

INFRARED RADIANT HEATING

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RADIANT principles discussed in this chapter apply to equipment with radiant source temperatures ranging from 300 to 5000°F. Radiant equipment with source temperatures in this range is categorized into three groups as follows:

- Low intensity
- Medium intensity
- High intensity

Radiant equipment with source temperatures from below room temperature to 300°F is classified as panel heating and cooling equipment. See [Chapter 6](#) for further information on panel heating and cooling systems.

Low-intensity source temperatures range from 300 to 1200°F. A typical low-intensity heater is mounted on the ceiling and may be constructed of a 4 in. steel tube 20 to 30 ft long. A gas burner inserted into the end of the tube raises the tube temperature, and because most units are equipped with a reflector, the radiant energy emitted is directed down to the conditioned space.

Medium-intensity source temperatures range from 1200 to 1800°F. Typical sources include porous matrix gas-fired infrared units or metal sheathed electric units.

High-intensity radiant source temperatures range from 1800 to 5000°F. A typical high-intensity unit is an electrical reflector lamp with a resistor temperature of 4050°F.

Low-, medium-, and high-intensity infrared heaters are frequently applied in aircraft hangars, factories, warehouses, foundries, greenhouses, and gymnasiums. They are applied to open areas including loading docks, racetrack stands, under marquees, outdoor restaurants, and around swimming pools. Infrared heaters are also used for snow and ice melting ([Chapter 50 of the ASHRAE Handbook—Applications](#)), condensation control, and industrial process heating. Reflectors are frequently used to control the distribution of radiation in specific patterns.

When infrared is used, the environment is characterized by

1. A directional radiant field created by the infrared heaters
2. A radiant field consisting of reradiation and reflection from the walls and/or enclosing surfaces
3. Ambient air temperatures often lower than those found with convective systems

The combined action of these factors determines occupant comfort and the thermal acceptability of the environment.

ENERGY CONSERVATION

Infrared heating units are effective for spot heating. However, due to efficient performance, they are also used for total heating of large areas and entire buildings (Buckley 1989). Radiant heaters transfer energy directly to solid objects. Little energy is lost during transmission because air is a poor absorber of radiant heat. Because

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an intermediate transfer medium such as air or water is not needed, fans or pumps are not required.

As infrared energy warms floors and objects, they in turn release heat to the air by convection. Reradiation to surrounding objects also contributes to comfort in the area. An energy-saving advantage is that radiant heat can be turned off when it is not needed; when it is turned on again, it is effective in minutes.

Human comfort is determined by the average of mean radiant and dry-bulb temperatures. With radiant heating, the dry-bulb temperature may be kept lower for a given comfort level than with other forms of heating (ASHRAE *Standard 55*). As a result, the heat lost to ventilating air and via conduction through the shell of the structure is proportionally smaller, as is energy consumption. Infiltration loss, which is a function of temperature, is also reduced.

Due to the unique split of radiant and convective components in radiant heating and cooling, air movement and stratification in the conditioned space is minimal. This reduces the infiltration and transmission heat losses.

Buckley and Seel (1987) compared energy savings of infrared heating with those of other types of heating systems. A New York State report (1973) identified annual fuel savings as high as 50%. Recognizing the reduced fuel requirement for these applications, Buckley and Seel (1988) noted that it is common for manufacturers of radiant equipment to recommend installation of equipment with a rated output that is 80 to 85% of the heat loss calculated by methods described in [Chapters 28 and 29 of the ASHRAE Handbook—Fundamentals](#).

Chapman and Zhang (1995) developed a three-dimensional mathematical model to compute radiant heat exchange between surfaces. A building comfort analysis program (BCAP) was developed as part of an ASHRAE-sponsored research project (657-RP) and is available from ASHRAE (Chapman and Jones 1994).

INFRARED ENERGY GENERATORS

Gas Infrared

Modern gas-fired infrared heaters burn gas to heat a specific radiating surface. The surface is heated by direct flame contact or with combustion gases. Studies by the Gas Research Board of London (1944), Plyler (1948), and Haslam et al. (1925) reveal that only 10 to 20% of the energy produced by open combustion of a gaseous fuel is infrared radiant energy. The wavelength span over which radiation from a heated surface is distributed can be controlled by design. The specific radiating surface of a properly designed unit directs radiation toward the load. Heaters are available in the following types (see [Table 1](#) for characteristics).

Indirect infrared radiation units ([Figures 1A, 1B, and 1C](#)) are internally fired and have the radiating surface between the hot gases and the load. Combustion takes place within the radiating elements, which operate with surface temperatures up to 1200°F. The elements may be tubes or panels with metal or ceramic components. Indirect infrared radiation units are usually vented and may require ducts.

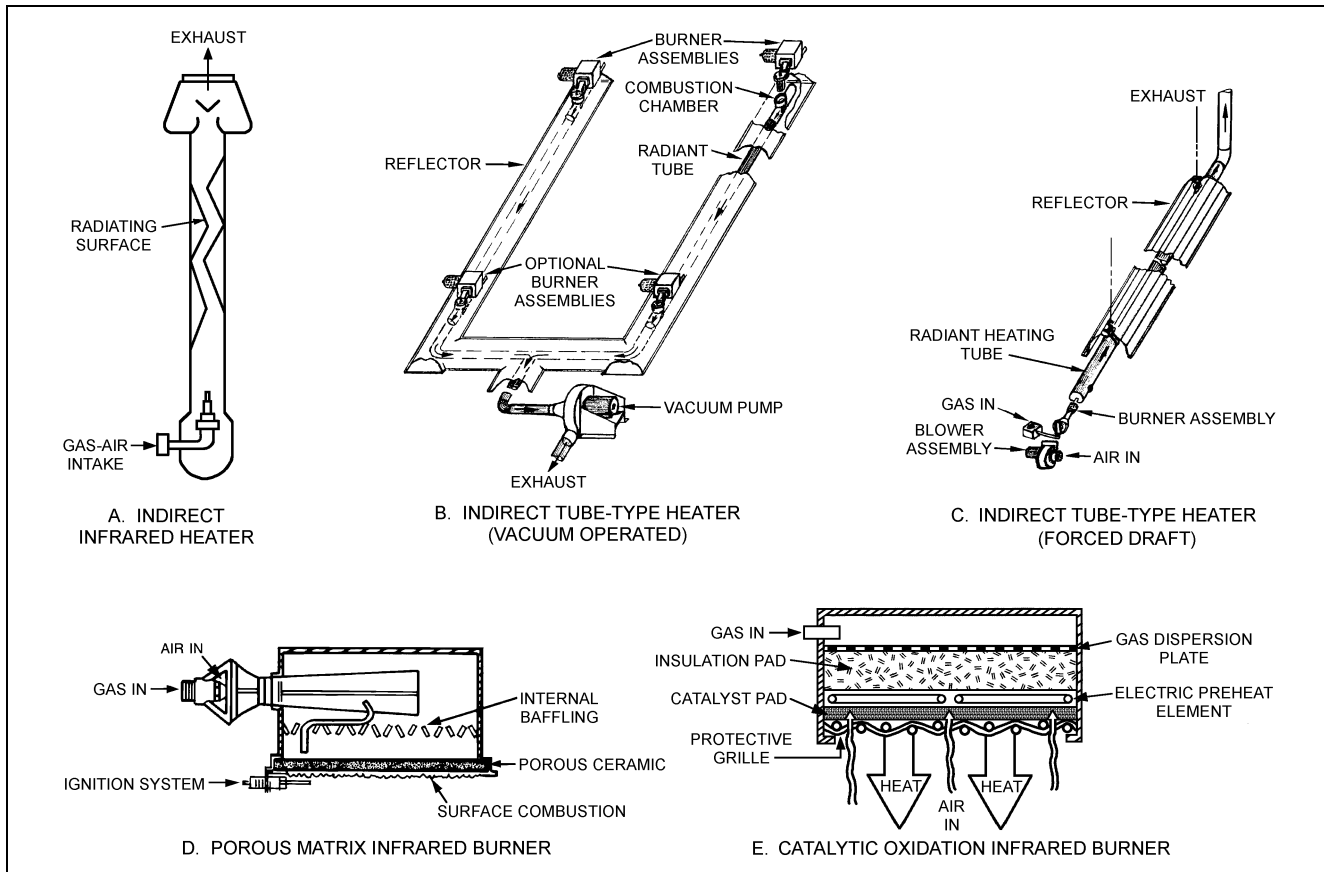


Fig. 1 Types of Gas-Fired Heaters

Table 1 Characteristics of Typical Gas-Fired Infrared Heaters

Characteristics	Indirect	Porous Matrix	Catalytic Oxidation
Operating temperature	To 1200°F	1600 to 1800°F	650 to 700°F
Relative heat intensity, ^a Btu/h · ft ²	Low, to 7500	Medium, 17,000 to 32,000	Low, 800 to 3000
Response time (heat-up)	180 s	60 s	300 s
Radiation-generating ratio ^b	0.35 to 0.55	0.35 to 0.60	No data
Thermal shock resistance	Excellent	Excellent	Excellent
Vibration resistance	Excellent	Excellent	Excellent
Color blindness ^c	Excellent	Very good	Excellent
Luminosity (visible light)	To dull red	Yellow red	None
Mounting height	9 to 50 ft	12 to 50 ft	To 10 ft
Wind or draft resistance	Good	Fair	Very good
Venting	Optional	Nonvented	Nonvented
Flexibility	Good	Excellent—wide range of heat intensities and mounting possibilities available	Limited to low heat intensity applications

^aHeat intensity emitted at burner surface.

^bRatio of radiant output to input.

^cColor blindness refers to absorptivity by various loads of energy emitted by the different sources.

Porous matrix infrared radiation units (Figure 1D) have a refractory material that may be porous ceramic, drilled port ceramic, stainless steel, or a metallic screen. The units are enclosed, except for the major surface facing the load. A combustible gas-air mixture enters the enclosure, flows through the refractory material to the exposed face, and is distributed evenly by the porous character of the refractory. Combustion occurs evenly on the exposed surface. The flame recedes into the matrix, which adds radiant energy to the flame. If the refractory porosity is suitable, an atmospheric burner can be used, resulting in a surface temperature approaching 1650°F. Power burner operation may be required if refractory density is high. However, the resulting surface temperature may also be higher (1800°F).

Catalytic oxidation infrared radiant units (Figure 1E) are similar to the porous matrix units in construction, appearance, and operation, but the refractory material is usually glass wool, and the radiating surface is a catalyst that causes oxidation to proceed without visible flames.

Electric Infrared

Electric infrared heaters use heat produced by current flowing in a high-resistance wire, graphite ribbon, or film element. The following are the most commonly used types (see Table 2 for characteristics).

Metal sheath infrared radiation elements (Figure 2A) are composed of a nickel-chromium heating wire embedded in an electrical insulating refractory, which is encased by a metal tube.

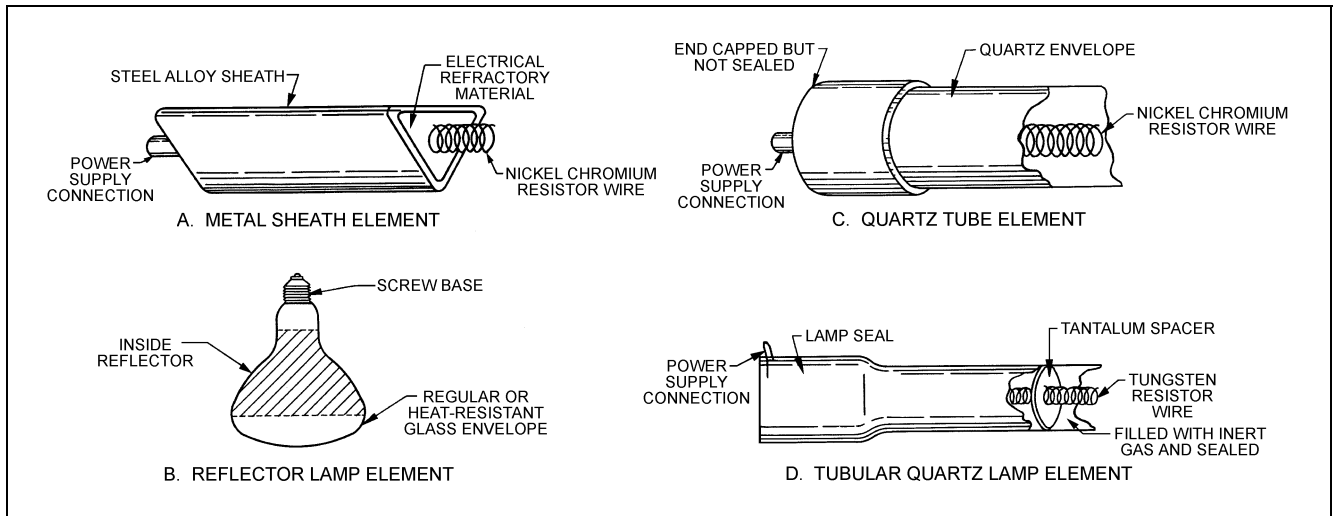


Fig. 2 Common Electric Infrared Heaters

Table 2 Characteristics of Four Electric Infrared Elements

Characteristic	Metal Sheath	Reflector Lamp	Quartz Tube	Quartz Lamp
Resistor material	Nickel-chromium alloy	Tungsten wire	Nickel-chromium alloy	Tungsten wire
Relative heat intensity	Medium, 60 W/in., 0.5 in. dia.	High, 125 to 375 W/spot	Medium to high, 75 W/in., 0.5 in. dia.	High, 100 W/in., 3/8 in. dia.
Resistor temperature	1750°F	4050°F	1700°F	4050°F
Envelope temperature (in use)	1550°F	525 to 575°F	1200°F	1100°F
Radiation-generating ratio ^a	0.58	0.86	0.81	0.86
Response time (heat-up)	180 s	A few seconds	60 s	A few seconds
Luminosity (visible light)	Very low (dull red)	High (8 lm/W)	Low (orange)	High (7.5 lm/W)
Thermal shock resistance	Excellent	Poor to excellent (heat-resistant glass)	Excellent	Excellent
Vibration resistance	Excellent	Medium	Medium	Medium
Impact resistance	Excellent	Medium	Poor	Poor
Wind or draft resistance ^b	Medium	Excellent	Medium	Excellent
Mounting position	Any	Any	Horizontal ^c	Horizontal
Envelope material	Steel alloy	Regular or heat-resistant glass	Translucent quartz	Clear, translucent, or frost quartz and integral red filter glass
Color blindness	Very good	Fair	Very good	Fair
Flexibility	Good—wide range of watt density, length, and voltage practical	Limited to 125-250 and 375 W at 120 V	Excellent—wide range of watt density, diameter, length, and voltage practical	Limited—1 to 3 wattages for each voltage; 1 length for each capacity
Life expectancy	Over 5000 h	5000 h	5000 h	5000 h

^aRatio of radiant output to input (elements only).

^bMay be shielded from wind effects by louvers, deep-drawn fixtures, or both.

^cMay be provided with special internal supports for other than horizontal use.

These elements have excellent resistance to thermal shock, vibration, and impact, and they can be mounted in any position. At full voltage, the elements attain a sheath surface temperature of 1200 to 1800°F. Higher temperatures are attained by such configurations as a hairpin shape. These units generally contain a reflector, which directs radiation to the load. Higher radiosity is obtained if the elements are shielded from wind because the surface-cooling effect of the wind is reduced.

Reflector lamp infrared radiation units (Figure 2B) have a coiled tungsten filament, which approximates a point source radiator. The filament is enclosed in a clear, frosted, or red heat-resistant glass envelope, which is partially silvered inside to form an efficient reflector. Units that may be screwed into a light socket are common.

Quartz tube infrared radiant units (Figure 2C) have a coiled nickel-chromium wire lying unsupported within an unevacuated fused quartz tube, which is capped (not sealed) by porcelain or metal terminal blocks. These units are easily damaged by impact and vibration but stand up well to thermal shock and splashing.

They must be mounted horizontally to minimize coil sag, and they are usually mounted in a fixture that contains a reflector. Normal operating temperatures are from 1300 to 1800°F for the coil and about 1200°F for the tube.

Tubular quartz lamp units (Figure 2D) consist of a 0.38 in. diameter fused quartz tube containing an inert gas and a coiled tungsten filament held in a straight line and away from the tube by tantalum spacers. Filament ends are embedded in sealing material at the ends of the envelope. Lamps must be mounted horizontally, or nearly so, to minimize filament sag and overheating of the sealed ends. At normal design voltages, quartz lamp filaments operate at about 4050°F, while the envelope operates at about 1100°F.

Oil Infrared

Oil-fired infrared radiation heaters are similar to gas-fired indirect infrared radiation units (Figures 1A, 1B, and 1C). Oil-fired units are vented.

SYSTEM EFFICIENCY

Because many factors contribute to the performance of a specific infrared system, a single criterion should not be used to evaluate comparable systems. Therefore, at least two of the following indicators should be used when evaluating system performance.

Radiation-generating ratio is infrared energy generated divided by total energy input.

Fixture efficiency is an index of a fixture's ability to emit the radiant energy developed by the infrared source; it is usually based on total energy input. The housing, reflector, and other parts of a fixture absorb some infrared energy and convert it to heat, which is lost through convection. A fixture that controls direction and distribution of energy effectively may have a lower fixture efficiency.

Pattern efficiency is an index of a fixture's effectiveness in directing the infrared energy into a specific pattern. This effectiveness, plus effective application of the pattern to the load, influences the total effectiveness of the system (Boyd 1963). Typical radiation-generating ratios of gas infrared generators are indicated in [Table 1](#). Limited test data indicate that the amount of radiant energy emitted from gas infrared units ranges from 35 to 60% of the amount of convective energy. The Stefan-Boltzmann law can be used to estimate the infrared output capability if reasonably accurate values of true surface temperature, emitting area, and surface emittance are available (DeWerth 1960). DeWerth (1962) also addresses the spectral distribution of energy curves for several gas sources.

[Table 2](#) lists typical radiation-generating ratios of electric infrared generators. Fixture efficiencies are typically 80 to 95% of the radiation-generating ratios.

Infrared heaters should be operated at rated input. A small reduction in input causes a larger decrease in radiant output because of the fourth power dependence of radiant output on radiator temperature. As a variety of infrared units with a variety of reflectors and shields are available, the manufacturers' information should be consulted.

REFLECTORS

Radiation from most infrared heating devices is directed by the emitting surface and can be concentrated by reflectors. Mounting height and whether spot heating or total heating is used usually determine which type of reflector will achieve the desired heat-flux pattern at floor level. Four types of reflectors can be used: (1) parabolic, which produce essentially parallel beams of energy; (2) elliptical, which direct all energy that is received or generated at the first focal point through a second focal point; (3) spherical, which are a special class of elliptical reflectors with coincident foci; and (4) flat, which redirect the emitted energy without concentrating or collimating the rays.

Energy data furnished by the manufacturer should be consulted to apply a heater properly.

CONTROLS

Normally, all controls (except the thermostat) are built into gas-fired infrared heaters, whereas electric infrared fixtures usually have no built-in controls. Because of the effects of direct radiation, as well as higher mean radiant temperature (MRT) and decreased ambient temperature compared to warm air systems, infrared heating requires careful selection and location of the thermostat or sensor. Some installers recommend placing the thermostat or sensor in the radiation pattern. The nature of the system, the type of infrared heating units used, and the nature of the thermostat or sensor dictate the appropriate approach. Furthermore, no single location appears to be equally effective during the periods after a cold start and after substantial operation. To reduce high and low temperature swings, a long rather than a short thermostat cycling time is preferred. A properly sized system or modulating or dual-stage operation can improve comfort conditions.

An infrared heater controlled by low-limit thermostats can be used for freeze protection.

On gas-fired infrared units, a thermostat usually controls an automatic valve to provide on-off control of gas flow to all burners. If a unit has a pilot flame, a sensing element prevents the flow of gas to burners (or to both burners and pilot) when the pilot is extinguished. Electrical ignition may be used with provision for manual or automatic reignition of the pilot if it goes out. Electric spark ignition may also be used.

Gas and electric infrared systems for full building heating may have a zone thermostatic control system in which a thermostat representative of one outside exposure operates heaters along that outside wall. Two or more zone thermostats may be required for extremely long wall exposures. Heaters for an internal zone may be grouped around a thermostat representative of that zone. Manual switches or thermostats are usually used for spot or area heating, but input controllers may also be used.

Electric infrared heating units with metal sheath or quartz tube elements are effectively controlled by input controllers. An input controller is a motor-driven cycling device in which *on* time per cycle can be set. A 30 s cycle is normal. When a circuit's capacity exceeds an input controller's rating, the controller can be used to cycle a pilot circuit of contactors adequate for the load.

Input controllers work well with metal sheath heaters because the sheath mass smooths the pulses into even radiation. The control method decreases the efficiency of infrared generation slightly. When controlled with these devices, quartz tube elements, which have a warm-up time of several seconds, have perceptible but not normally disturbing pulses of infrared, with only moderate reduction in generation efficiency.

Input controllers should not be used with quartz lamps because the cycling luminosity would be distracting. Instead, output from a quartz lamp unit can be controlled by changing the voltage to the lamp element. The voltage can be changed by using modulating transformers or by switching the power supply from hot-to-hot to hot-to-ground potential.

Power drawn by the tungsten filament of the quartz lamp varies approximately as the 1.5 power of the voltage, while that of metal sheath or quartz tube elements (using nickel-chromium wire) varies as the square of the voltage. Multiple circuits for electric infrared systems can be manually or automatically switched to provide multiple stages of heat. Three circuits or control stages are usually adequate. For areas with fairly uniform radiation, one circuit should be controlled with input control or voltage variation control on electric units, while the other two are on full on or off control. This arrangement gives flexible, staged control with maximum efficiency of infrared generation. The variable circuit alone provides zero to one-third capacity. Adding another circuit at full *on* provides one-third to two-thirds capacity, and adding the third circuit provides two-thirds to full capacity.

PRECAUTIONS

Precautions for the application of infrared heaters include the following:

- All infrared heaters covered in this chapter have high surface temperatures when they are operating and should, therefore, not be used when the atmosphere contains ignitable dust, gases, or vapors in hazardous concentrations.
- Manufacturers' recommendations for clearance between a fixture and combustible material should be followed. If combustible material is being stored, warning notices defining proper clearances should be posted near the fixture.
- Manufacturers' recommendations for clearance between a fixture and personnel areas should be followed to prevent personnel stress due to local overheating.

- Infrared fixtures should not be used if the atmosphere contains gases, vapors, or dust that decomposes to hazardous or toxic materials in the presence of high temperature and air. For example, infrared units should not be used in an area with a degreasing operation that uses trichloroethylene unless the area has a suitable exhaust system that isolates the contaminant. Trichloroethylene, when heated, forms phosgene (a toxic compound) and hydrogen chloride (a corrosive compound).
- Humidity must be controlled in areas with unvented gas-fired infrared units because water formed by combustion increases humidity. Sufficient ventilation (NFPA/AGA *National Fuel Gas Code*), direct venting, or insulation on cold surfaces helps control moisture problems.
- Lamp holders and grounding for infrared heating lamps should comply with Section 422-15 of the *National Electrical Code* (NFPA *Standard 70*).
- Adequate makeup air (NFPA/AGA *National Fuel Gas Code*) must be provided to replace the air used by combustion-type heaters, regardless of whether units are direct vented.
- If unvented combustion-type infrared heaters are used, the area must have adequate ventilation to ensure that products of combustion in the air are held to an acceptable level (Prince 1962).
- For comfort, personnel should be protected from substantial wind or drafts. Suitable wind shields seem to be more effective than increased radiation density (Boyd 1960).

In the United States, refer to Occupational Safety and Health Administration (OSHA) guidelines for additional information.

MAINTENANCE

Gas- and oil-fired infrared heaters require periodic cleaning to remove dust, dirt, and soot. Reflecting surfaces must be kept clean to remain efficient. An annual cleaning of heat exchangers, radiating surfaces, burners, and reflectors with compressed air is usually sufficient. Chemical cleaners must not leave a film on reflector surfaces.

Both main and pilot air ports of gas-fired units should be kept free of lint and dust. The nozzle, draft tube, and nose cone of oil-fired unit burners are designed to operate in a particular combustion chamber, so they must be replaced carefully when they are removed.

Electric infrared systems require little care beyond the cleaning of reflectors. Quartz and glass elements must be handled carefully because they are fragile, and fingerprints must be removed (preferably with alcohol) to prevent etching at operating temperature, which causes early failure.

DESIGN CONSIDERATIONS FOR BEAM RADIANT HEATERS

Chapter 53 of the *ASHRAE Handbook—Applications* introduces the principles of design for spot beam radiant heating. The effective radiant flux (ERF) represents the radiant energy absorbed by an occupant from all temperature sources different from the ambient. ERF is defined as

$$ERF = h_r(\bar{t}_r - t_a) \tag{1}$$

where

- ERF = effective radiant flux, Btu/h·ft²
- h_r = linear radiation transfer coefficient, Btu/h·ft²·°F
- \bar{t}_r = mean radiant temperature affecting occupant, °F
- t_a = ambient air temperature near occupant, °F

ERF may be measured as the heat absorbed at the skin-clothing surface from a beam heater treated as a point source:

$$ERF = \frac{\alpha_K I_K (A_p/d^2)}{A_D} \tag{2}$$

where

- α_K = absorptance of skin-clothing surface at emitter temperature (Figure 3), dimensionless
- I_K = irradiance from beam heater, Btu/h·sr
- A_p = projected area of occupant on plane normal to direction of heater beam, ft²
- d = distance from beam heater to center of occupant, ft
- A_D = body surface area of occupant, ft²

A_p/d^2 is the solid angle subtended by the projected area of the occupant from the beam heater. See Figure 5 in Chapter 53 of the *ASHRAE Handbook—Applications* for a representation of these variables. The value of the DuBois area A_D has been defined as follows:

$$A_D = 0.108 W^{0.425} H^{0.725}$$

where

- W = mass of occupant, lb
- H = height of occupant, in.

Two radiation area factors are defined as

$$f_{eff} = A_{eff}/A_D \tag{3}$$

$$f_p = A_p/A_{eff} \tag{4}$$

where A_{eff} is the effective radiating area of the total body surface. Equation (2) becomes

$$ERF = \alpha_K f_{eff} f_p I_K / d^2 \tag{5}$$

Fanger (1973) developed precise optical methods to evaluate the angle factors f_{eff} and f_p for both sitting and standing positions and for males and females. An average value for f_{eff} of 0.71 for both sitting and standing is accurate within ±2%. The variations in angle factor f_p over various azimuths and elevations for seated or standing positions are illustrated in Figures 4 and 5, and according to Fanger, they apply equally to both males and females.

Manufacturers of infrared heating equipment usually supply performance specifications for their equipment (Gagge et al. 1967). Design information regarding sizing infrared heating units is also

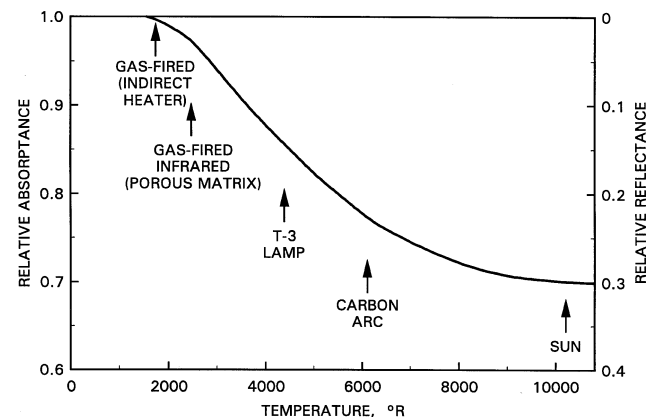


Fig. 3 Relative Absorbance and Reflectance of Skin and Typical Clothing Surfaces

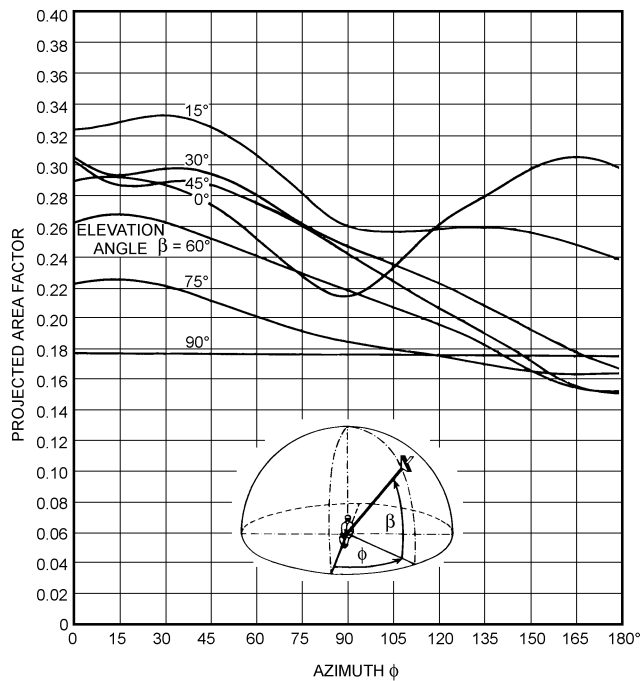


Fig. 4 Projected Area Factor for Seated Persons, Nude and Clothed (Fanger 1973)

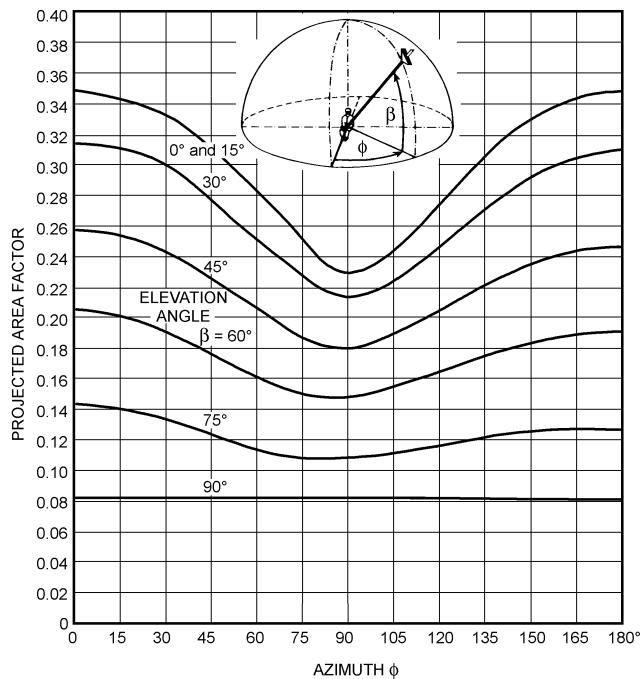


Fig. 5 Projected Area Factor for Standing Persons, Nude and Clothed (Fanger 1973)

available (Howell and Suryanarayana 1990), as is the relation between color temperature of heaters and the applied voltage or wattage is also available. Gas-fired radiators usually operate at constant emitting temperatures of 1340 to 1700°F (1800 to 2160°R). Figure 3 relates the absorptance α_K to the radiating temperature of the radiant source. Manufacturers also supply the radiant flux

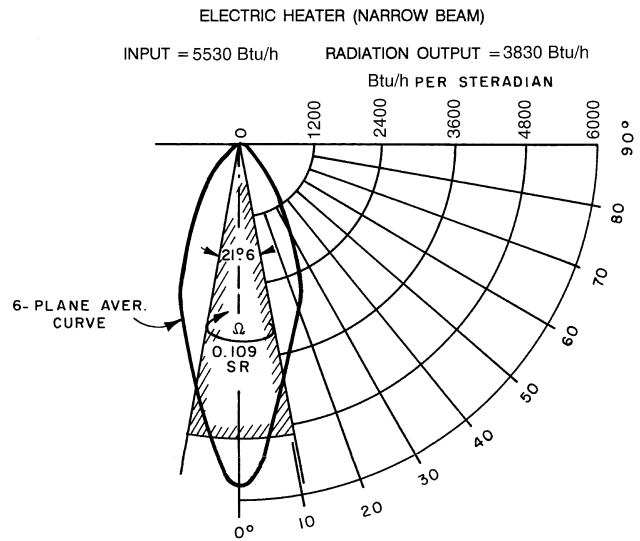


Fig. 6 Radiant Flux Distribution Curve of Typical Narrow-Beam High-Intensity Electric Infrared Heaters

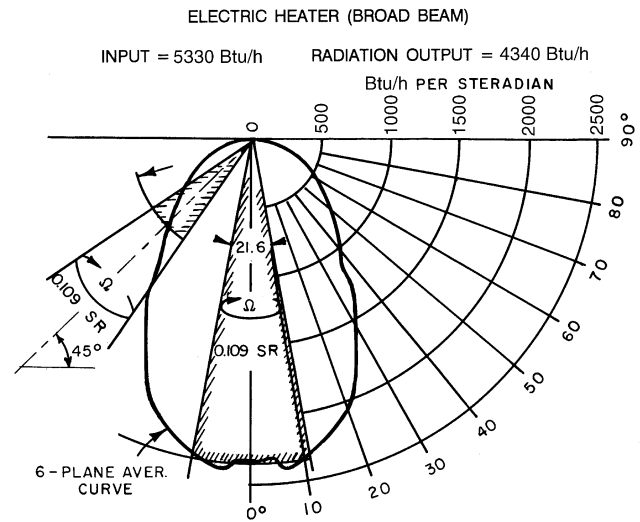


Fig. 7 Radiant Flux Distribution Curve of Typical Broad-Beam High-Intensity Electric Infrared Heaters

distribution of beam heaters with and without reflectors. Figures 6 through 9 illustrate the radiant flux distribution for four typical electric and gas-fired radiant heaters. In general, electrical beam heaters produce as much as 70 to 80% of their total energy output as radiant heat, in contrast to 40% for gas-fired types. In practice, the designer should choose a beam heater that will illuminate the subject with acceptable uniformity. Even with complete illumination by a beam 0.109 sr (21.6°) wide, Figure 6 shows that only 8% ($100 \times 1225 \times 0.109/1620$) of the initial input wattage to the heater is usable for specifying the necessary I_K in Equation (5). The corresponding percentages for Figures 7, 8, and 9 are 5%, 4%, and 2%, respectively. The last two are for gas-fired beams.

The input energy to the beam heater not used for directly irradiating the occupant ultimately increases the ambient air temperature and mean radiant temperature of the room. This increase will reduce the original ERF required for comfort and acceptability. The continuing reradiation and convective heating of surrounding walls and

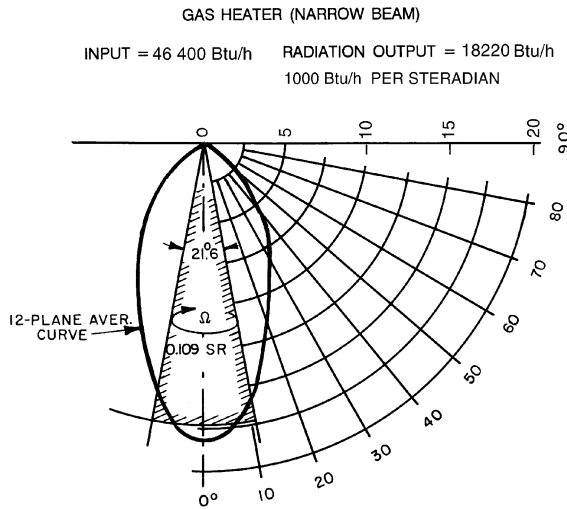


Fig. 8 Radiant Flux Distribution Curve of Typical Narrow-Beam High-Intensity Atmospheric Gas-Fired Infrared Heaters

the presence of air movement make precise calculations of radiant heat exchange difficult.

The basic principles of beam heating are illustrated by the following examples.

Example 1. Determine the beam radiation intensity required for comfort from a quartz lamp (Figure 6) when the worker is sedentary, lightly clothed (0.5 clo), and seated. The ambient t_a is 59°F, with air movement 30 fpm. The lamp is mounted on the 8 ft high ceiling and is directed at the back of the seated person so that the elevation angle β is 45° and the azimuth angle ϕ is 180°. Assume the ambient and mean radiant temperatures of the unheated room are equal. The lamp operates at 240 V and has an emitter temperature of 4500°R.

Solution: The ERF for comfort can be calculated as 21.5 Btu/h·ft² by procedures outlined in the section on Design Criteria for Acceptable Radiant Heating in Chapter 53 of the ASHRAE Handbook—Applications. $\alpha_K = 0.85$ at 4500°R (from Figure 3); $f_{eff} = 0.71$; $f_p = 0.17$ (Figure 4); $d = 8 - 2 = 6$ ft, where 2 ft is sitting height of occupant.

From Equation (5), the irradiance I_K from the beam heater necessary for comfort is

$$I_K = \text{ERF} \cdot d^2 / \alpha_K f_{eff} f_p$$

$$= 21.5(6)^2 / (0.85 \times 0.71 \times 0.17) = 7540 \text{ Btu/h} \cdot \text{sr}$$

Example 2. For the same occupant in Example 1, when two beams located on the ceiling and operating at half of rated voltage are directed downward at the subject at 45° and at azimuth angle 90° on each side, what would be the I_K required from each heater?

Solution: The ERF for comfort from each beam is 21.5/2 or 10.75 Btu/h·ft². The value of f_p is 0.25 (from Figure 4). At half power, $V = 170$, $R \approx 3600$, and $\alpha_K \approx 0.9$. Hence, the required irradiation from each beam is

$$I_K = 10.75(6)^2 / (0.9 \times 0.71 \times 0.25)$$

$$= 2420 \text{ Btu/h} \cdot \text{sr}$$

This estimate indicates that two beams similar to Figure 7, each operating at half of rated power, can produce the necessary ERF for comfort. A comparison between the I_K requirements in Examples 1 and 2 shows that irradiating a sitting person from the back is much less efficient than irradiating from the side.

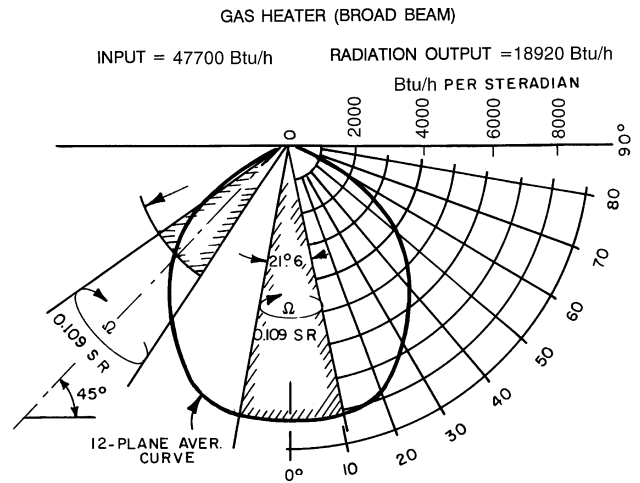


Fig. 9 Radiant Flux Distribution Curve of Typical Broad-Beam High-Intensity Atmospheric Gas-Fired Infrared Heaters

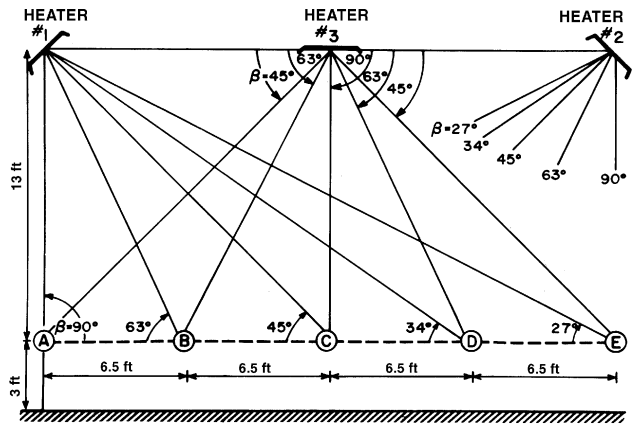


Fig. 10 Calculation of Total ERF from Three Gas-Fired Heaters on Worker Standing at Positions A Through E

Example 3. A broad-beam gas-fired infrared heater is mounted 16 ft above the floor. The heater is directed 45° downward toward a standing subject 13 ft away (see Heater #1 in Figure 10, position C).

Question (1): What is the resulting ERF from the beam acting on the subject?

Solution: From Equation (5),

$$\text{ERF} = \alpha_K f_{eff} f_p I_K / d^2 = 4.2 \text{ Btu/h} \cdot \text{ft}^2$$

where

- $\alpha_K = 0.97$ (Figure 3)
- $f_{eff} = 0.71$
- $f_p = 0.26$ (Figure 5 at $\beta = 45^\circ$ and $\phi = 0^\circ$)
- $I_K = 8000 \text{ Btu/h} \cdot \text{sr}$ (Figure 9)
- $d^2 = 13^2 + 13^2 = 338 \text{ ft}^2$ (The center of the standing man is 3 ft above the floor.)

If the heater were 10 ft above the standing subject (13 ft above floor), the ERF would be 5.3 Btu/h·ft².

Question (2): How does the ERF vary along the 0° azimuth, every 6.5 ft beginning at a point directly under Heater #1 (Figure 10) and for elevations $\beta = 90^\circ$ at A, 63.4° at B, 45° at C, 33.6° at D, and 26.6° at E?

From Figure 5, the values for f_p for the five positions are (A) 0.08, (B) 0.19, (C) 0.26, (D) 0.30, and (E) 0.33.

Solution: Because the beam is directed 45° downward, the respective deviations from the beam center for a person standing at the five positions A through E are 45°, 18.4°, 0°, 11.4°, and 18.4°; the corresponding I_K values from Figure 9 are 5000, 8000, 8000, 8000, and 8000 Btu/h·sr. The respective d^2 are 169, 211, 338, 549, and 845 ft². The ERFs for a person standing in the five positions are (A) 1.6, (B) 4.9, (C) 4.2, (D) 3.0, and (E) 2.1 Btu/h·ft².

Question (3): How will the total ERF at each of the five locations A through E vary if two additional heaters (#2 and #3 in Figure 10) are added 16 ft above the floor over positions C and E? The center heater is directed downward, the outer one directed as above, 45° towards the center of the room.

Solution: At each of five room locations (A, B, C, D, E), add the ERF from each of the three radiators to determine the total ERF affecting the standing person.

A	1.6 + 2.5 + 2.1	or	6.2
B	4.9 + 4.2 + 3.0	or	12.1
C	4.2 + 2.5 + 4.2	or	10.9
D	3.0 + 4.2 + 4.9	or	12.1
E	2.1 + 2.5 + 5	or	6.2

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