/3}$. Again referring to Figure 9, a 10-km tropopause corresponds to mid- and higher latitudes, while a 12-15 km tropopause corresponds to the tropics. Thus we see that for 1 Mt bursts, dust will be raised as high as 12 km at high latitudes or 18 km in the tropics.

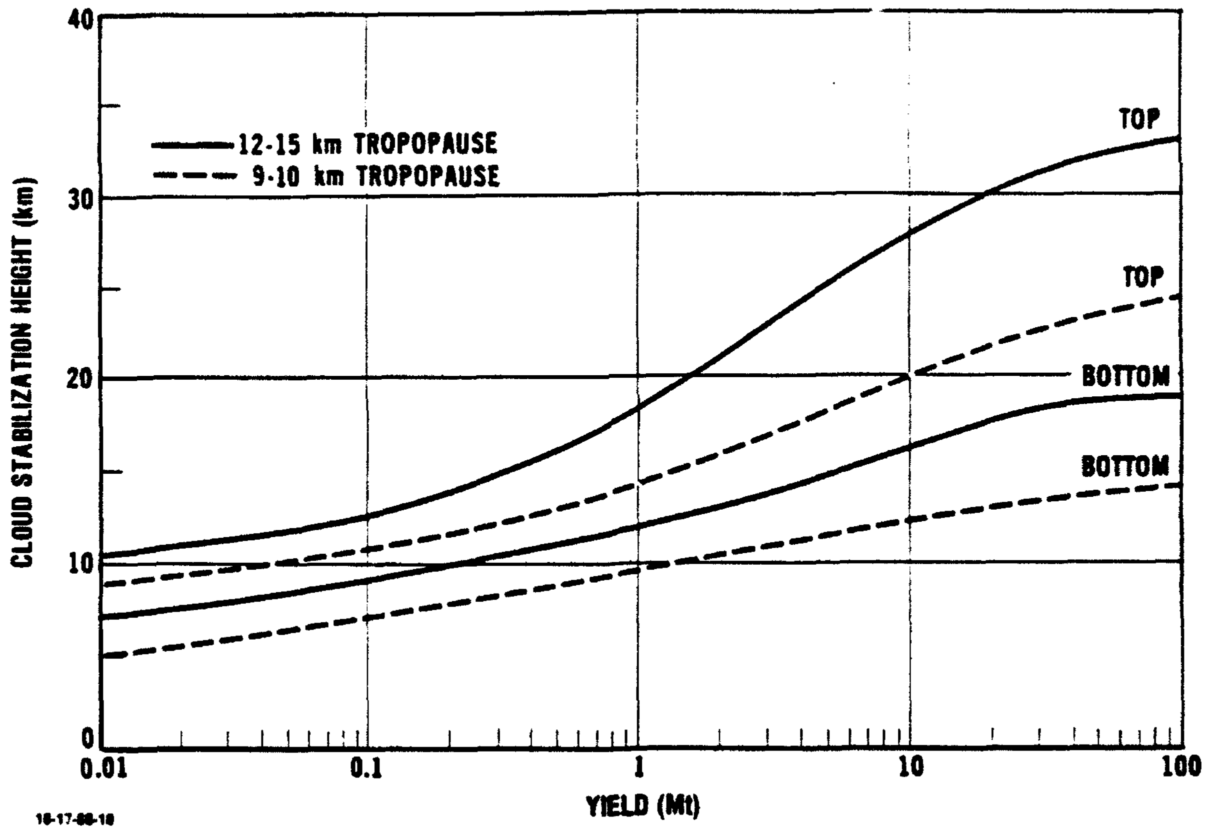

Figure 9. Nuclear Cloud Rise Height as Function of Yield [Synthesized by H. Mitchell (Falcon Research) from various sources; see, e.g., Bauer, Gilmore, Mitchell, 1984.]

3.0 EFFECTS OF ATMOSPHERIC VARIABILITY

3.1 GENERAL COMMENTS

As has been pointed out previously, in the lower, dense atmosphere the geometric extent of the region impacted by a single nuclear explosion is much more confined than in the very tenuous upper atmosphere; relevant scales are ~ 1-5 km for 1 Mt in the lowest 0-10 km as against 100-500 km above 100-200-km altitude. The inherent variability of the dense lower atmosphere can produce significant effects both on remote sensing and on vulnerability. Here we present some examples of effects. The point is that especially for the very sensitive modern electro-optical surveillance systems, the effects of atmospheric variability can be significant. It is not clear a priori which factors have to be considered for SDS modeling. The factors to be considered will depend on the threat scenario under consideration, such as the altitude and yield of the nuclear bursts and the nature of sensors under consideration (IR, UV/VIS, MMW; spectral and spatial resolution; sensitivity; active vs. passive sensors).

The environmental description in an engagement model may be severely constrained by computer capability, and the answers to the above questions will help define a computer model which makes an optimal tradeoff between the fidelity of the model and the running time it requires.

It should be recognized that the stabilization height of a low nuclear air burst of tactical yield may vary significantly, depending on ambient atmospheric conditions. The careful analysis of Sowle and Schluter, 1978, finds a random error in stabilization altitude of 0.6 km for free air bursts and 0.8 km for bursts that interact strongly with the ground, plus a variation of 20-30 percent due to differences in actual meteorological conditions.

3.2 ATMOSPHERIC TURBULENCE AND CLOUD SPREADING

The atmosphere is normally in turbulent motion, which can have a variety of effects of different scales and types. For instance, seeing through the atmosphere is significantly affected by the variability of the underlying atmosphere. Astronomers have long known that telescopes are best placed on tops of remote mountains in a cloud-free environment, and that seeing is generally better at night than in the daytime when solar heating enhances the turbulence. To some extent deficiencies in seeing can be corrected by adaptive optics, using techniques developed for the propagation of high-energy laser beams through the atmosphere (see, e.g., Finkbeiner, 1991, Greenwood et al., 1992).

Another effect of atmospheric turbulence is on the spreading and expansion of various kinds of clouds in the atmosphere. Figure 10 (from Bauer, 1983, supplemented by recent comments from John Cockayne, SAIC) shows the range of the dispersion of clouds of assorted tracers in the atmosphere. Note the large variability, which is a measure of how much atmospheric turbulence and winds can change. Table 4 (whose items are shown in Fig. 10) may be interpreted as a measure of atmospheric turbulence as described by two experienced atmospheric scientists. I do not consider the specific names of the phenomena ("plumes, mechanical and isotropic turbulence, hot towers, etc.") to be as important as the range of space and time of the underlying atmospheric motions, which agrees quite well with the various data (itemized in Bauer, 1983) that generally lie between the bounds of curves I and IV of Fig. 10.[1]

The question addressed is, how rapidly does a cloud of inert tracer spread in the atmosphere from a point release?

There are a number of points to consider:

a. The results apply generally to the troposphere and the stratosphere, say, at altitudes below 1 km to 30 km.

b. The description refers to turbulence, i.e., motion perpendicular to the mean (horizontal) wind.

c. Except at the smallest scales (say, less than a few hundred meters) the vertical dispersion is much slower than horizontal spreading.[2]

Figure 10 can be useful for a variety of applications--to smoke and conventional meteorological clouds as well as to a dust application such as that of Fig. 9--as long as one asks for lowest order results averaged over time, and over a wide range of meteorological conditions. Obviously, if one has available detailed ambient meteorological data for a given region it is possible to make much more refined and precise estimates than those of Fig. 10.

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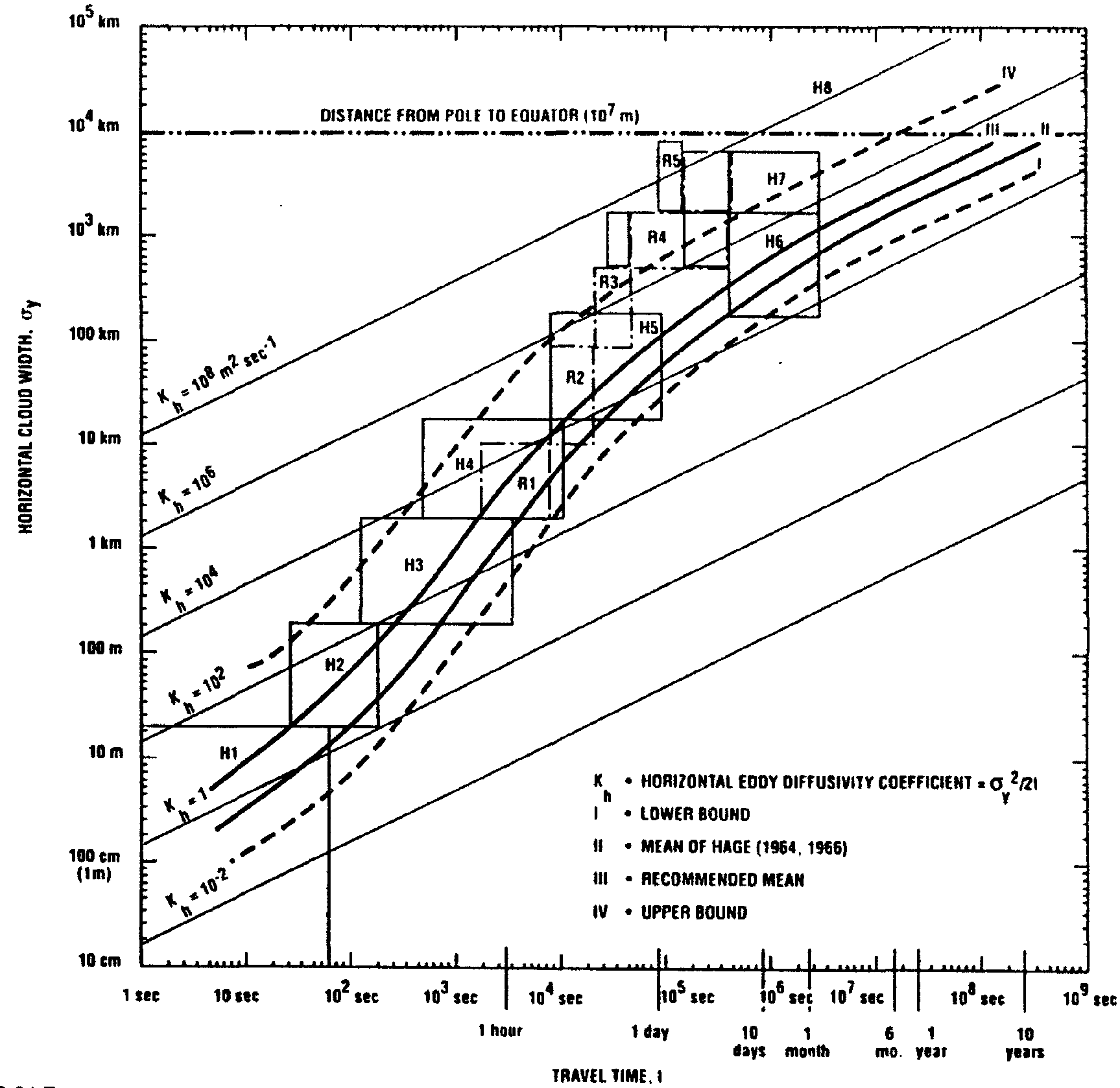
1 Note that the largest scale phenomena, in particular item H8, corresponds to exceedingly large scales (greater than the pole-to-equator distance) and thus should not be interpreted too rigorously.

2 At scales less than a few hundred meters the tracer dispersion is isotropic, but as a result of gravitational stratification a tracer cloud will normally not extend beyond this range in a vertical direction.



9 13 91 7m

Figure 10. Horizontal Cloud Width as Function of Travel Time. The blocks H1, H2, ..., R1, R2,... come from Table 4. (Source: Bauer, 1983)

Table 4. Scales of Atmospheric Motions

Region on Fig. B-1	Scale	Phenomena	Approximate Affected Scale	
			Horizontal Dimension	Time
(From Hobbs, 1981: Different Atmospheric Motions)				
H1	Micro-γ, δ	Plumes, Mechanical and Isotropic Turbulence	2 mm to 20 m	1 sec to 1 min
H2	Micro-β	Dust Devils, Thermals, Wakes	20 m to 200 m	0.5 min to 3 min
H3	Micro-α	Tornadoes, Deep Convection, Short Gravity Waves	200 m to 2 km	2 min to 1 hr
H4	Meso-γ	Thunderstorms, Internal Gravity Waves, Clear Air Turbulence, Urban Effects	2 to 20 km	6 min to 3 hr
H5	Meso-β	Nocturnal Low-Level Jet, Inertial Waves, Cloud Clusters, Mountain and Lake Disturbances, Rain Bands, Squall Lines	20 to 200 km	2 hr to 1 day
H6	Meso-α	Front Hurricanes	200 km to 2,000 km	5 days to 1 month
H7	Macro-β	Baroclinic Waves	2,000 km to 5,000 km	2 days to 1 month
H8	Macro-α	Standing Waves, Ultra-Long Waves, Tidal Waves	> 10,000 km	> 1 day
(From Ramage, 1976: Turbulence Bursts on Different Scale)				
R1	Convective	Hot Towers	2 km to 10 km	15 min to 2 hr
R2	Mesoscale	Flash Floods	10 km to 100 km	2 hr to 6 hr
R3	Sub-synoptic	Tornadoes, Clear Air Turbulence, etc.	100 km to 500 km	6 hr to 12 hr
R4	Synoptic	Continuous Thunderstorms, Large-Scale Convection	500 km to 2,000 km	12 hr to 48 hr
R5	Planetary	Hurricanes, etc.	2,000 km	24 hr to 48 hr

As an application, Fig. 11 sketches the problem of looking down to the ground from space or high altitude through a post-nuclear dust cloud. There are two distinct questions:

1. How much dust is raised per Mt at the location indicated? This is clearly variable, depending on the scaled height of burst as well as on the geology, ground cover, and weather. Figure 7 (above) presents a quantitative discussion of the existing data base on dust loading as a function of scaled height of burst, km/Mt$^{1/3}$. The dust particle size distribution assumed is shown in Fig. 8.
2. Does the dust that goes up into the atmosphere spread rapidly or slowly? The rate depends on the ambient atmospheric turbulence, which is quite variable. It can be parameterized by an effective (scale-dependent) horizontal eddy diffusivity K_h (m^2/sec), which is also shown in Fig. 10.

3.3 CLOUDS

Cloudiness varies with location, season, and time of day, but basically water/ice clouds occur frequently and are highly variable on scales of hours to days. Table 5 indicates the average frequency of occurrence of clouds at some representative locations in both winter and summer. Notice that in many locations worldwide clouds occur significantly more than half the time.

Most clouds occur between 1- and 5-km altitude, but some go up to the tropopause, whose mean altitude ranges from 8 km at polar latitudes, 11 km at midlatitudes, to 16 km at equatorial latitudes. Typically lower altitude clouds are optically thicker than are higher altitude clouds, because at lower altitudes the temperature is higher, and the water vapor saturation pressure increases greatly with increases in temperature. The condensed water density is normally some fraction (10-50 percent) of the saturated water vapor density at the appropriate temperature.

Clouds interfere with light propagation and thus with optical viewing through them.[3] One normally cannot see through a thick, low-altitude, water cloud, and while it is

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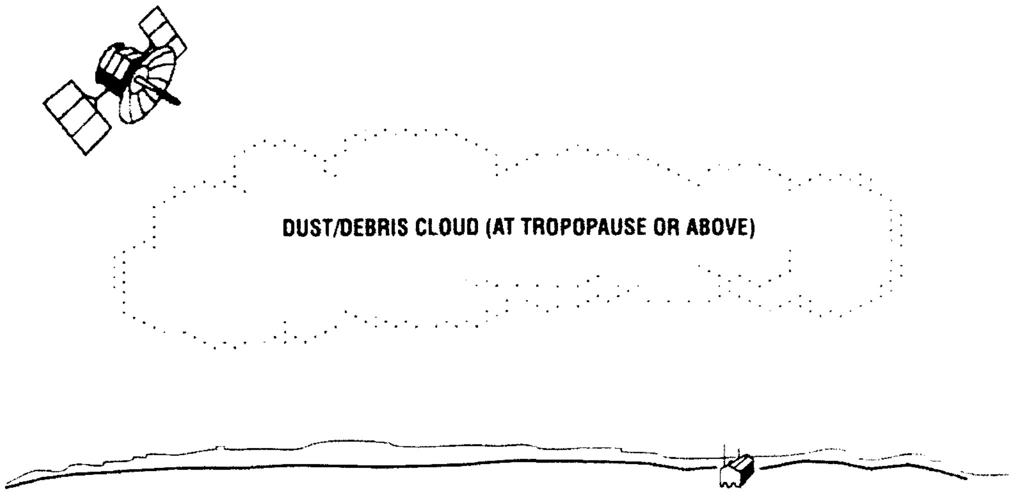
[3] It is very difficult to make this statement quantitative. Thus, typically, a cloud has optical thickness $\tau = n\,\sigma\,L \sim 10 - 100$, where n = number of water droplets per unit volume, σ = extinction (= absorption + scattering) cross-section of a droplet, and L is the geometrical thickness of a cloud. In the visible, the illumination below a cloud is reduced by 2-3 photographic lens stops, i.e., by a factor 4-8 below the illumination above the cloud, rather than by a factor $e^{-\tau}$. The reason for this is that in the visible there is very little absorption so that the radiation is simply diffused by multiple scattering. By contrast, in the LWIR where there is significant absorption, the intensity is reduced to a factor approaching $e^{-\tau}$.



a. The Problem

Time after Burst (hr)	1	6	12	24	
Fast cloud spreading (Curve IV of Fig. 10)					
Horizontal Cloud Width (km)	80	600	800	1000	Large extent
Percent Degradation of Target Contrast	40	3	1	0	Rapid recovery
Slow cloud-spreading (Curve II of Fig. 10)					
Horizontal Cloud Width (km)	7	40	85	130	Small extent
Percent Degradation of Target Contrast	> 99	86	37	10	Slow recovery

b. Impact of a 1-Mt Surface Burst

Figure 11. Surveillance from Space Through a Nuclear Dust Cloud. (Source: Bauer, 1985)

Table 5. High and Total Cloudiness at Representative Locations in the Northern Hemisphere. (3DNEPH data from Malick and Allen, 1978, 1979)

Location	Coordinates		High/Total Cloudiness	
	Longitude	Latitude	January	July
China Lake, CA	36°N	117°W	.17/.38	.12/.18
Grand Forks, ND	48°N	95°W	.38/.63	.31/.56
Maui, HI	21°N	156°W	.14/.40	.12/.50
Hudson Bay	60°N	88°W	.06/.36	.08/.29
N. Atlantic S	52°N	35°W	.24/.81	.13/.70
N. Atlantic N	62°N	30°W	.18/.76	.16/.72
Jan Mayen Is.	71°N	10°W	.20/.81	.16/.85
Thule	76°N	68°W	.10/.35	.11/.73
Barrow, AK	71°N	156°W	.08/.34	.11/.64
Arabian Sea	8°N	65°E	.02/.23	.16/.55
Teheran	36°N	52°E	.14/.38	.02/.22
Ionian Sea	39°N	18°E	.07/.54	.01/.06
Moscow	56°N	39°E	.22/.61	.24/.46
Tyuratam	46°N	64°E	.16/.49	.13/.30
Lop Nor	40°N	91°E	.22/.48	.24/.57
Vladivostok	43°N	132°E	.11/.43	.22/.66
Japanese Trough	35°N	150°E	.16/.67	.12/.37
Anadyr	64°N	177°E	.28/.59	.21/.75
Murmansk	69°N	34°E	.22/.70	.16/.66

Notes:

a. High/total cloudiness means, for example, that at China Lake in January high clouds occur 0.17 of the time and total cloudiness occurs 0.38 of the time.

b. These data come largely from downward viewing satellites such as NOAA-6 and DMSP, which tend to under-report optically thin clouds.

c. Clouds are reported as present when at least 1/10 of the appropriate field of view is covered by clouds.

d. High clouds are those above 7 km, with the altitude determined by the effective radiative temperature in the 10- to 12-μm infrared band as compared with the atmospheric temperature/altitude profile.

e. High clouds are thus mainly moderately thick cirrus or cirrostratus, plus some cumulonimbus (thunderclouds) at the lower latitudes ($\lesssim$30°).

sometimes possible to see through a thin, high-altitude, ice cloud, yet the quality of seeing is degraded. Another effect of clouds is to screen targets from the thermal radiation from atmospheric nuclear explosions (until the cloud is vaporized by energy deposition). Overall, clouds have diverse effects on military systems: CIDOS (Cloud Impacts on DoD Operations and Systems) is a Tri-Service community with an annual meeting. Reports, which include a listing of key players and problems addressed, may be obtained through Don Grantham, PL/GP-LYA, Geophysics Directorate, Phillips Laboratory, AFSC, Hanscom AFB, MA 01731-5000, telephone (617) 377-2982.

3.4 ATMOSPHERIC OZONE, AND UPPER ATMOSPHERIC VARIABILITY

There is a somewhat variable ozone layer in the stratosphere, mainly between 20 and 30 km, and, in addition to this, smog near the surface contains both ozone and other polyatomic molecules and aerosols. All these materials absorb ultraviolet radiation (generally below 300 nm) and also radiation in some regions in the IR. Thus they will screen targets from the UV thermal radiation produced by nuclear explosions above the ozone or smog layer.

In addition, some variability has been observed in IR limb viewing near 80-km tangent altitude. This may be due in part to variations in the concentration of molecular trace species, as well as to the occasional presence (at high latitudes, in summer) of polar mesospheric clouds (cf. Thomas, 1991).

3.5 WEATHER--RAIN

Heavy rain occurs very infrequently in most locations, and even light to moderate rain which can interfere with EHF radio propagation occurs on the average only 1-3 percent of the time. Figure 12 gives seasonal and annual precipitation at Potsdam, Germany, which may be taken as representative of many midlatitude temperate locations. Note that 1 percent of the time on an annual clock-hour basis it rains more than 1.6 mm/hr, and 0.1 percent of the time it rains more than 5.6 mm/hr; light rain is often defined as 1 mm/hr, and moderate rain as 5 mm/hr. Thus, 98 percent of the time at midlatitudes there is no rain, or less than 1 mm/hr.

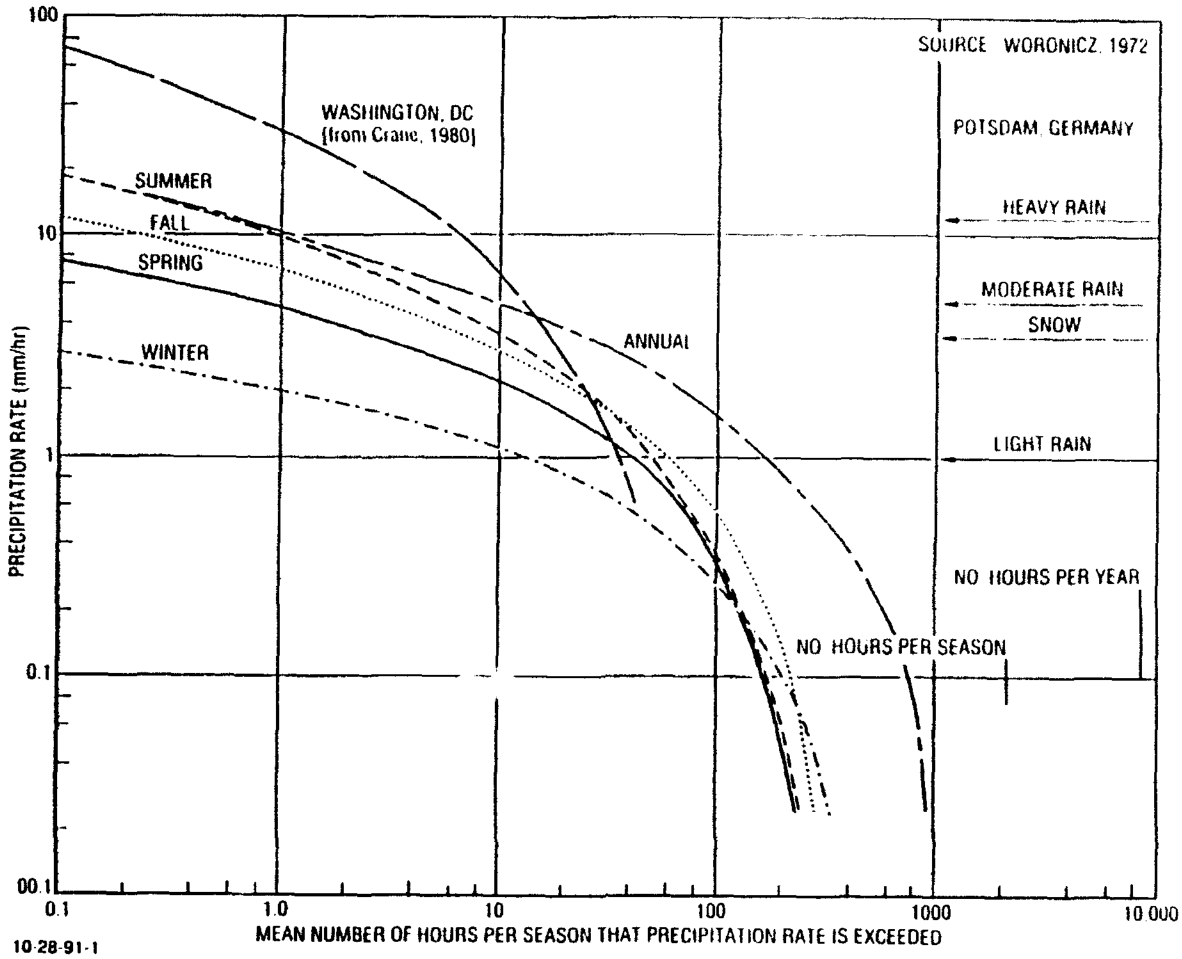


Figure 12. Frequency of Seasonal and Annual Occurrence of Rain at Potsdam, Germany (Woronicz, 1972) and (Annual Only) in Washington, D.C. (Crane, 1980)

In Fig. 12 we also show the annual mean precipitation figures for Washington, D.C., (from Crane, 1980) which differ somewhat from the Potsdam data by showing more high-intensity precipitation, as one would expect from the higher frequency of convective activity (thunderstorms, etc.) at lower latitudes.

Crane, 1980, shows data comparable to Fig. 12 for a variety of climatological regions. When the rain rate exceeds 1 mm/hour, the zenith attenuation at 60-100 GHz exceeds 1.5-2.5 dB.

3.6 SMOKE FROM FIRES

Smoke is highly variable, but it can obscure sensors and screen thermal radiation. Smoke particles are often quite small, and thus sometimes LWIR sensors can see through smoke clouds much better than visible sensors. The occurrence and intensity of fires depends on ambient meteorological conditions--rain, ground moisture, wind, and turbulence. For references, see, e.g., Small, 1989.

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APPENDIX A

REVISION OF DNA NUCLEAR CRATER SPECIFICATIONS

Source: Frederickson, 1991

APPENDIX A
REVISION OF DNA NUCLEAR CRATER SPECIFICATIONS

DNA has recently completed an "end-to-end" cratering validation program that resulted in dramatic reduction of the crater size thought to result from the surface detonation of modern strategic weapons. Although a major field exploration and several underground nuclear tests conducted in this program occupied the spotlight, numerical simulations were in many ways more central to DNA's success. This article recounts the integrated role of the numerical simulations, re-interpretation of existing nuclear data, and additional field events in the evolution of DNA's view on nuclear cratering.

DNA developed a crater specification methodology for its 1972 Capability of Nuclear Weapons - Effects Manual Number 1 (EM-1) with the acknowledgment that the nuclear database was incomplete and probably inappropriate for application to strategic yield surface burst weapons. The cratering events conducted at the Nevada Test Site (NTS) employed low yield sources suspected to produce larger craters than modern weapons of strategic interest. Data from the several high yield cratering events conducted at the Pacific Proving Grounds (PPG) were considered flawed by the atoll reef geology that was highly dissimilar to sites of interest. The 1972 EM-1 methodology was an attempt to reconcile these shortcomings.

The strategic source surface burst crater specifications were based on high yield PPG data, calibrated to sites of interest by comparison of low yield nuclear and high explosive craters in various geologies. Figure A.1 depicts 1 Megaton crater profiles for two geology types as specified in 1972 EM-1.

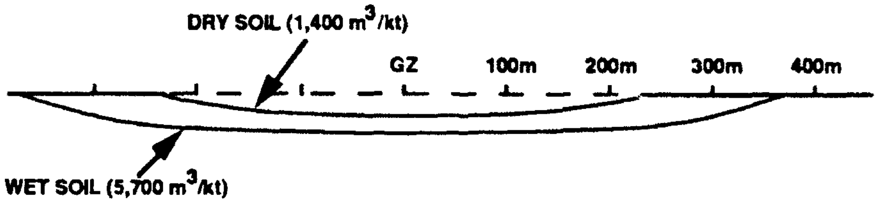

Figure A.1. 1 Mt Contact Burst Crater Profiles for Two Generic Geologies as Specified by DNA EM-1 (1972)

To address the database deficiencies, DNA developed computer code capabilities and applied them to numerically simulate cratering phenomenon. In the Benchmark Cratering Program (1976-1981), the 500 ton MIDDLE GUST high explosive event was conducted and its crater used to calibrate the numerical codes for simulation of a nuclear event on the same scaled geology. As seen in Figure A.2, the resulting simulated crater was markedly smaller and more bowl-shaped than the characteristically dish-shaped EM-1 specifications. Simulations of high yield PPG events were also conducted and similar discrepancies with the reported crater profiles resulted.

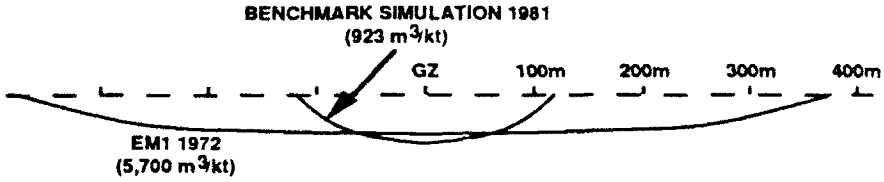

Figure A.2. Comparison of 1 Mt Contact Profiles for Two Generic Geologies as Specified by EM-1 (1972) and Predicted by DNA Benchmark Numerical Simulation (1981)

Resolution of the discrepancy between crater specifications based on the existing but flawed database and the new numerical simulations became a central theme in DNA's Cratering and Ground Shock Program. The program sought to validate the simulation capability in separate, overlapping phenomenology components which, when placed end-to-end, spanned the entire nuclear cratering process. The phenomenology can be summarized in four component areas:

- <u>Coupling of x-rays and very high velocity debris energy from radiative sources to ground materials</u>. Process occurs in first several microseconds for a Megaton yield event.
- <u>Conversion of coupled energy to ground motion field</u>. This process is driven by the high pressure equation of state of ground materials and occurs in microsecond to several tens of milliseconds time regime.
- <u>Ground motion, transient crater development to peak size</u>. Thought to be dominated by the ejection of ground material from the ground, this period lasts 100s of milliseconds for dry porous sites to several seconds for saturated soil sites.
- <u>Late time effects, crater evolution to final form</u>.

The key elements of the end-to-end validation process and the phenomenology component addressed by each element are identified in Figure A.3.

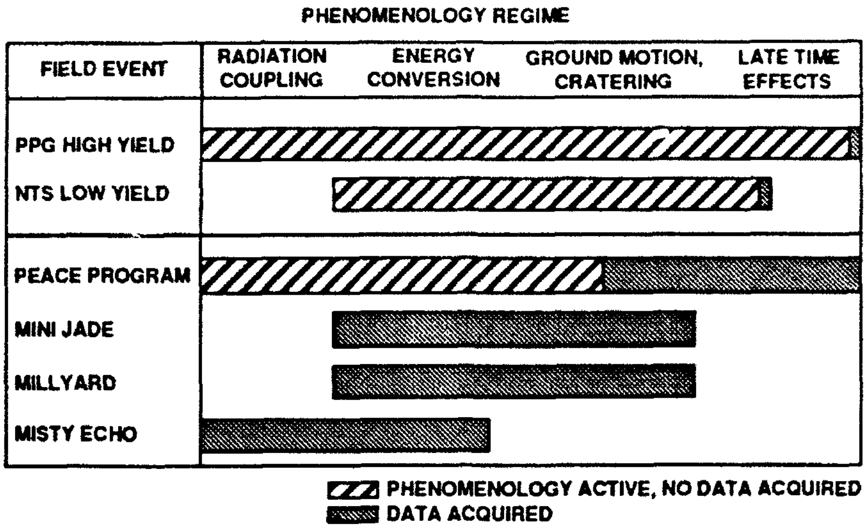

Figure A.3. Components of End-to-End Crater Validation Program Referenced to Phenomenology Regime Addressed

The program addressed the last phenomenology components first. In the PEACE program (Pacific Enewetak Atoll Crater Exploration), DNA re-surveyed two high yield craters with the intent of determining whether small bowl-shaped ejecta/flow craters might have been formed within the overall reported crater dimensions. The theory to be tested was that such initial craters were subsequently altered by late time processes such as subsidence, slumping, or ocean washing that were not modeled in the simulations. The survey, conducted in 1983-1984, found compelling evidence that this was the case. For the first time, due to the insight gained from numerical predictions of the cratering process, a survey had been conducted that looked for the right data in the right places. Previous surveys had quantified crater extent based on observed deformations that had nothing to do with the environments of interest to vulnerability/survivability studies. With this new understanding of the Pacific craters, the large discrepancy with numerical simulations was gone. However, the unique atoll reef geology of the PPG meant this accomplishment was a necessary but not sufficient test for validation of simulations when applied to sites of strategic interest.

Past tests provided craters and ground shock data in good agreement with pretest numerical simulations. The numerical simulations indicated that strategic yield sources would produce craters one-third to one-fifth the scaled size produced in these events due to the relative inefficiency of the x-ray coupling process relative to hydrodynamic coupling.

This early time x-ray coupling piece of the end-to-end validation was still missing. Numerical simulations were again utilized to determine what might be accomplished in a cavity using the higher yield source necessary to produce adequate x-ray output. It was found that a space-time window would exist in the same sized cavity used in MINI JADE and MILLYARD (Figure A.4) such that the pertinent coupling physics could occur prior to the arrival of signals from the cavity walls.

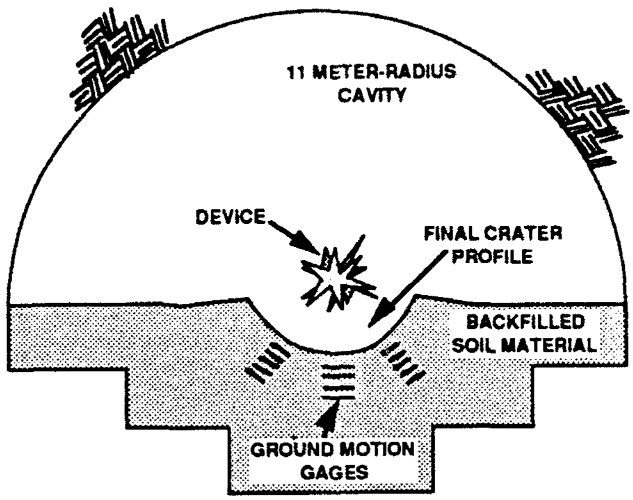

Figure A.4. Configuration of MINI JADE and MILLYARD Underground Nuclear Cavity Tests

Today, DNA relies on numerical cratering and ground shock simulations as key integral parts of its experimental program. They are the basis for cratering specifications for near-surface bursts in EM-1, 1991. Figure A.5 compares 1991 EM-1 craters on two geology types to the profiles perceived in 1972. This dramatic shift in perception is based on the compelling evidence obtained in the highly successful field program discussed in this article. The current DNA reliance on numerical simulations is a result of the recognition that they provided the motivation for this program, enabled the success of the field activities, and today provide the means to apply this text experience to specific strategic weapon and geology combinations of interest.

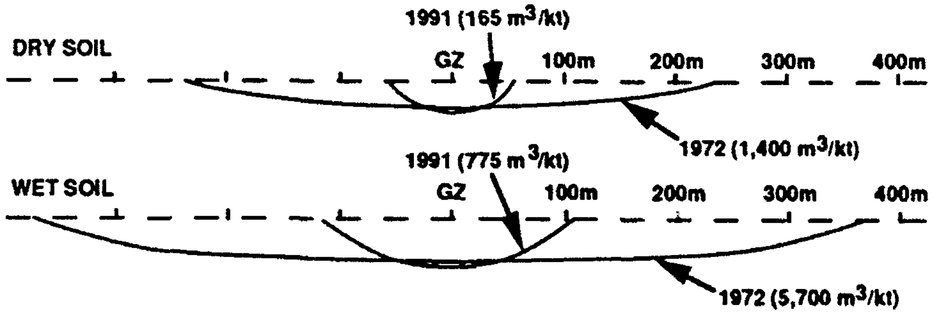

Figure A.5. Comparison of Current DNA Specification for 1 Mt Crater Profiles with 1972 Specifications