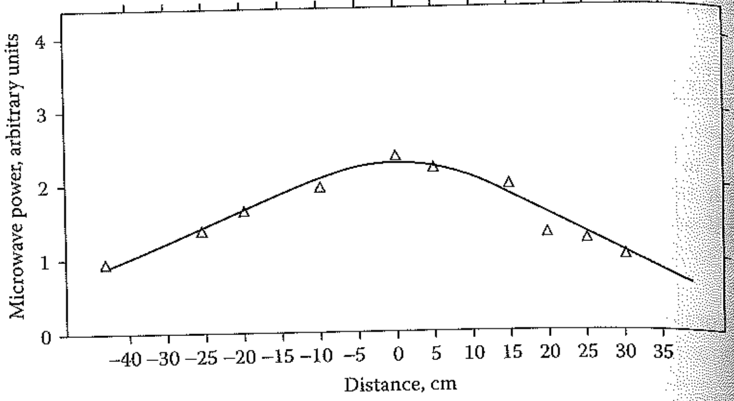

FIGURE 5.22
Horn pattern transverse to axis of propagation.

incorporated into an evacuated bell jar or pressurized gas bag to further extend the air–vacuum interface. Its main attribute is that it takes a TM_{01} feed and produces a directed beam with a nearly Gaussian profile. This makes it a very good match to the cylindrically symmetric microwave sources (MILO, Vircator, Cerenkov, etc.) that generate power in the TM_{0n} modes. The Vlasov antenna takes power from these sources and puts the peak power density at the center of the microwave beam (as opposed to casting a beam with a null at its center, as is usually the case when TM_{0n} modes are directly radiated) without the complication of including a mode converter. In fact, the antenna is the descendant of the mode converter (Figure 5.23a). Figure 5.23b shows a schematic of a Vlasov antenna being fed by a MILO HPM source.

The Vlasov antenna has two main shortcomings. First, the antenna is constructed from a circular waveguide by making a slant cut through the guide's cross section at an angle between 30 and 60°. This does not produce a large aperture (when compared to those characteristic of parabolic reflectors or even pyramidal and conical horns). Therefore, the Vlasov antenna is rarely used in applications requiring high gain (>>20 dB). Second, the propagation angle, θ (the angle between the waveguide axis and the main lobe), is a function of the microwave frequency, f:

$$\theta = 90^\circ - \cos^{-1}\left[\sqrt{1-\left(\frac{f_c}{f}\right)^2}\right] \tag{5.28}$$

where f_c is the antenna's cutoff frequency. This means that if the frequency chirps within a microwave pulse, then the beam direction will sweep rapidly.

Antenna arrays have been slow to come into use in HPM systems (Figure 5.24). Their utility follows from three factors:

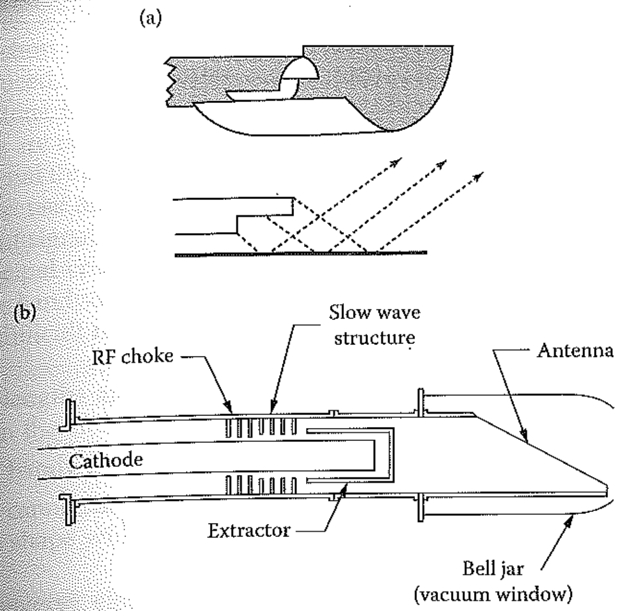

FIGURE 5.23
Vlasov antenna. (a) Mode converter, the origin of the antenna. (b) Antenna being fed by a MILO source.

1. Higher powers will require larger areas to avoid breakdown.
2. Super-high powers (~100 GW) will ultimately be generated from phase-locked arrays of sources, which implies multiple-output waveguides requiring multiple antennas.
3. Arrays are compatible with rapid electronic tracking and illuminating of targets, with great directivity.

Arrays are termed *broadside* if the direction of maximum radiation is perpendicular to the plane of the array and *end fire* when the radiation maximum is parallel to the array. End-fire arrays have lower gain, so broadside arrays are the focus of interest. If array size L is large compared to λ, contributions from each element will change rapidly as angle is changed from the normal, producing a sharp maximum of beam width ~2λ/L with gain L^2/λ^2. The physical separation of the elements introduces *grating lobes* nearby. If individual aperture separation d is less than λ, grating lobes can be greatly reduced. This condition is difficult to meet at high power due to air breakdown constraints on antenna size. Consequently, grating lobes are a problem in practical systems and must be suppressed by some means, such as power splitting, to increase the number of elements, or by sidelobe suppression with local absorbers.

The beam can be scanned by controlling the phase of each element separately with phase shifters. For configurations using power amplifiers driven by a master oscillator (MOPA; see Section 4.10), phase control is done at low

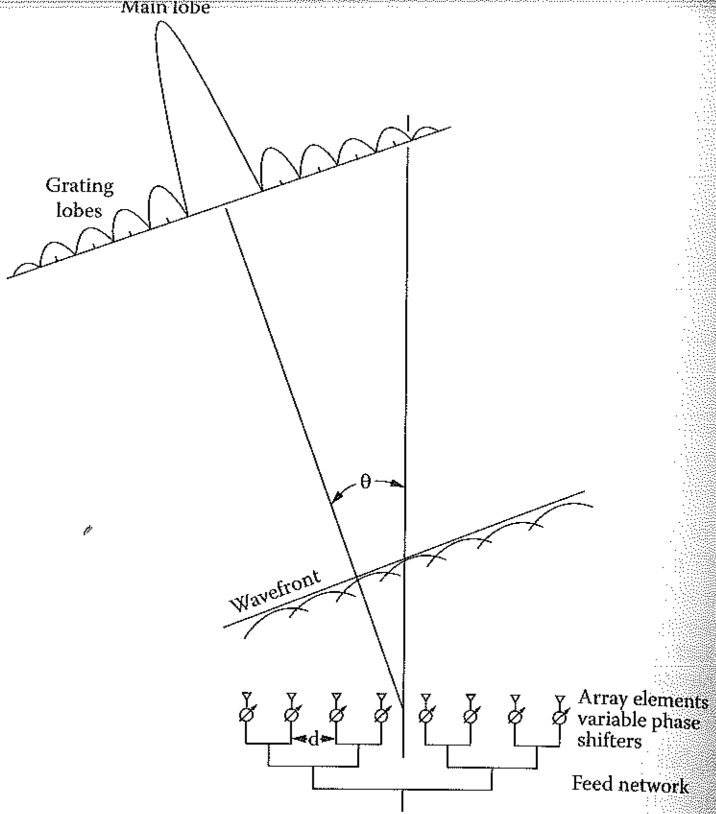

FIGURE 5.24
Antenna array launches wavefront, forming narrow main lobe.

power prior to the amplifier stage, and therefore conventional technology is used. For oscillator arrays, conventional phase shifters (Figure 5.24), even high power ferrite devices, do not approach the required power regime. At present, only electromechanical devices have been developed: waveguide stretchers with piston-driven telescoping U sections and broad-wall waveguide deformation techniques are currently under development. For large arrays with $>10^2$ elements, phase shifter cost will be a limiting factor. In order to achieve dense packing to reduce grating lobes, the cross-sectional dimensions of the shifter should be near those of the waveguide, so that the feeds can be densely packed.

5.5.4 Wideband Antennas

High-gain, low-dispersion wideband antennas present a substantial challenge. When pulse duration becomes of the order of a nanosecond, antenna design becomes much more taxing. The *fill time* of an antenna is several light-transit times across the diameter. If the pulse-length wave entering the antenna is short compared to the fill time, then the full aperture is not used, gain is reduced, and the pulse is dispersed. These effects are important for all applications, but especially for impulse radar (see Chapters 3 and 6). Two approaches are used for impulse radar antennas. The first is to transmit the impulse signal through a low-dispersion antenna with wide bandwidth. The second is to use antenna dispersion to generate an impulse signal from a longer input signal.

The principal criteria for the low-dispersion type of antenna are that it have a wide bandwidth, typically a factor of 2, a high gain, and low sidelobes. These are difficult requirements because:

1. Wavelengths are so large (10 to 100 cm) that high gain is difficult within the antenna sizes imposed by applications.
2. Wide bandwidth makes it difficult to suppress sidelobes.
3. Gain cannot be constant for all wavelengths, so the propagating pulse shape will be distorted.

The transverse electromagnetic (TEM) horn has been used for most impulse radar work to date (Figure 5.25). It is simply two metal strips flared in roughly an exponential shape. Pulses with durations of 1 nsec can be radiated with such horns, and bandwidths are ~1 GHz. Gain tends to be nonuniform across the bandwidth, so that pulse distortion occurs in the far field. A key factor is that the TEM horn transmits a differentiated signal,

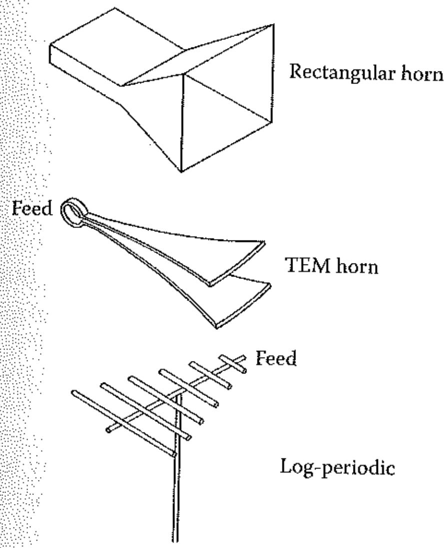

FIGURE 5.25
Typical conventional antenna types that are used as wideband HPM antennas.

allowing applied monopulse or unidirectional pulses to be radiated as a single cycle.

The basic approach to producing low dispersion, i.e., little variation of phase velocity with frequency, is to flare the input waveguide into the antenna aperture so that the impedance varies slowly from that of the waveguide to that of free space (377Ω). In the sidelobes, the pulse is stretched to substantially longer than the original duration. Therefore, for impulse radar, the pointing accuracy of both transmitting and receiving antennas is very important to obtaining return signals, i.e., pulses off bore sight can be so long as to be useless.

Rather than minimizing antenna dispersion, dispersion can be used to generate the desired impulse signal by the log-periodic antenna (Figure 5.25). The signal fed to the antenna has strong frequency chirping, i.e., frequency rises during the pulse. The dispersive properties of the antenna, if well matched to the input pulse, can produce the desired compressed output pulse. Designs for high power have not been published. Issues with the log-periodic antenna are large beam width and consequent low gain, and pulse shaping of the feed pulse to give the correct output pulse. Achieving constant gain across the desired bandwidth is also difficult.

However, the above methods are becoming obsolete for many applications due to the introduction of a new type of antenna, the Impulse Radiating Antenna, discussed in Section 6.3.

5.6 Diagnostics

High power devices differ from their conventional relatives in three significant ways. First, of course, "high power" means that high electric fields exist and all diagnostics must avoid breakdown. Second, the pulse durations are short, less than a microsecond and typically less than 100 nsec. This implies fast response on the part of the diagnostics since rise times and critical features can occur on a timescale of a few nanoseconds. Lastly, HPM sources have yet to be operated at high repetition rates or continuously. Therefore, diagnostics are typically required to analyze a single shot or a few shots. Some advantages follow from these features: high power means that it is possible to directly measure the energy of a pulse in a single shot. A low number of shots means that sophisticated data handling is not required, and sampling techniques cannot be used to reduce the data rate.

Historically, HPM diagnostics have borrowed many techniques from conventional microwave diagnostics. They are used to characterize three spatial regions: the source, the radiated field, and the interior of test objects. Here we discuss the diagnosis of the microwave pulse. Diagnostics of plasma processes inside the source are as yet in a primitive state. The sophisticated nonintrusive diagnostics developed in plasma research are beginning to know and understand the plasmas inside HPM devices. To better understand pulse shortening, the HPM community must measure the actual electromagnetic structure and plasma properties of HPM sources. More detailed diagnostics are needed, particularly of microwave field distributions *in situ*, plasma location and motion, and velocity distribution of both electrons and ions. The nonintrusive methods developed by other parts of the plasma physics community, such as that of fusion, should be applied to HPM. Time-frequency analysis of microwave signals and noise spectra can be widely exploited in the analysis of HPM device operation. Future methods will be measurements of time-dependent bandwidth, beam loading (at high currents), and noise spectra.

The principal quantities to be measured can be described by:

$$E(\bar{x},t) = A(t)\sin(\omega t + \phi)S(\bar{x}) \tag{5.29}$$

where E is the RF electric field, A is the peak electric field amplitude, ω is the angular frequency, ϕ is the phase angle, and S is the spatial variation of the electric field. If several frequencies are present, the pulse is defined by a sum of electric fields at various frequencies. The power of the pulse is proportional to the square of the electric field and the energy to its time integral of the power. We will review each of the quantities in Equation 5.29 in turn.

5.6.1 Power

The most common diagnostic method is the use of diodes to rectify microwaves and detect the envelope of a microwave pulse, generating a DC output nonlinear in the instantaneous electric field, giving the power envelope. Typically, probes mounted inside a waveguide feed the detector and an RC low-pass filter passes the lower-frequency power envelope while blocking the microwaves. In addition to rectification, the nonlinear diode can be exploited to produce a power measurement directly. For sufficiently low powers, the diode current is directly proportional to the square of the voltage across the diode, and therefore to the incident microwave power. Square law operation is possible only at power levels less than ~100 μW. Therefore, substantial attenuation is required to stay within the square law domain. If multiple frequencies are present, this technique will still give the total RF power.

Both point contact and Schottky barrier diodes are available in the microwave regime. The principal advantages are that they are relatively inexpensive, have rise times of ~1 nsec, have a reasonably flat frequency response over a limited bandwidth, and are simple to operate. Their disadvantage is that they can handle only a small amount of power, typically 0.1 W for the point contact and about 1 W for the Schottky diodes. Therefore, substantial attenuation of the pulse is necessary before rectification. This is done with directional couplers, which reduce the signal 30 to 70 dB. Minor difficulties with diodes are that they are fragile and must be handled carefully; there is a substantial unit-to-unit variation in their characteristics, and they are very sensitive to x-rays and moderately sensitive to temperature. Because of these latter factors, diodes must be carefully calibrated on a frequent basis.

The key factor in using diodes is accurate attenuation. Commercial components such as directional couplers are sufficient for this task as long as the mode propagating in each component is the one for which the calibration was made. Here sensitivity to calibration error is great. Another method for attenuating the signal is to broadcast the radiation onto a receiving horn. The signal then goes through a directional coupler in the waveguide, and hence to the diode. This method gives the local fluence, and by taking readings in a number of locations, both the pattern and the total radiated power can be deduced.

5.6.2 Frequency

The simplest frequency diagnostic is the direct measurement of E(t) on fast oscilloscopes, but expense is prohibitive. Other methods require interpretation and care in their use (see Problem 6).

5.6.2.1 Bandpass Filters

The basic technique for a coarse survey of frequency is the bandpass filter. They are similar to lumped element electronic filters in performance, but instead use waveguide cutoff to pass a discrete band. In the high power regime, directional couplers are used to reduce power to a level where commercial filters can be used. There are many kinds of microwave filters. They are available in the domain up to 40 GHz and are inexpensive and straightforward in their use. Their disadvantages are that they have a coarse frequency resolution and that they often have periodic attenuation characteristics, allowing frequencies considerably higher than the bandpass to propagate. Figure 5.26a shows the use of a bandpass method in a vircator experiment by Sze et al.[30] The rapid chirp of the vircator is captured by a set of four bandpass filters, and the power envelope in each band is recorded by a crystal detector.

5.6.2.2 Dispersive Lines

This widely employed simple diagnostic for frequency uses the frequency-dependent transit time of a short pulse down a waveguide. Higher-frequency components arrive first. With a sufficient length of waveguide, a measurement of the time delay between the individual peaks in the dispersed signal and the start of the radiation pulse yields the frequency spectrum on a single shot. Dispersive lines come in two types: long evacuated waveguides and solid-state crystals, typically yttrium iron garnet.[31]

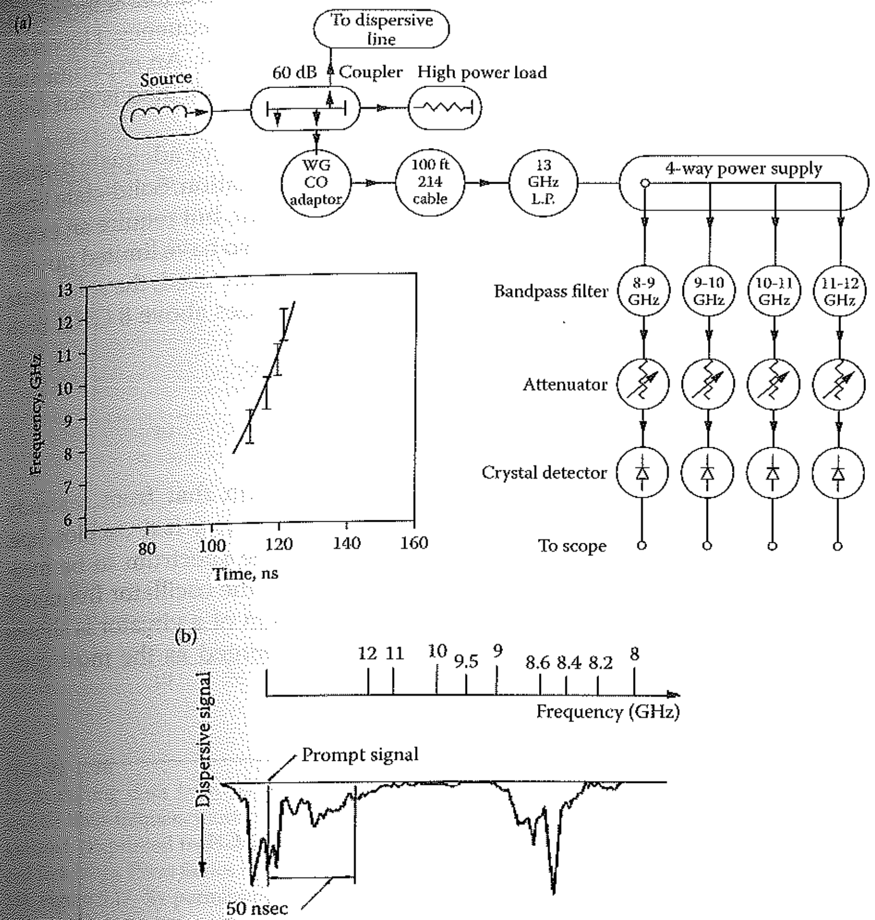

FIGURE 5.26
Frequency measurement methods. (a) Four bandpass filters resolve the vircator source upward chirp (inset). (b) Dispersive line signal for frequency measurement. Timing reference signal ("promp") is superimposed on the dispersed signal.

Waveguide devices operate with waves propagating in the fundamental mode at the frequency-dependent group velocity. The frequency that arrives at a distance L down the waveguide at a transit time t is

$$f = \frac{f_{co}}{\left[1-\frac{L}{ct}\right]^{1/2}} \tag{5.30}$$

For short pulses, the assumption is made that all frequency components are emitted simultaneously. Frequency resolution is directly proportional to pulse length, so only short pulses can be resolved. Resolution is increased if dispersion is enhanced by working near the cutoff frequency. However, waveguide attenuation also increases rapidly near cutoff. An experimental example is shown in Figure 5.26b. An advantage of this method is that only two detectors are required, one at each end of the line.

Waveguides are simple, but long lengths are required for adequate dispersion. They also have high frequency–dependent attenuation. Solid-state lines have higher dispersion and are frequency independent, but require an external magnetic field with a tailored distribution. They also have limited power-handling capability. Both devices have been successfully used, the solid-state devices at frequencies less than 5 GHz and waveguides above 8 GHz. Both methods can achieve dispersions of ~300 nsec/GHz.

5.6.3 Heterodyne Detection

In this method, the microwave signal is mixed with that from a steady oscillator and the beat signal is displayed directly on a fast oscilloscope. Fourier analysis of the heterodyne signal allows the spectrum to be measured. The frequency can be determined by shifting the oscillator frequency over several shots. An example of a Fourier spectrum of a vircator is shown in Figure 5.27.[32] The heterodyne technique has emerged as the most com-

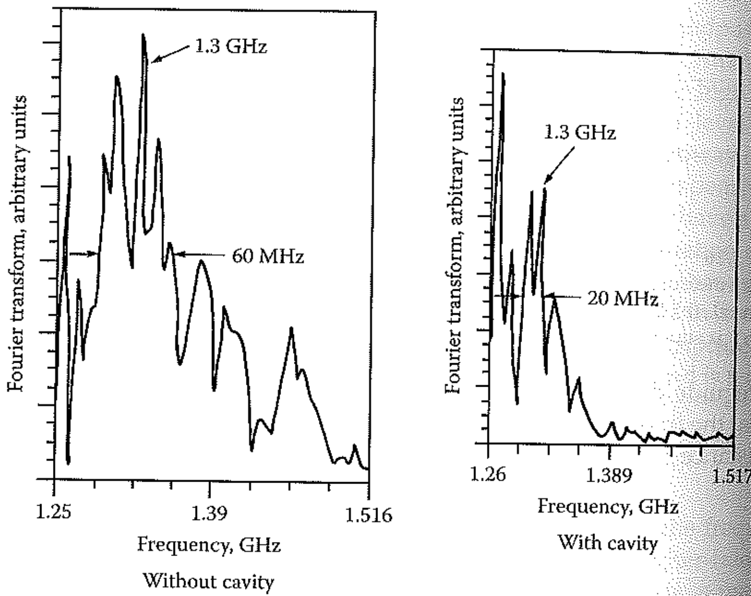

FIGURE 5.27
Fourier spectrum of a vircator. The introduction of a surrounding cavity reduces bandwidth. (See Chapter 10.)

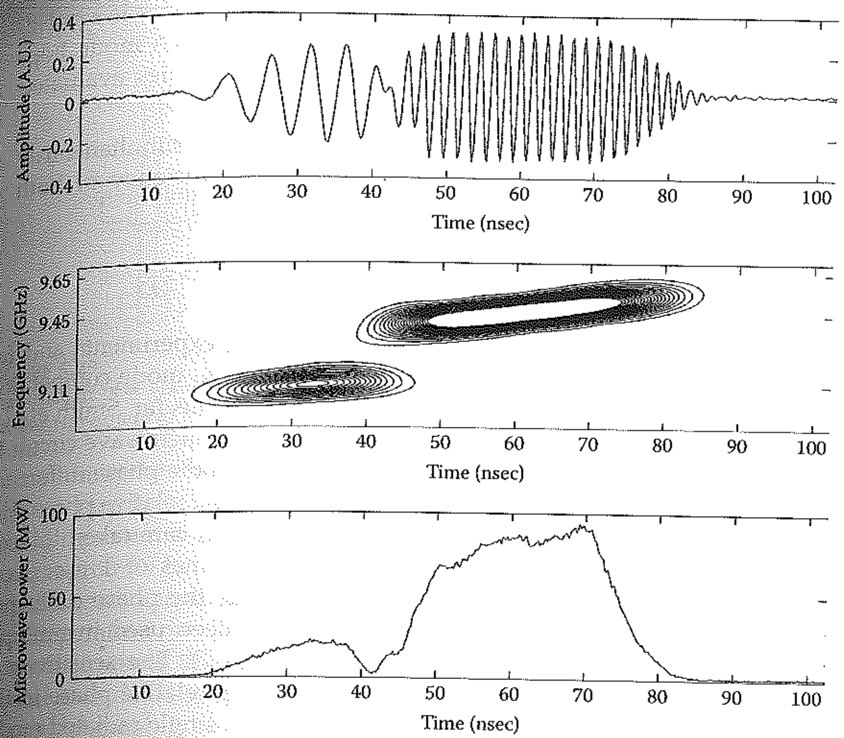

FIGURE 5.28
Mode-shifting data from the University of New Mexico. BWO: upper, heterodyned signal; middle, time–frequency analysis of heterodyne data shows mode (frequency) shift; lower, power radiated. (Reprinted from Barker, R.J. and Schamiloglu, E., Eds., *High-Power Microwave Sources and Technology*, Press Series on RF and Microwave Technology, IEEE Press, New York, 2001, p. 148, Figure 5.17. By permission of IEEE.)

monly used method of measuring frequency because it is an easy-to-use, easy-to-interpret, time-resolved measurement.

5.6.3.1 *Time–Frequency Analysis*

This powerful diagnostic provides Fourier-analyzed frequency signatures. Figure 5.28 shows *time–frequency analysis* (TFA) of a variety of phenomena inside a BWO.[33] The darker line denotes higher power. Some mechanisms that can be shown in TFA are:

1. *Frequency chirping and detuning* of the resonance condition caused by e-beam voltage fluctuations. Even modest voltage fluctuations can cause large frequency chirping, which causes microwave power fluctuations by detuning from the cavity resonance interaction. For electron beam–driven microwave devices, voltage regulation (flatness) is one of the most crucial parameters.

2. *Mode hopping* between two competing resonance modes is a pulse-shortening mechanism. The conditions under which mode hopping occurs can be critically examined and remedies evaluated with TF analysis.
3. *Mode competition* between two modes that can exist simultaneously and radiate. Mode competition destroys the efficiency of both modes, lowering the total power.

5.6.4 Phase

Phase measurements are required for phase-locking experiments and for measurements of the coherence of a radiation field, i.e., mode competition in the radiated waves. Two methods have been used thus far. Smith et al.[34] used an Anaren phase discriminator, which utilizes a microwave circuit to produce two signals, one proportional to the cosine of the phase difference between the input signals and the other to the sine of the relative phase. The inverse tangent was calculated to give the angle, with care taken to keep track of which quadrant the angle falls into. Rise times of 1 nsec were obtained. This method was used to directly measure the phase difference between resonators in a magnetron and has since been used in multiple magnetron phase-locking experiments (see Chapter 7). The sensitivity is about 10°. Price et al.[32] used this method to measure relative phase in the radiation pattern of a vircator, showing existence of a single radiated mode.

Friedman et al.[35] used a more sensitive method to measure phase-locking and spectral purity of a relativistic klystron. The method compares the klystron output to the signal injected into the amplifier by a magnetron. Phase variation is measured to be less than 3°.

5.6.5 Energy

Calorimetry is the fundamental energy diagnostic technique. The power of the pulse can also be determined from the energy measurement by combining it with the pulse shape. Intercepting HPM pulses in a calorimeter can produce electric fields of ~100 kV/cm, so breakdown is an issue. The total energy deposited is typically 1 to 100 J, requiring sensitive measurements of temperature change in the calorimeter. In principle, the calorimeter is quite simple: if a thermally isolated mass m with specific heat c_p absorbs a quantity of energy Q, the temperature rise is

$$T = \frac{Q}{mc_p} \tag{5.31}$$

In practice, the method is valid only if thermal losses are negligible. Therefore, losses due to convection, conduction, and radiation must be minimized

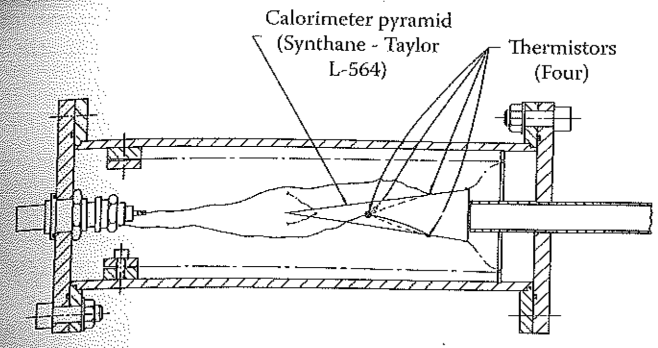

FIGURE 5.29
Construction of a graphite pyramidal microwave calorimeter. Pulses are received from the circular waveguide to the right.

by mounting the absorber material inside an evacuated chamber using thin support members and small transducer leads. In addition, the absorber should represent a matched load to the waveguide it intercepts. Any design is a compromise between large absorber size to better match the waveguide impedance and small size in order to reduce the absorber mass and increase the temperature rise. The absorber material should have a high thermal conductivity to reach thermal equilibrium before losses drain energy away. The typical material is graphite. A common design, shown in Figure 5.29, uses pyramidal graphite absorbers tapered over a distance of 5 to 10 wavelengths. Absorption is typically better than 90%. Orientations both facing and reversed from the Poynting vector have been used, the latter to prevent breakdown.

Temperature rise is usually monitored with thermistors attached to the absorber and connected electrically in series, constituting one arm of an electrical bridge circuit. Temperature changes on the order of a millidegree can be measured. Early et al.[36] have introduced a number of calorimeter designs that use another approach: microwave power is absorbed in a sheet of resistive *space cloth* having the same impedance as the waveguide, and the waveguide is terminated $\lambda/4$ behind the cloth. The cloth heats the intervening layer of air and the pressure is measured. Such methods have the advantage of eliminating electrical connections, and therefore electrical pickup. Infrared measurement of absorber heating has also been used, as have wire calorimeters, which avoid noise problems from x-rays or thermal infrared (IR) signals from the source.

Because source efficiencies are low in many cases, substantial amounts of electrical energy are converted to UV, IR, heated gas, and x-rays. There can also be energy from fields induced from the pulsed power. Use of a calorimeter must be validated by null tests to eliminate these spurious signals. This is frequently the most difficult aspect of experimentation with calorimeters.

Calorimeters are in principle useful over the entire microwave frequency domain. The advantages of the calorimeter are that it operates over a broad band, has relatively simple construction, and can be calibrated without high

... Its limitations are that it must match the waveguide impedance, which makes low-frequency operation more difficult, and use small absorber mass while meeting all other criteria.

5.7 High Power Microwave Facilities

The primary activities for which HPM facilities are being developed are source research and electronics effects testing. The former is done exclusively indoors and the latter both indoors and outdoors. The requirements of these two applications place many constraints on facilities, the foremost of which are interference-free acquisition of data and safety. Researchers should carefully consider their facility requirements. Operation of an HPM facility is frequently more expensive and time consuming than first anticipated. Experimenters should contemplate using available industrial or government facilities rather than constructing their own, at least in the early stages of their work.

5.7.1 Indoor Facilities

A typical indoor microwave facility does both source development and effects testing, with unified instrumentation and safety systems. The most notable feature of indoor facilities is the anechoic room, i.e., a room in which microwave reflections are minimized by use of absorbers on the wall, as shown in Figure 5.30. The usual method for separating functions is to have the microwave source and its associated pulsed power exterior to the anechoic room with waveguide to transmit the microwaves to an antenna located just inside the room. This location for the antenna maximizes the distance between source and test object, making more efficient use of the anechoic room. The room itself is sized by the requirement that test objects not be too close, i.e., greater than $0.2\ D^2/\lambda$ (see Section 5.5.2). Dimensions of anechoic rooms in use vary from a few meters for high-frequency work to >10 m for large target volumes. Anechoic rooms frequently incorporate a turntable for rotation of test objects and a side room containing ancillary equipment for the test object (pneumatics, control systems, and any diagnostics for which cable length must be short). Anechoic rooms must be provided with fire safety and audio alarms, and abort switches to prevent firing of the source while humans are present in the room. The absorbing pyramidal anechoic material can provide an attenuation of ~40 dB, producing a *quiet zone* several meters in diameter. The material is hung on the wall of an electromagnetic screen room that provides ~60 dB of attenuation; thus, in a typical experiment, microwave signals cannot be detected outside the anechoic room. This more than fulfills the microwave safety requirements described below. The size and other aspects of the anechoic room usually determine much of the geometry of a facility.

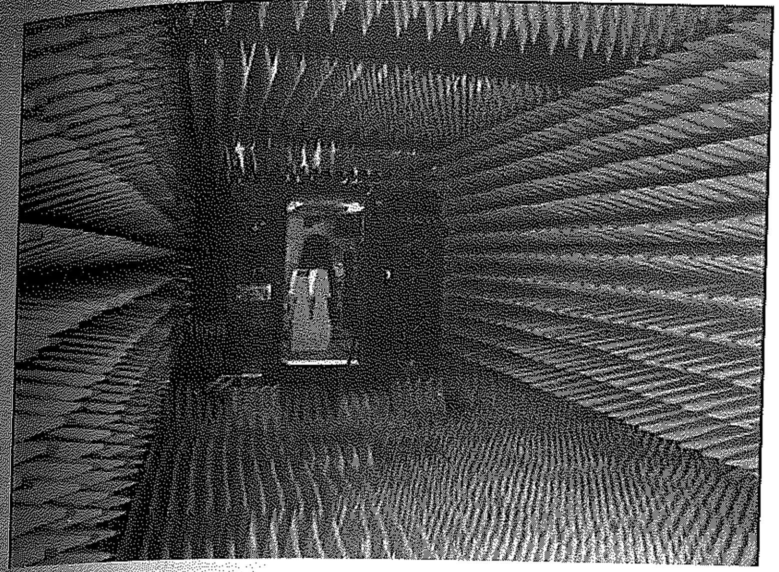

FIGURE 5.30
Anechoic room with absorbing pyramids covering the walls.

Electronic instrumentation for control and diagnostics is carried on conductor or (increasingly) fiber-optic cables (most conveniently located overhead in trays) to screen rooms or to control panels. One of the most crucial issues in facilities is proper handling of the ground plane, to avoid ground loops, which cause noise on instrumentation. A minimum requirement is to locate oscilloscopes sufficiently far from microwave sources (which are almost always x-ray sources) to prevent clouding of the screen.

Because of the overlapping requirements of x-ray, microwave, and other safety issues, access to the facility must always be controlled. The basic requirement is to prevent exposure to radiations by creation of *controlled* and *uncontrolled* areas (defined in the U.S. by CFR 49). Uncontrolled areas are those in which people are allowed access because exposure cannot occur. In controlled areas, exposure can occur, and therefore access must be prevented during times of irradiation. The most effective safety procedure is to provide a gate interlock key for each person entering the facility. All areas that can be irradiated should have a personnel access gate at which the interlock key panel is located. A key missing from the interlock panel will disable the pulsed power and prevent radiation. This system requires vigilance in monitoring on the part of the facility operator to ensure that personnel carry the keys. All personnel must also carry an irradiation badge at all times in a controlled area. Before firing the machine, the operator must inspect the area to ensure that it is clear of all personnel. The gate must be closed and electrical interlocks set before firing can commence. It is advisable to use rotating beacons and loud distinctive warning sirens strategically located to alert everyone in the area of an impending test. Continuous-wave (CW) anechoic rooms will require a fire safety analysis. Note that anechoic rooms can prevent exterior sirens from being heard inside the chamber. A firing abort switch should be inside the anechoic room.

5.7.2 Outdoor Facilities

Outdoor facilities are fraught with their own issues, especially if they are transportable. First, many experimental subsystems will be weather sensitive, and measures must be taken to ensure against the problems of rain, heat, dust, etc. All radiation leakage must be controlled, usually by local shields or simply by standoff distance. Protection from fratricide damage to nearby electronics is made more difficult because of the absence of anechoic rooms and high-quality shielded rooms for the diagnostics. Site security must be controlled more carefully. Finally, because there are many uses of the microwave spectrum, those contemplating outdoor experiments should consult the *Reference Data for Radio Engineers* and FCC regulations to find if their intended frequency is already in use. Aircraft are the principal concern. Ultimately, no apparatus can ensure the safety of a facility. Eternal vigilance is the price of true site security.

Orion is the state-of-the-art transportable, self-contained HPM test facility first fielded in 1995 and currently in operation (Figure 5.31).[37] The system is housed and transported in five ISO containers, has complete fiber-optic-linked computer controls and data acquisition, and carries its own prime power.[38] At the heart of the system is a suite of four tunable magnetrons (Chapter 7), each capable of delivering 400 to 800 MW. The frequency tuning is continuous, with no gaps in performance over the range from 1.07 to 3.3 GHz. Orion fires 1000 pulses in a burst at repetition rates up to 100 Hz. The thyratron-based modulator that drives the magnetrons has a pulsed power output that can be increased in discrete 50-nsec steps up to a maximum duration of 500 nsec. The microwaves are radiated from a high-efficiency, offset, shaped, parabolic antenna that illuminates a 7×15 m, 3-dB beam spot at a 100-m range.

Orion pulsed power is a two-stage, oil-insulated, thyratron-switched modulator that pulse charges an 11-section ladder network PFN through a step-up transformer and triggered gas output switch.[39] Its main performance features are pulse duration variable, 100 to 500 nsec; voltage variable, 200 to 500 kV; and repetitive up to 100 Hz. Impedance is 50 Ω; rise time, <30 nsec; and flatness, ±8%. Pulse duration is varied by manually removing inductors in 50-nsec increments (Figure 5.32).

The four continuously tunable relativistic magnetrons use stepper-motor tuners and explosive emission cathodes, operate at a vacuum of 10^{-6} to 10^{-7} Torr (cyropumps), use a 10-vane, rising-sun design and two-port extraction, and are surrounded by a conformal Pb x-ray shield. The magnetic field is provided by cyromagnets, up to 10 kG. The cyrofluids can operate for 3 days between refillings.

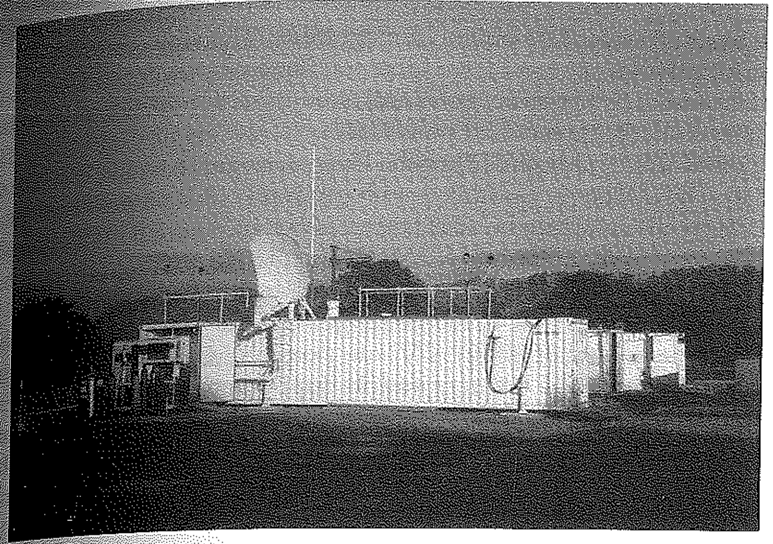

FIGURE 5.31
The Orion outdoor testing facility. (Reprinted by permission of Smith, I., L-3 Communications, San Leandro, CA.)

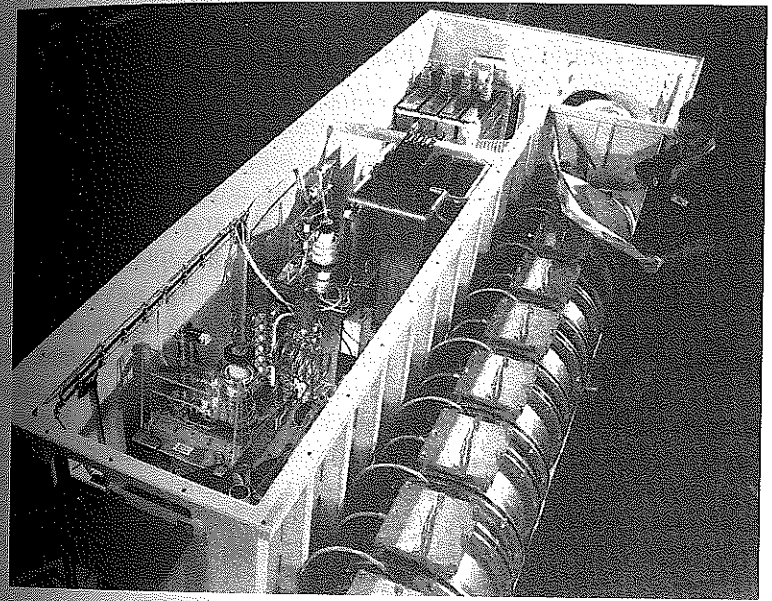

FIGURE 5.32
Orion pulsed power. (Reprinted by permission of Smith, I., L-3 Communications, San Leandro, CA.)

After the magnetron, a combiner/attenuator network provides continuous power variation over five orders of magnitude. The waveguide combiner/attenuator consists of a hybrid tee/phase-shifter and power combiner to sum output from two magnetron arms, followed by a hybrid tee/phase-shifter attenuator to vary the radiated power over five orders of magnitude. There is a separate waveguide circuit for the three waveguide bands WR770, -510, and -340. The system is controlled with programmable stepper-motors.

The Orion antenna system, which can be seen in Figure 5.31, includes two off-set, shaped, parabolic reflectors each with two pyramidal feed horns designed to maximize efficiency, reduce sidelobe level, and produce a 7 × 15 m elliptical beam spot at a 100-m range. Gain is 468 (26.7 dB). Modest pointing adjustments of about ±10° are possible with flexible waveguide sections and shims. The antenna and its supports are designed for ease of assembly, storage, and rapid deployment by two workers (see Problem 7).

Orion is a point of departure and reference that other efforts to bring HPM technology out of the laboratory and into the field may draw upon. Features of the Orion facility that should be considered by anyone contemplating an outdoor facility are:

- There are two diesel generators, one for container and ancillary power and one for the HPM system, with a total power of 1.1 MW maximum. Although the maximum microwave average power out of the antenna is only 5 kW, the differences due mostly to losses.
- Separate containers are required because of their very different functions — for control, prime power, and storage (waveguides, antennas, spare parts, tools).
- Many functions must be built in. For transportability, all contents in each container are mounted with shock and vibration isolation provisions. Smoke detectors, fire extinguishers, and audio intercoms are included in each container. Safety interlocks and abort buttons are provided throughout all ISO containers and are incorporated into the Orion safety interlock system.
- The Orion system is completely computer controlled. The computer provides timing, monitoring, and control of the HPM system. The data acquisition system (DAS) computer provides setup, data archiving, and analysis of the DAS digitizers. All links between containers are fiber optic to avoid grounding and shielding problems. The range safety officer is provided external audio communication and video surveillance.

5.7.3 Microwave Safety

Safety issues can usually be addressed in a straightforward way if taken into account in the initial facility design. The hazards of electromagnetic radiation are becoming the focus of intense public scrutiny. Microwave radiation hazards are divided into three groups: biological hazards to personnel; hazards to ordnance, where a potential exists for munitions or electro-explosive devices to be initiated; and hazards to fuel, where there is a potential for spark ignition of volatile combustibles. In the military, these hazards are referred to, respectively, as HERP (personnel), HERO (ordnance), and HERF (fuel).

Absorption of RF energy by the human body is very frequency dependent. In general, the body's absorption is maximized when the long axis of the body is parallel to the incident electric field and its length is 0.4 λ. Therefore, whole-body resonance for humans is maximized at about 70 MHz, where absorption is sevenfold higher than at 2.5 GHz.[40] Since the photon energy of even high-frequency microwaves is two orders of magnitude below the thermal energy of molecules at room temperature, microwaves are definitely not ionizing radiation. Therefore, they are below the threshold at which effects are cumulative, in contrast to x-rays. However, x-rays have become an accepted hazard; public sensitivity to microwave risk is largely due to a lack of familiarity.

The lowest power effect known in humans is *microwave hearing*. A single 10-μsec pulse of microwave energy absorbed in the head at 10 μJ/g results in an acoustic response, i.e., false sound. At 0.1 J/cm^2, nerve activity can be influenced at the cellular level. At higher levels, confusion and a wide variety of mental effects can occur. At the highest energy levels, local heating can elevate the brain temperature. Unfortunately, little is known about short-pulse, high power effects, and it is a subject of considerable experimental study at present.

For purposes of facility operation, some threshold standard must be adopted. The most common approach is to find an exposure level for pulsed HPM where no adverse effects are observed, and then modify it by a safety factor. A commonly used standard is that of the American National Standards Institute (ANSI), based on a specific absorption rate (SAR), the rate of energy absorption per tissue mass. The ANSI standard uses a constant SAR limit of 0.4 W/kg, which is 10% of the value thought to be the threshold for adverse effects. The 1991 ANSI levels as well as HERO limits are shown in Figure 5.33. In the microwave regime, 10^{-2} W/cm^2 should be an adequate level for average powers. In 1992, the IEEE C95.1-1991 safety standard was introduced; it is two-tiered, with a distinction between controlled and uncontrolled environments (the latter for locations where there is exposure of individuals who have no knowledge or control of their exposure, e.g., living quarters or workplaces that are not clearly identified, so not a microwave facility). The maximum permissible exposures for controlled environments are in Table 5.3. The level rises linearly from 0.3 to 3 GHz, then remains constant at 10 mW/cm^2. The time over which variable intensity exposures can be averaged is generally 6 min, but falls off above 15 GHz to 10 sec at 300 GHz. For example, at 10 GHz, 10 mW/cm^2 exposure over 6 min is within the guideline, and so if exposure is to 60 mW/cm^2, only 1 min is within it.

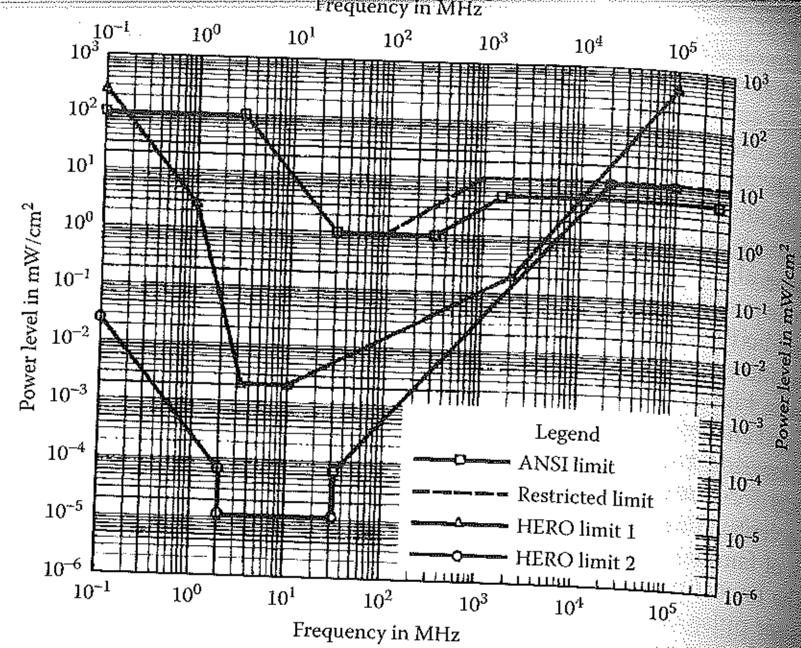

FIGURE 5.33
Safety standards for microwaves.

TABLE 5.3

Safety Guidelines for Microwaves in Controlled Areas

Frequency	Power Density	Averaging Time
0.3–3 GHz	1–10 mW/cm²	6 min
3–15 GHz	10 mW/cm²	6 min
15–300 GHz	10 mW/cm²	6–0.165 min

For peak power limits, the situation is unsettled. Primates exposed to 5 W/cm² peak experienced no effects. Protecting personnel in a microwave facility at this level may be considered safe. Shielding by wearing conducting suits is very effective; shielding of –50 dB can be obtained. However, such suits are rarely used in HPM. In practice, most facilities use screen/anechoic rooms to attenuate below measurable levels.

The HERO specification in Figure 5.33 is to prevent dudding or premature activation of electro-explosive devices (EEDs), which are alleged to have caused accidents during the Vietnam war. The HERO-2 limit gives the maximum safe fields for bare EEDs; the HERO-1 limit is the safe power level for fully assembled ordnance in normal operations. These levels are experimentally based. Ordnance is more sensitive than humans because it reacts to peak power, whereas human reactions appear to be dominated by average power effects. Of course, ordnance liberates great energy, and therefore the safety requirement is greater. Ordnance is also more easily protected by shielding than humans. The consequences for igniting fuels are large, especially when handling motor vehicle and aviation fuels. Measurements near transmitting antennas have shown that a minimum voltage gradient of 50 kV/cm is required for fuel ignition.

Operating microwave sources in an outdoor site in the U.S. comes under the purview of the Federal Communications Commission and its regulations for radio frequency devices, specifically FCC regulation 18.301, which allocates operating frequencies for industrial, scientific, and medical equipment. These regulations specify radiating bands for which unlimited radiated energy is allowed with the proviso that harmful interference is prohibited, i.e., interfering with radio navigation, safety devices, or radio communication. The experimenter should consult the appropriate federal regulations. As a practical operating point, note that the Trestle EMP simulator in Albuquerque, NM, is located near the city airport and does not operate when field strengths near aircraft will exceed 1 kV/m, which corresponds to a power density of 0.26 W/cm². Radar altimeters and other aircraft systems operate at microwave frequencies, so the prudent approach is to find and avoid frequencies and power levels that have been determined to interfere with or damage on-board systems.

5.7.4 X-Ray Safety

X-rays are ionizing radiation produced as a by-product of electron beam microwave sources. The most frequently used unit for radiation is the *rad* (1 rad = 100 erg/g), which is a measure of the radiation energy absorbed in a mass. Exposure to one *roentgen* of radiation results in an absorbed dose of about 1 rad for x-rays. The absorbed dose for biological systems is also frequently expressed in the rem unit (for x-rays, rem = rad). The current standard for an uncontrolled area is 0.5 rem/year.[41] A radiation shield must be designed that, in conjunction with $1/r^2$ falloff, can reduce the fluence in uncontrolled areas to below this level. For safety calculations, one assumes that the full beam energy is deposited in an x-ray converter, i.e., the worst case. For example, a 1-MV, 200-kA, 100-nsec electrical pulse, operating at 10 shots/day, requires about 50 cm of concrete shield. High Z materials such as lead give thinner, heavier shields. Locating this shield close to the source would minimize the volume, in which case lead might be more advantageously used, allowing access to the source. The widely used alternative is to place concrete shields at a distance and use them to define the controlled area. Maze entrances to the radiation area prevent line-of-sight escape of radiation. The interlock safety gate is usually placed at the entrance of the maze to provide the access point to the controlled area. An often overlooked x-ray hazard is *sky shine*: reflection of x-rays from the ceiling or air above the source. Scattering calculations are required to establish the magnitude