MICROWAVE RADIATION HAZARDS

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Excessive exposure to microwave radiation could lead to biological damage. The criteria for maximum permissible exposure limits derived from experiments by several countries are discussed. Recommendations made for safety of operating personnel based on a recent protection survey are also presented.

It is well known that microwave radiation could lead to biological damage from heating effects resulting from absorption of energy of the microwave radiation in the body depending upon the physical, physiological and environmental parameteres of exposure. Certain organs such as the eyes and the testes are known to be more susceptible to microwave radiation than other organs of the body. With the advent of high power microwave generators and their excessive applications in radar and communication net works, the possibility has arisen of a large number of persons working in this area getting exposed to potentially hazardous levels of microwave radiation. An attempt has been made in this paper to analyse the hazards involved and the steps to be taken to prevent exposure of personnel to excessive levels of microwave radiation.

The microwave radiation energy impinging on an object may be scattered, transmitted or absorbed. Only the absorbed energy constitutes a hazard. The penetration of radiation into the body and its absorption will depend upon the physical dimensions of the body, the electrical properties of the tissues and the frequency (or wavelength) of the microwave radiation. It has been estimated that the depth of penetration of microwave radiation in human tissue is approximately one-tenth of the wavelength of the radiation in question.

Most of the well documented biological effects of microwave radiation have been known to result from the heat generated in the body due to the absorption of microwave energy. At frequencies below 1 GHz heat is developed primarily in deep tissues as a result of penetration of the radiation. Hence, radiation at frequencies below 1 GHz will not be detected by human sensory system as the heat sensing elements of the body are located primarily in the skin tissues. Radiation of frequency greater than 3 GHz causes heating of tissues much the same way as does infrared radiation or direct sunlight since absorption takes place on the surface of the body. Radiation at frequencies between 1 and 3 GHz is subject to varying degrees of penetration and is absorbed both by the surface tissues and deeper tissues. The biological effectiveness of the absorbed energy at any wavelength depends upon the heat dissipating characteristics of the tissues themselves. If the organism cannot dissipate heat as fast as it is produced, the internal temperature of the body will rise. This may result in damage to the tissue and if the rise is sufficiently high the organism may be destroyed. The body's ability to dissipate heat successfully depends upon many related factors such as environmental air circulation rate, humidity, air temperature, body metabolic rate, clothing, power density of the microwave radiation field, the amount of energy absorbed and duration of exposure. Temperature regulation in the human body is accomplished primarily through the action of sweat glands and by heat exchange resulting from peripheral circulation of blood. If only portions of the body are exposed, where the exposed areas are cooled by an adequate flow of blood through the vascular system there is less likelihood of tissue damage resulting from heat generation; however, in areas in which relatively little blood circulates the temperature will rise considerably since there is little means for heat exchange. Consequently tissue damage is more likely in exposed areas where there is inadequate blood circulation for heat exchange.

Effect on Dogs

Data on whole body heating in dogs[1] indicate that lethal effects would result from 0·2 GHz microwave radiation when the body temperature is rised by 9°F and maintained for a period of 15 minutes. Addington et al.[2] have reported measurements of temperature development in the rectum of dogs and guinea pigs exposed to 0·2 GHz radiation. The actual rise in rectal temperature depended upon the orientation of the animal in addition to other parameters such as power, frequency etc. In majority of instances animals which developed high temperature due to irradiation showed digestive upset usually in the form of extensive *diarrhoea* during and subsequent to the exposure. Further, autopsy data showed the existence of several "hot spots" developed in the body. Mortality was observed in dogs exposed to 165 mW/cm² for a period of more than 18 minutes. The medium lethal dose for guinea pigs was estimated to be in the neighbourhood of 400 500 mW/cm² for a period of 20 minutes.

Howland et al.[3] have shown that prolonged exposure of dogs to microwave radiation produces leucocytosis following a transient decrease in white blood cells. An early manifestation of the effects of prolonged exposure was found to be haemodilution. Later this was followed by haemoconcentration as a result of subsequent dehydration of the body. They have further shown that weight loss occurs at a rapid rate in dogs exposed to microwave radiation.

Effect on Human Beings

However, no evidence of human death caused by exposure to microwave radiation has been reported. Mermagen[4] has shown by phantom experiments that in a larger size body like of a human being, the rate of temperature rise would be slower than that in rats or dogs. Hence human beings can presumably tolerate higher exposures than rats and dogs.

From the physiological considerations cited above certain organs such as the lens of the eye, the testes, the lungs, the gallbladder and the urinary bladder are known to be more susceptible to microwave radiation than other organs of the body. Of these organs, presently available information indicate that the eyes and the testes are most vulnerable to microwave radiation exposure.

Eye

The transparent cells of the lens of the eye are known to be easily damaged by heat generated by the absorption of microwave energy, since the vascular system in the lens is insufficient to remove the heat. The damaged (and dead) cells may lose their transparency slowly and result in the formation of cataract. The first documented case of microwave cataract formation was reported by Hirsch & Parker[5] in 1952, in a technician operating a microwave generator in the range of 1·5 GHz. It was estimated that the amount of energy delivered to his eyes was in the order of hundreds of milliwatts per square centimetre at a minimum, and probably ranged in the order of watts. A crude relation can be established between the dose of microwave radiation delivered to the eye and the time for cataract formation[1]. Where the lens was believed to be exposed repeatedly to 5 watts/cm² energy density, the cataract was fully formed within two months. Where the lens was believed to be exposed repeatedly to 500 mW/cm² many months passed before early opacification appeared and many years before the cataract was fully formed. Recently LaRoche et al.[6] have reported several cases of microwave injury in persons accidentally exposed to high power levels.

Testis

Testicular reaction to heat injury resulting from microwave radiation appears to be the same as the reaction to high fever associated with many illnesses. Conditions of temporary sterility and damage to seminiferous tubules may occur. Evidence indicates that moderate testicular damage is probably reversible while the damage to the eye is cumulative and non-reversible. This is of considerable importance, since human exposure takes place at low power levels over long periods of time.

In addition to these thermal effects several athermal effects, ranging from chromosome damage and mutations in male fruit fly to decrease in efficiency of rats to perform trained tasks, have also been observed[7].

Limits of Exposure to Microwave Radiation

An analysis of the extensive experimental data and a few human exposure data, have led to the establishment of recommended exposure limits for persons working with microwave radiation during the course of their occupation. In the United States, until recently military and private industry limited the exposure of personnel to microwave radiation to power density levels not greater than 10 mW/cm². The maximum permissible level was the same regardless of the duration of exposure. The increasing power output levels in new radar and microwave systems and certain tactical requirements of the military had combined to make this limit difficult to comply with. Therefore this level has been modified in such a way as to equate higher exposure levels with the duration of exposure. The United States Army and Air Force have adopted figures which permit exposures exceeding 10 mW/cm² based on the formula.

$$T_p = \frac{6000}{W^2}$$

Where T_p = permissible exposure time in minutes during any one period.

W = Power density in mW/cm^2 in the area to be occupied.

The C-95 committee of the American Standards Association[8] and the Canadian Standards Association[9] have recommended, for normal environmental conditions and for incident electromagnetic energy of frequencies from 100 GHz that the radiation level of 10 mW/cm as averaged over any possible 0·1 hour period shall not be exceeded. This would mean (a) power density of 10 mW/cm for periods of 0·1 hour or more and (b) energy density of 1 mWh/cm^2 (milliwatt hour per square centimetre) during any 0·1 hour period. These levels apply whether the radiation is continuous or intermittent, for whole body as well as for partial body exposures.

For off-normal environmental conditions, these values have to be modified. Under conditions of intensive cold, higher values may be appropriate while under moderate to severe heat stress lower values have to be considered. Recently Mumford[10] has calculated the reduction factors appropriate for conditions of moderate to severe heat stress arising from off-normal environmental conditions.

The Soviet Union, Poland and Czechoslovakia set more stringent limitations on exposure standards which range from 2·5 μ W/cm^2 to 1 mW/cm^2 depending on the length of exposure. It is to be noted that their levels are far below the levels set by U. S. A. & Canada. While experiments in U.S.A. have shown that continuous exposure at 10 mW/cm^2 only raises the human body temperature by a maximum of 1°C with no apparent physical harm, the Soviet Union and other Eastern European nations have consistently reported observing effects on the central nervous system resulting in headache, fatigue etc.

Instruments for Measurement of Microwave Power Density

The four basic methods of measuring power are calorimetry, bolometry, voltage measurements and radiation pressure measurements on reflecting surfaces. Of these, bolometric measurements based on absorption of power in temperature sensitive resistive elements, are the most widely used. A thermistor is generally employed as the temperature sensing element. Based on this principle, a portable, battery operated instrument has been fabricated in the Directorate of Radiation Protection, Department of Atomic Energy for rapid detection and measurement of microwave radiation fields. The detector consists of a spiral antenna at the centre of which is mounted a thermistor. The thermistor forms one arm of a Wheatstone bridge as shown in Fig. 1. A compensator thermistor is placed on the other arm to compensate the effect due to environmental temperature variations. The bridge is excited by a 6 volt battery and the unbalance caused by the rf energy absorption in the detector is measured by a 20μA full scale meter calibrated in milliwatts per square centimetre (mW/cm^2) in two ranges namely 0—20 mW/cm^2 and 0-2 mW/cm^2. The instrument has been calibrated against a factory calibrated Narda Microline Model B 86 B 3 Electromagnetic Radiation Monitor. Fig. 2 shows a photograph of the instrument. In actual use, the bridge is first balanced by adjusting the zero control to inject direct current into the bridge. When the unit is placed in a microwave radiation field, the power absorbed by the thermistor causes the bridge to be unbalanced resulting in a meter deflection corresponding to the unbalance and thus to the power level at that position.

Protection Survey of a Microwave Installation

Because of the hazards involved in exposure to microwave radiation all microwave installations must be periodically surveyed in order to evaluate the potential hazards to operating personnel. As a first step it may be necessary to estimate the microwave radiation levels at various distances from a given antenna. The theoretical aspects of this problem have been investigated by several authors.[11,12,13]

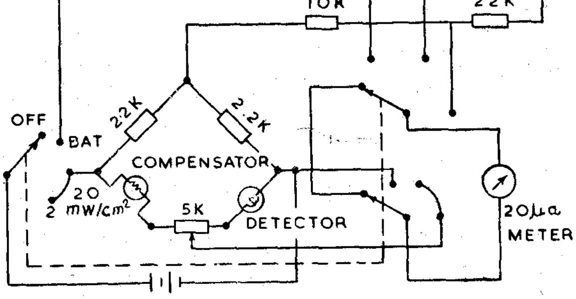

Fig. 1—Microwave radiation monitor (circuit).

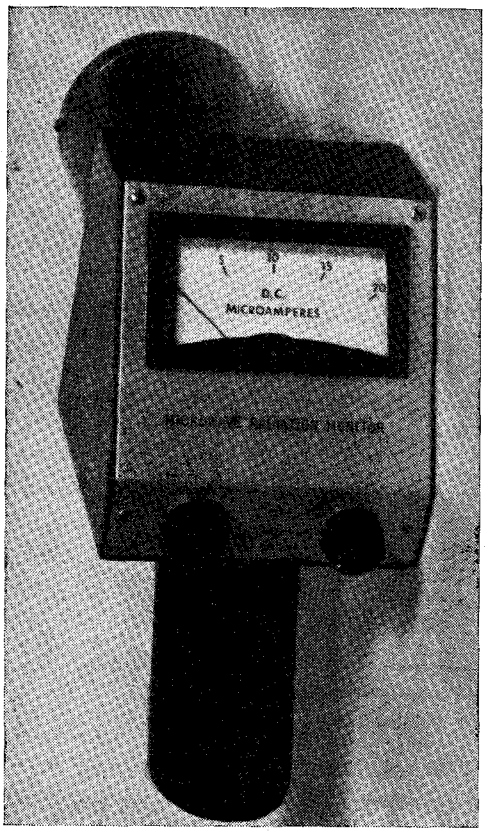

Fig. 2—Microwave radiation monitor (instrument).

As the electromagnetic energy leaves the antenna, its intensity decreases with distance. However, for a uniformly illuminated antenna the power-density remains approximately constant upto a certain distance and is collimated in a beam of approximately the same size as the antenna aperture. This zone is called the 'near field' region. Beyond this region the beam begins to diverge and the power density gradually decreases approaching inverse square reduction at large distances. This region is called the 'far field' region. Since there is no sharp boundary between these regions the cross over zone is called the 'intermediate field'.

The power density as a function of distance on the axis of the antenna under uniform illumination is given by the following equation :—

$$P = (4\,W\,K/\pi\,a^2)\,[\sin\,(\pi\,a^2/2\lambda r)\,]^2 \qquad (1)$$

where P = Power density

r = distance from antenna

a = radius of aperture

λ = wavelength of radiation

W = average power delivered from the antenna

K = an empirical correction factor lying between 0 and 1. It is normally taken as 0·6.

Since the value of r is small for the near field, the sine square term oscillates between 0 and 1 resulting in a series of peaks and valleys in the power level. Since, for protection purposes the peak power density is to be considered, the power density in the near field region is given by

$$P_{nf} = \frac{16WK}{\pi D^2} \qquad (2)$$

where D is the diameter of the antenna aperture.

It may be noted that in the near field region the peak power density is 4 times the average power density.

For large values of r, in the far field region equation (1) predicts an inverse square reduction of the power level as

$$P_{ff} = WK\,\frac{D^2}{4\lambda^2\,r^2} \qquad (3)$$

In the intermediate region an empirical relation of the type

$$P_{if} = 0{\cdot}87\,(W/\lambda r) \qquad (4)$$

is given to fit the theoretical values.

The distances from the antenna at which the near field, the intermediate field and the far field exist cannot be given uniquely. Calculations by Overman[12] show that the distances at which the intermediate and far field regions start are given by

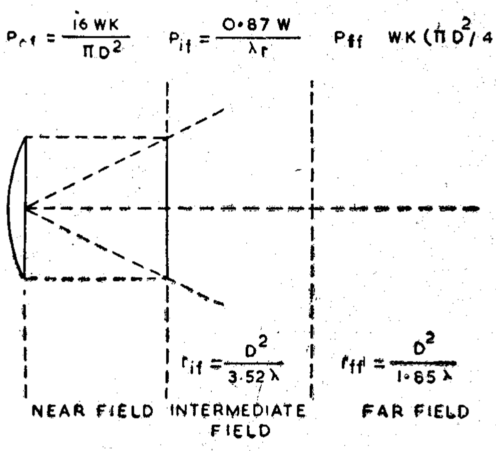

Fig. 3—Radiation zones.

$$r_{if} = D^2/3{\cdot}52\,\lambda$$

and $$r_{ff} = D^2/1{\cdot}85\lambda$$

A schematic representation of the radiation zones based on these calculations is shown in Fig. 3.

Substituting the value of 10 mW/cm^2 as the maximum permissible exposure level for continuous operation in (2), (3) & (4) Overman[12] has developed quick formulae for calculating safe distances from an antenna. These, in a modified form are shown in Fig. 4.

AVERAGE POWER IN WATTS (W)	**SAFE DISTANCE IN METRES**
Less than 32·7D²	**SAFE** (Power density at any point does not exceed 0·01W/cm²)
Between 32·7D² and 62·2D²	$\dfrac{0{\cdot}87W}{\text{Wave length in cm}}$
Over 62·2D²	$\dfrac{6{\cdot}85D\sqrt{W}}{\text{Wave length in cm}}$

Chart applies to pencil-beam radar with parabolic or microwave lens antenna of diameter D metres. Safe distances are based on power density of ·010 watt/cm²

Fig. 4—Quick formulae for calculating safe distances from an antenna.

Scanning Antennas

The maximum permissible limits discussed above have been based on the average power. In the case of a scanning antenna, the average power absorbed by a stationary object in the far field will be reduced by a factor which is given by the ratio of the effective beam width to the scanned angle. Accordingly, the potentially hazardous distances are reduced by the square root of this ratio. The effective beam width in the far field may be taken as 3 db beam width for protection purposes[13].

In the near field the effective beam width will vary with distance since the field is collimated. The effective beam width is approximately given by $\frac{D}{2\pi r}$ 360° where r is the distance in the near field from the antenna aperture. Hence, the average power density of a scanning antenna in the near field is given by

$$P_{nf} = \frac{WK}{\pi a^2} \times \frac{D}{2\pi r} \times \frac{360}{\theta}$$

for $\theta \geqslant \frac{D}{2\pi r} 360°$ where θ is the scanned angle. Substituting $P = 0{\cdot}01$ W/cm^2 and D in metres the safe distance is given by $r_{safe} = \frac{43{\cdot}2\, W}{\theta\, D}$ metres (for $\theta \geqslant \frac{D}{2\pi r} 360°$). For $\theta < \frac{D}{2\pi r}$ 360° the point of interest would always remain in the beam; hence computations valid for a fixed antenna are applicable.

These estimates may be modified by several field conditions such as ground reflection, transmission loss in the system etc. and hence serve only as approximate guidelines and must be confirmed by actual measurements.

Recently a radar installation was surveyed for microwave hazards. The results are presented below :—

Microwave radiation levels were measured with the unit operating at 'high power radiation' and under 'dummy load' conditions, as given below :—

Operating Conditions

Peak power	:	60 kW
Maximum voltage applied to Magnetron	:	15 kV
Maximum current	:	19 A
Wavelength of the radiation	:	3 cm (10 GHz)
Peak work load	:	about 6 units under test

Operation at 'High Power Radiation'

Fig. 5 & 6 show the radiation levels around a single radar unit when test operated at 'high power radiation' in 'lock-on' and 'search modes'. In the 'lock-on' mode the beam was locked in zero position and hence was fixed in space. In the 'search mode' the beam was scanning a cone of apex angle about 60°. Whereas the levels shown for the 'lock-on' mode in Fig. 5 were constant, the levels for the 'search mode' (Fig. 5, 6) at any point in space were for that fraction of the time for which the beam was turned in that direction.

Operation at 'Dummy Load' Condition

The power generated by the radar was absorbed by a 'dummy load'. For purposes of testing, the radar received 10 mW power from an external antenna placed at a distance from the radar and the radiation level at all positions around the radar unit was negligible.

Testing of 'Range Measuring Units'

Peak Power Level	:	6 to 7 kW
Wavelength	:	3 cm (10 GHz)
Antenna gain	:	550 db

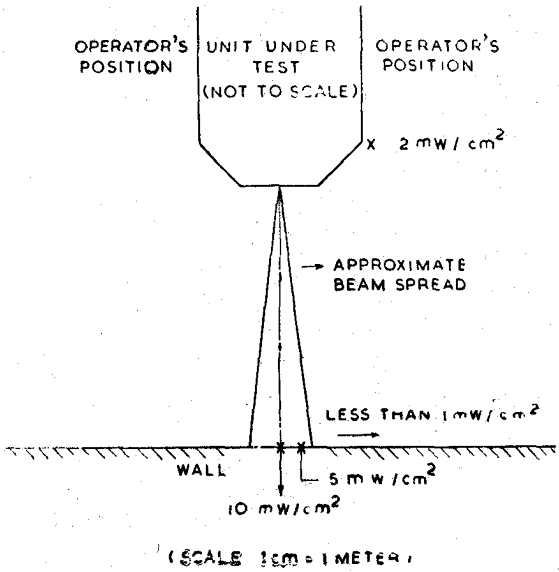

Fig. 5—High power radiation test—lock on mode.

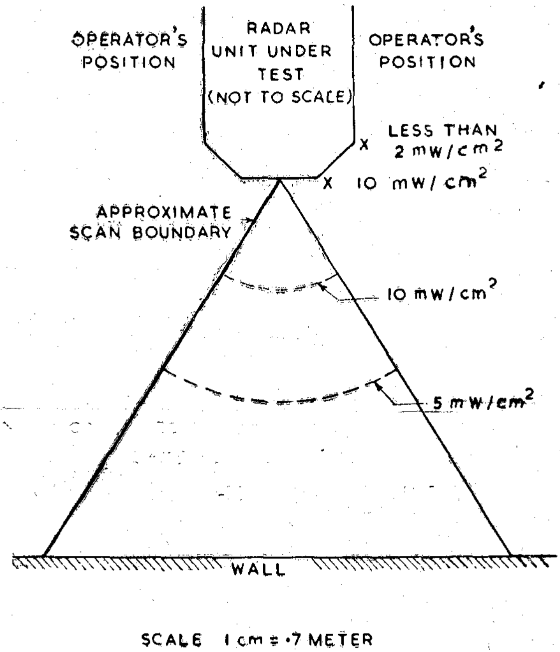

Fig. 6—High power radiation test—search mode.

With the 'dummy load', radiation level around the unit was negligible. However, when the antenna was attached the levels were as follows :

Mode B—Sharp beam (6·5° width)—6 mW/cm² at 1 metre

Mode A—Wide beam (18° width)—5 mW/cm² at 50 cm

X-ray Hazards from Microwave Generators

X-rays are generated in microwave generating systems because the electronic tubes such as Klystrons, Magnetrons, travelling wave tubes and high voltage thyratrons possess some basic physical parameters which allow them to act as X-ray generators. The most important parameter is the extremely high voltage required to operate the tubes utilised in the generation of microwave energy. In the radar installation that was surveyed, the whole magnetron assembly was enclosed in its regular case made of magnesium alloy and hence the X-radiation level around the magnetron was negligible. When the cover was removed during transreceiver testing, with the magnetron operating at 15 kV, the X-radiation level at about 15 cms from the tube was about 6 mR/hour. It is to be noted that this is not an excessive level capable of causing any significant radiation hazard. Further, the operator seldom approaches the unit at closer distances because of the electrical hazards associated with the high voltages. Hence, in the present situation hazards from X-radiation were negligible. However, tubes operating at much higher voltages can produce more intense and penetrating X-radiation. It is known that as the anode voltage increases the X-ray intensity rises very sharply[14]. This is shown in the Fig. 7. An increase in the anode voltage from 20 to 40 kV (a factor of 2) would increase the X-ray intensity almost ten times. Hence, microwave generators operating at high voltages could become potential sources of X-ray hazards. However, it is generally accepted that manufacturers of electronic tubes intended for microwave generation are aware of the X-ray by product, and incorporate sufficient shielding in the design of their equipment to afford adequate protection to operating personnel. Studies conducted by the United States Army Environmental Hygeine Agency and other investigating organisations[14] have established that no potential personnel hazard, attributable to X-rays produced by microwave systems, is present so long as the manufacturer's protective shielding remains intact. Hence, it is necessary that, during routine maintenance or normal operating procedure, the integrity of tube shielding be preserved to avoid inadvertent X-ray exposures to personnel. Interlocks introduced into the system components are of considerable value in accomplishing this purpose. Whenever these safety devices are deliberately interfered with, a careful evaluation of the potential hazards must be undertaken. In carrying out X-ray

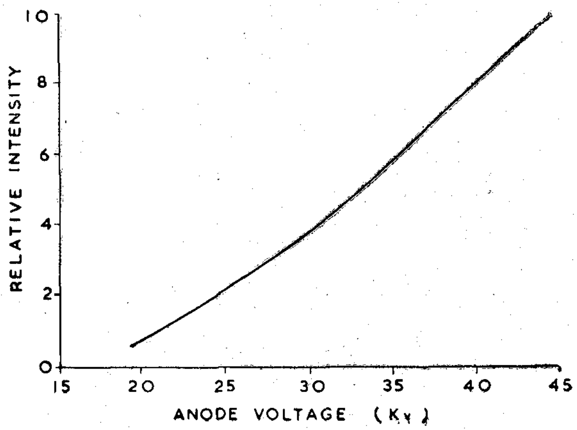

Fig. 7—Relative intensity of X-rays as a function of anode voltage.

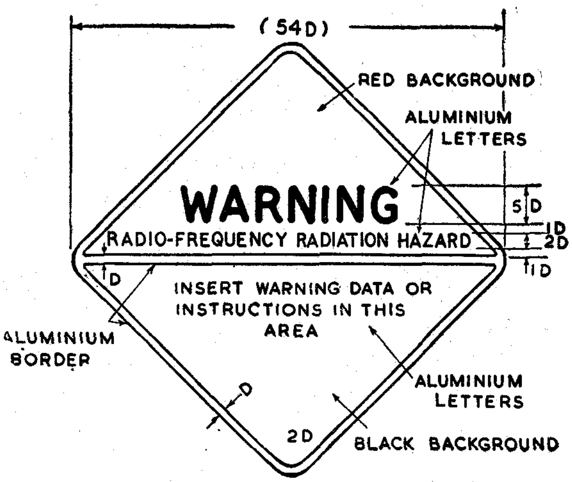

Fig. 8—Radio-frequency radiation hazard warning symbol.

measurements, it should be borne in mind that the rf fields present in the vicinity of the microwave generator could cause strong potential gradients within the X-ray detector and its associated electronic circuit. This may result in erroneous indication of the X-ray intensity. Hence, such instruments should be carefully shielded, during measurement, from rf interference.

All efforts must be made to protect personnel from the hazards of microwave radiation, without at the same time severely restricting the functional capabilities of the system. This could be achieved by careful evaluation and measurement of the microwave radiation levels in working areas and by applying occupancy restrictions based on maximum permissible exposure criteria. In general, visual inspection of feed-horns, open ends of wave guides, and any opening emitting rf energy should not be made unless the equipment is made safe for such an inspection. Areas with radiation levels exceeding 10 mW/cm^2 must be cordoned off to limit access to those areas. Radio-frequency radiation hazard warning symbols of the type shown in Fig. 8 must be displayed conspicuously in the cordoned area[15]. Creating a general awareness of the existence of microwave radiation levels and the associated hazards will go a long way in controlling these hazards.

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