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Naval Fire Fighting Trainers - Thermal Radiation Effects Associated with the 19F4 FFT

David W. Stroup

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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NOMENCLATURE

A	area
d	diameter of the fire at its base
dA	area taken as a differential element
$\dot{E}_r$	the radiative power output of the fire
F	a geometric "view factor" dependent on the relative flame and target geometry
g	acceleration of gravity
h	flame height or length/flame radius, dimensionless
L	flame height
$\dot{m}''$	mass burning rate per unit area of the fire source
r	distance from target element to flame element along a line
r_f	equivalent radius of fire area
S	distance to target from flame axis/flame radius, dimensionless
T	temperature
u	velocity
$\dot{V}$	volume flow rate of fuel
β	angle between the normal to differential element dA and the line from the target to the radiation source
ΔH_c	the heat of combustion of the fuel
ϵ	emissivity of the flame
ν_a	kinematic viscosity of ambient air
ρ	density
σ	Stefan-Boltzmann constant (1.71×10^{-9} Btu/hr ft^2 R^4)
τ	the transmissivity of the atmosphere to thermal radiation
χ	the fraction of the fire's energy which is radiated

Subscripts

a	ambient
f	fire or flame
v	fuel vapor
w	wind
1	radiation target
2	radiation source

Superscripts

*	dimensionless quantity

NAVAL FIRE FIGHTING TRAINERS - THERMAL RADIATION EFFECTS ASSOCIATED WITH THE 19F4 FFT

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ABSTRACT

This report presents an analysis of the thermal radiation produced by flames from the U.S. Navy 19F4 Fire Fighter Training facility. The 19F4 facility is used to simulate airplane crash fires on aircraft carrier flight decks and aircraft carrying ships. A simple methodology for calculating radiative heat transfer to targets is developed from a review of available literature. Of particular importance is the influence of wind on flame size and shape, the calculation procedure accounts for this effect. The radiation heat fluxes at various distances from the trainer are presented in the form of graphs. The fluxes received by a crane and the 19F4 instructor's tower adjacent to the facility are calculated and shown to be substantial under certain conditions. Recommendations for placement of the crane and the instructor's tower are provided.

Key words: aircraft carriers; aircraft carrying ships; aircraft fires; crash fires; fire fighting training; flame height; flame radiation; radiation heat flux; radiative heat transfer; thermal radiation; training devices; wind effects

1. INTRODUCTION

The U.S. Navy Training Systems Center is engaged in the design and construction of several fire fighter training facilities in various areas of the country. These facilities include many different buildings and other structures designed to simulate various problems which may be encountered by Navy fire fighters. This report describes results of an analysis of one training structure. The structure is designated 19F4. The 19F4 structure is designed to simulate crashed aircraft fires on the flight decks of both an aircraft carrier and a helicopter equipped surface ship. It consists of an open training deck measuring 112 ft by 66 ft. A metal grate, 52 ft by 36 ft, is located in the center of the training deck. The grating forms the floor of the training deck in this area and is used to cover the "fireplace". The "fireplace" is the source of the training fires. The remaining bounding areas of the training deck are constructed of concrete. In addition to real and mock-up fire fighting equipment located on the training deck, a crane with a thermal radiation shield is provided immediately adjacent to the "fireplace". A two story instructor's station is located approximately 50 ft from a corner of the "fireplace" [1][1]. The burners located 4 ft below the deck must produce flames 16 ft in height (12 ft above the metal deck). A plan view of the 19F4 training facility is shown in figure 1. Figure 2 presents an elevation view of the trainer including the crane.

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[1] Numbers in brackets refer to literature references at the end of this report.

This report analyzes the potential thermal radiation exposures associated with operation of the 19F4 facility. A simple methodology for calculating the radiant heat transfer from large open fires to target objects is developed from a review of the available research into flame radiation. This calculation procedure is used to estimate the radiation heat flux at various distances from the trainer. The thermal radiation reaching the instructor's tower and the crane (and its radiation shield) and the resulting temperature increases are of particular concern. The radiation fluxes to these objects are specifically identified and compared to available measures of radiation hazard. Finally, recommendations for minimizing the effect of thermal radiation on these structures are presented.

The amount of radiant energy received by an object exposed to an open flame is influenced by a number of factors. These factors include: the flame size and shape, the flame emissive power, the transmissivity of the atmosphere, and the flame to target geometry. To the extent possible, values for these factors are calculated from the conditions associated with the 19F4. At the time of this analysis, the design of the 19F4 "fireplace" burner(s) has not been completed. In order to carry out this analysis, an important assumption must be made concerning the flames produced by this "fireplace". The burner or burners must produce buoyancy driven, turbulent flames. These are the type of flames that would be produced by a burning hydrocarbon pool. The properties of the flames are of fundamental importance in the determination of flame heights.

2. SOLUTION METHODOLOGY

The general procedure for computing the radiant flux to a target surface outside a fire involves a series of calculations. The steps are as follows:

(1) calculate the flame shape, usually defined by centerline length and angle of inclination,

(2) calculate the flame emissivity,

(3) calculate the transmissivity of the atmosphere,

(4) calculate the geometric view factor of the target surface relative to the assumed flame shape, and finally,

(5) calculate the radiant flux incident on the target surface.

2.1 Radiation Flux

The radiation flux, $\dot{q}''$, incident on any target of interest located at some distance from a flame can be expressed by the general formula

$$\dot{q}'' = \tau \ F \ \epsilon \ \sigma \ T_f^4 \tag{1}$$

The emissivity, ϵ, accounts for the fact that the flame is a gray emitter, i.e. not an ideal black body radiator. The flame emissivity is a combination of the emissivities of several combustion products (soot, water vapor, and carbon dioxide). Calculation of this combined emissivity is extremely difficult. In addition, the emissivity depends on the path length through the fire.

For the purposes of this analysis, the flame emissivity, ϵ, will be assumed to be 1. An optically thick flame that radiates as a black body would have an emissivity of one. Since the emissivity will vary depending on the trainer test conditions, an emissivity value of unity represents a worst case and thus is the most appropriate choice for a safety analysis.

The transmissivity of the atmosphere, τ, reflects the fact that radiant energy from a flame is only partially transmitted by the atmosphere due to the presence of water vapor. The magnitude of the transmissivity depends on the spectral distribution of the flame radiation, on the length of the path to the target, and on the composition of the atmosphere, including especially the absolute humidity. While some data on transmissivity is available in the literature, a value of 1 (representing a clean, dry atmosphere) will be assumed for this analysis. Once again, this will simplify the calculations and provide results representative of the worst case situation.

The radiation "view factor", F, between a fire and a target element outside of the fire depends on the flame's shape, the relative distance between the fire and the receiving element, and the relative orientation of the element. In order to facilitate computation of the radiative flux at a target, a regular shape must be assumed for the flame, such as a parallelpiped or cylinder. The dimensions and angle of inclination of the shape are chosen to approximate the base area, the flame length, and the wind induced flame angle of tilt.

The radiation temperature, T_f, of the flame is a difficult quantity to measure. However, the radiative power output from fires using propane or similar fuels has been studied and measured by several researchers [2,3,4]. The radiative power output per unit flame surface area is related to the radiation flame temperature according to the expression

$$\dot{E}_r'' = \epsilon \sigma T_f^4 \tag{2}$$

Research by Markstein [2] on propane turbulent diffusion flames has shown a linear relationship between the radiative power output of the fire and the total fire heat release rate. Values for this ratio determined by Markstein experimentally range from 0.238 to 0.264. Markstein's results [2] were obtained using small scale tests (fuel flow rates between 1.16 and 19.3 $in.^3/s$ and burner diameters from 3.7 in. to 7.9 in.). Hägglund and Persson [3] obtained similar results using square JP-4 pools ranging in size from 3.3 ft to 32.8 ft. Their results indicate that the percentage of fire energy released as radiation decreases with increasing fire size. Specifically, for the 3.3 ft square fire, 39 percent of the total energy generated by the fire was released by radiation. This ratio decreased to 10 percent for the 32.8 ft square fire [3].

For an arbitrary flame shape, this relationship may be expressed as

$$\dot{E}_r'' = \chi \Delta H_c \dot{m}'' A_{fire}/A_{flame\ surface} \tag{3}$$

In equation (3), the quantity A_{fire} refers to the area involved in the fire, and the quantity $A_{flame\ surface}$ is the surface area of the flames. Implicit in this equation is the assumption that the radiative intensity is constant over the surface of the flame. If the fire is assumed to be shaped like a cylinder, A_{fire} would be the area of the base of the cylinder while $A_{flame\ surface}$ would be the surface area of the cylinder plus the area of its top and bottom. Since the exact 19F4 burner geometry is not known, radiation to and/or from the top and bottom areas of the flame will be ignored. This will provide a worst case scenario. The effect of assuming different radiation fractions, χ, will be analyzed later in this report.

Combining equations (2) and (3) yields:

$$\dot{E}'' = \epsilon\ \sigma\ T_f^4 = \chi\ \Delta H_c\ \dot{m}''\ A_{fire}/A_{flame\ surface} \tag{4}$$

This equation expresses the radiative power output from the fire in terms of either the radiation flame temperature or the total fire energy generation rate.

Substituting equation (2) into equation (1) yields:

$$\dot{q}'' = \tau\ F\ \dot{E}_r'' \tag{5}$$

With the assumption of unity for atmospheric transmissivity and using equation (3), this equation reduces to

$$\dot{q}'' = F\ \chi\ \Delta H_c\ \dot{m}''\ A_{fire}/A_{flame\ surface} \tag{6}$$

or

$$\dot{q}'' = F\ \chi\ \Delta H_c\ \dot{V}\ \rho_v/(\pi\ d\ L) \tag{7}$$

where $\dot{V}$ - volume flow rate of fuel,

ρ_v - density of fuel vapors,

d - diameter of the fire area, and

L - height of the flames.

Equation (7) is appropriate when the flame shape is assumed to be a cylinder and the volume flow rate of fuel is known. Equation (6) and its alternative formulation, equation (7), form the basis for the rest of the analysis presented in this paper.

Using the middle and right-hand parts of equation (4), it is possible to obtain the following expression for flame temperature:

$$T_f = \left[\frac{\chi\ \Delta H_c\ \dot{m}''\ A_{fire}}{\epsilon\ \sigma\ A_{flame\ surface}} \right]^{1/4} \tag{8}$$

Equation (8) can be used to evaluate the validity of the assumed flame shape and equation (6). For a parallelpiped flame shape, equation (8) becomes

$$T_f = \left[\frac{\chi \, \Delta H_c \, \dot{V} \, \rho_v}{\epsilon \, \sigma \, 2 \, (x + y) \, L} \right]^{1/4} \tag{9}$$

where L - height of the parallelpiped,

x - length of one side of the parallelpiped (parallel to the ground), and

y - length of adjacent side of the parallelpiped.

Equation (8) for a cylindrical flame shape would be

$$T_f = \left[\frac{\chi \, \Delta H_c \, \dot{V} \, \rho_v}{\epsilon \, \sigma \, \pi \, d \, L} \right]^{1/4} \tag{10}$$

where d - diameter of the cylinder base and

L - height of the cylinder.

(The top and bottom of the parallelpiped and the cylinder have been ignored in calculating the $A_{flame\ surface}$ quantities used in equations (9) and (10).)

Using the data for propane from Table 1, a fuel flow rate of 27.5 ft^3/s (1650 ft^3/min), a flame height of 12 ft, and rectangular base dimensions of 52 ft by 36 ft, equation (9) yields a flame temperature of 2061 R. For a fire assumed to be shaped like a cylinder with a base diameter of 50 ft, the flame temperature calculated using equation (10) is 2121 R. Researchers studying radiation from flames generated by burning propane and/or polymethyl-methacrylate (PMMA) have quoted radiation flame temperatures in the range 1800

R to 2500 R [2,5,6,7]. Specifically, Orloff [6] has determined an average flame temperature of 2270 R for PMMA burning at the rate of 0.003 lb_m/ft^2 s. Using equation (8), a conical flame shape, and Orloff's data [6], the flame temperature is estimated to be 2259 R. The details of how this flame temperature was calculated from Orloff's data [6] are shown in Appendix A. The flame temperature values calculated here using various flame shapes agree quite well with the quoted values. This indicates that equation (6) and its alternative formulations are valid for use in this analysis.

2.2 Configuration Factor

The configuration or view factor represents the fraction of energy emitted from a surface that is incident on some receiving body. View factors depend on the size and shape of the source and the distance between the source and the target. A flame is a hot, luminous mass of burning gas which does not have a defined surface. The flame shape and size vary considerably during burning because of turbulence. Fortunately, fluctuations in the instantaneous flame geometry usually average out to a relatively constant value for a given fire over some period of time. In order to calculate view factors for flames, it is necessary to assume that the flame has some average shape and size.

The flame shape can be approximated as either a plane rectangular radiator or as a cylindrical radiator. Due to differences in configuration factors, a plane radiator yields a higher heat flux value than a cylindrical one. Reference [5] suggests that, in general, the cylindrical radiator assumption agrees more closely with experimental data than does a plane radiator. Using the cylindrical geometry, the target location relative to the source is not as important. The effect of using different flame shapes for calculating view factors will be analyzed later in this report.

When the exposure fire is not circular, the diameter of an equivalent circular area or the longest dimension of the rectangle may be used to calculate the view factor. Using the larger of these two dimensions will produce conservative results, i.e., higher heat flux values at a given distance.

2.2.1 Flame Height

For a fire having a specified diameter, d, it is necessary to know the flame height and the angle of inclination of the flame before a view factor can be computed. Numerous investigators [8,9,10,11,12,13] have studied the relationship between fire diameter, energy release rate, and flame height. The flame height is generally defined as the height at which the flame is observed at or above that height 50% of the time. Several methods have been used to determine flame heights during fire tests. Visual observation tends to yield slight overestimates of flame heights. Video tape analysis or averaging a number of one-second-exposure photographs appear to yield acceptable results [14].

For buoyancy driven turbulent flames, there is general agreement among researchers that flame height is proportional to the rate of heat release to the two-fifths power divided by the diameter of the fire source. However, the recommended constant of proportionality for this relationship varies between 0.18 and 0.23. The reader is referred to reference [14] for an excellent summary of available flame height correlations. In addition, reference [14] provides several general recommendations concerning calculation of flame heights.

Heskestad [9] has correlated data from a wide variety of sources, including pool fires using the equation

$$L = 0.23\ \dot{q}_c^{2/5} - 1.02d \tag{11}$$

The rate of energy generation by the fire, $\dot{q}_c$, may be related to its mass loss rate per unit fire area, $\dot{m}''$, according to

$$\dot{q}_c = \dot{m}''\ \Delta H_c\ A_f \tag{12}$$

Using equation (12), equation (11) becomes

$$L = 0.23\ (\dot{m}''\ \Delta H_c\ A_f)^{2/5} - 1.02d \tag{13}$$

The correlation has been shown to be very satisfactory, although it has not been tested outside the range $7 < \dot{q}_c^{2/5}/d < 700\ kW^{2/5}/m$. Zukoski et al. [15] comment that for values of $L/d < 1$, the flame breaks up into a number of small flamlets which are apparently independent. Such behavior has been observed in very large mass fires [16].

Figures 3 and 4 relate burner diameter to mass flow rate of fuel for 16 foot flame heights using equation (13). The 19F4 will operate using flames 16 ft high (12 ft above the deck). Equation (13) indicates that 16 foot high flames would be obtained at a fuel flow rate of 1650 ft^3/min (19F4 specification) in a burn area 46 ft in diameter. The Navy test facility is specified to have a rectangular burn area 36 ft by 52 ft. So, this fuel flow rate is adequate for the test area based on analysis using the Heskestad equation.

A burning pool of hydrocarbon fuel would produce buoyancy driven flames. The upward velocity of these flames is driven by the density difference between the hot gases making up the flames and the ambient air. The fuel has no initial upward velocity. The flame height calculations discussed here assume that the flames are turbulent and buoyancy driven. The 19F4 training fires will be generated using a combination of several burners. If these burners are to simulate a pool fire, they must produce buoyancy driven flames. A burner design which will provide for immediate dissipation of the fuel velocity as it exits the burner should be developed. If it is assumed that each burner will produce a 16 foot high flame (12 ft above the grate), figures 3 and 4 together with equation (13) may be used to estimate the number of burners and their diameters required to produce turbulent, buoyancy driven flames. Equation (13) may be used to estimate similar results for flames of any assumed height. If the fuel has substantial velocity as it exits the burner, these flame height calculations will not be valid.

2.2.2 Wind Effects

The previous discussion relates to calculation of flame heights with no wind. The wind will influence the size and shape of flames. The flames will bend away from the wind and either elongate or shorten depending on the wind speed. Based on data obtained from experiments using wood cribs, Thomas [8] developed a correlation for determining flame lengths in the presence of wind. The correlation is

$$\frac{L}{d} = 55 \left[\frac{\dot{m}''}{\rho_a \sqrt{gd}} \right]^{0.67} \left[u^* \right]^{-0.21} \tag{14}$$

where u^* is the nondimensional wind velocity given by

$$u^* = \frac{u_w}{\left[\frac{g\ \dot{m}''\ d}{\rho_v} \right]^{1/3}} \tag{15}$$

The wind induced angle of tilt of the flame from the vertical can be predicted from the correlation of Welker and Sliepcevich [17]. This correlation was derived by making a fundamental momentum balance on the flame which is assumed to behave as a tethered balloon. The correlation was compared to experimental data obtained using fires ranging from 4 inches to more than 100 ft in diameter. The correlation equation fits the data very well. The flame angle, θ, as measured from the vertical, is given by

$$\frac{\tan\theta}{\cos\theta} = 3.3 \left[\frac{d\, u_w}{\nu_a}\right]^{0.07} \left[\frac{u_w^2}{gd}\right]^{0.8} \left[\frac{\rho_v}{\rho_a}\right]^{-0.6} \qquad (16)$$

Equations (14), (15) and (16) may be used to characterize the size and shape of the flame in the presence of wind in order to calculate view factors.

2.2.3 Calculating View Factors

In general, the geometric view factor, F, in equation (1) can be obtained from

$$F_{dA_1-A_2} = \int_{A_2} (\cos\beta_1 \cos\beta_2)/(\pi r^2)\, dA_2 \qquad (17)$$

where dA_1 = target area, taken as a differential element

A_2 = effective emitting area of flame

r = distance from target element to flame element along a line from dA_1 to dA_2

β_1 = angle between the normal to dA_1 and the line from dA_1 to dA_2

β_2 = angle between the normal to dA_2 and the line from dA_1 to dA_2.

The geometry used for calculation of view factors is shown in figure 5. Equation (17) must be integrated over the effective emitting area of the flame, A_2, that can be seen by a differential element of the target, dA_1, to obtain the view factor. Textbooks and handbooks give algebraic solutions to equation (17) for particular geometries. In some books, the solutions are presented in the form of graphs.

In the solid flame model of radiation used in this analysis, the turbulent flame is approximated by a cylinder. Under conditions of no wind, the cylinder is vertical. In the presence of wind, the cylinder is assumed to be tilted. The two configurations are shown in figure 6. The algebraic solutions for horizontal and vertical view factors for a vertical cylinder are given by Raj and Kalelkar [18] and Sparrow [19] as:

$$F_H = \frac{1}{\pi}\left[\frac{(B - 1/S)}{B^2 - 1} \tan^{-1}\left[\frac{(B+1)(S-1)}{(B-1)(S+1)}\right]^{1/2} - \frac{(A - 1/S)}{A^2 - 1} \tan^{-1}\left[\frac{(A+1)(S-1)}{(A-1)(S+1)}\right]^{1/2}\right] \tag{18}$$

$$F_V = \frac{1}{\pi}\left[\frac{1}{S} \tan^{-1} \frac{h}{S^2 - 1} - \frac{h}{S}\left[\tan^{-1}\left[\frac{S-1}{S+1}\right]^{1/2}\right.\right.$$

$$- \frac{A}{A^2 - 1} \tan^{-1} \left[\frac{(A + 1)(S - 1)}{(A - 1)(S + 1)} \right]^{1/2} \Bigg] \Bigg] \qquad (19)$$

where $h = L/r_f$,

$S = r/r_f$,

$A = (h^2 + S^2 + 1)/(2S)$, and

$B = (1 + S^2)/(2S)$

The maximum view factor is the vectorial sum of the horizontal and vertical view factors

$$F_m = \sqrt{(F_H^2 + F_V^2)} \qquad (20)$$

However, for most cases of interest here, the horizontal view factor alone is used.

Rein et. al. [20] present graphs of view factors versus distance to target for cylinders tilted at various angles. The graphs were developed by numerically integrating equation (17). Mudan [21] presents an analytical solution to equation (17) for tilted cylinders based on work presented in reference [18]. A number of errors, presumably typographical, were found in the equations presented in reference [21]. Since the original source document [18] could not be obtained in the limited amount of time available for completion of this study, a numerical approach was used to calculate the tilted cylinder view factors. In the numerical approach, view factors are determined by dividing the cylinder into a number of incremental rectangular areas and summing the view factors for each of these small elemental areas.

The view factors for both vertical and tilted cylinder geometries approach similar values at large distances from the fire. As a check, view factors for vertical cylinders to targets oriented perpendicular to the ground were calculated using both the analytical solution and the numerical method. The results agreed to within one percent.

2.3 Computer Program for Calculating Radiation Heat Flux

In an effort to facilitate the computation of radiation heat flux values, the methodology described in the preceding sections was coded into a user-interactive computer program. The FORTRAN 77 source code is contained in Appendix B of this report. The program requires input data describing the fuel, the source and target geometries, and the wind speed. Specifically, the density of the fuel vapors and its heat of combustion must be specified. The fuel flow rate and the diameter of the fire area must also be provided. The height of the target and its angle of tilt relative to the ground are required. The flame emissivity, the transmissivity of the atmosphere, and the fraction of the fire energy release rate that is released as radiation are assumed to have values of 1. These values may be altered by the user, if desired. The program will calculate the radiation heat flux at any distance (up to a user-specified maximum) from the fire source for each user-specified wind speed (including no wind). The flame length, its angle of inclination, and the configuration factor are calculated for each wind speed. The computer program presented in the Appendix B was used to generate figures 7 through 11.

3. ANALYSIS OF 19F4 TRAINER RADIATION EFFECTS

The previously discussed results for flame geometry and configuration factors together with equation (6) were used to calculate the radiation flux values at various distances from the flame. In particular, the radiation flux to the instructor's tower and the crane were determined. The properties of propane and air used in this analysis are summarized in Tables 1 and 2, respectively.

In order to develop estimates of potential damage, the radiation heat flux levels produced during operation of the 19F4 must be related to those levels determined to cause structural damage and human injury. The radiation flux at which unprotected humans begin to feel pain is about 600 Btu/hr ft^2 [5,22]. Skin burns have been determined to occur at flux levels at or above 1500 Btu/hr ft^2 [4,5]. The threshold flux for equipment damage varies widely. In addition to the flux intensity, the minimum potentially damaging flux level strongly depends on the duration of the flux and the size (mass) of the structure. The ignition of wood, both piloted and spontaneous, has been the subject of extensive research. The radiation flux at which ordinary combustibles such as wood, paper, etc. will spontaneously ignite is estimated to be approximately 10000 Btu/hr ft^2 [4,5,23]. Piloted ignition of wood has been determined to occur at radiation heat flux levels as low as 4500 Btu/hr ft^2 [5,24]. Reference [25] recommends a maximum allowable radiation heat flux exposure for equipment of 3000 Btu/hr ft^2.

Figure 7 presents results showing the flame length extension due to wind effects. The calculations presented in figures 7, 8, and 9 are based on a cylindrical flame shape with a diameter of 52 ft and a height of 12 ft. Initially at lower wind speeds, the flame length increases due to the "stretching" effect produced as the wind passes over the flame. At moderate wind speeds, the flame length will decrease below its value for the no-wind condition (12 ft). This phenomena has been observed experimentally by Thomas [8]. He suggests that the flame length decrease may result from locally improved mixing and better combustion efficiency. The variation of the flame angle of tilt with increasing wind speed is shown in figure 8. As the wind speed increases, the flame bends more and more away from the wind. Figure 9 shows the variation of the height of the flame tip above the deck with wind speed. This value is calculated by multiplying the flame length by the sine of its angle of inclination at any given wind speed.

The variation of the radiation flux with distance from the centerline of the flame due to wind effects is shown in figures 10 and 11. Again, the results presented in figures 10 and 11 are based on a cylindrical geometry with a diameter of 52 ft and a height of 12 ft. The radiation flux values presented are appropriate for use in estimating the potential hazard to targets located at least 26 ft away from the burner centerline. The results presented in these figures assume that 100 percent of the energy produced by the fire is radiated. This would correspond to assuming χ in equation (6) is equal to one. For propane flowing at the rate of 27.5 ft^3/s, the total energy released at any given time is 60390 Btu/s.

In actual practice as described earlier, the amount of energy radiated by flames will vary depending on the test conditions (smoke blockage, fuel type, etc.). Usually, it will be substantially less than 100 percent. To adjust figures 10 and 11 for a χ value other than one, simply multiply the heat flux scale (vertical scale) by the assumed χ value. Regardless of the assumed radiation fraction, the general trend of the results will be the same.

As the wind speed increases, the radiation flux at distances close to the fire increases. At some point (approximately 45 ft from the centerline of the fire in this analysis), this trend reverses. Increasing wind speed decreases the radiation flux. At distances less than about 45 ft from the burner centerline, the maximum radiation flux is obtained at a wind speed of about 5 mph. At wind speeds above 5 mph, the calculated radiation flux begins to decrease. Eventually, the wind influenced radiation flux values fall below the corresponding no wind values.

Initially at low wind speeds, the flame bends and its length increases. This increases the view factor and results in higher radiation flux values. As the wind speed increases, the flames continue to bend; however, they also shorten. While this does place the flame tip closer to a particular target, it decreases the projected area of the flame as viewed from the target. This in turn decreases the amount of radiation received by the target object. The Navy fire fighter training facilities will be located in several regions of the country. The influence of the wind speed and direction on the radiation flux levels produced is very important. The layout of each training facility must be based on an analysis of the prevailing conditions in the area in which it is located. A generic site layout valid for all locations cannot and should not be provided.

The instructor's tower will be located approximately 80 ft from the burner centerline (50 ft (15.2 m) from the edge). At this location and assuming a value of 0.4 (40 percent) for χ, the radiation flux, from figure 11, is between 700 and 2200 Btu/hr ft^2 (0.4 × 5500 Btu/hr ft^2 for 5 mph wind condition) depending on the wind speed. According to references [2] and [3], forty percent radiation was the maximum amount measured for propane flames. It is interesting to note that wind speeds, in the direction of the instructor's tower in excess of 25 mph, keep the radiation flux below 1200 Btu/hr ft^2. This phenomena reflects the importance of configuration factors. As the wind speed increases, the instructor's tower is able to "see" less of the flame surface. The flux levels at wind speeds less than 25 mph are at or above the pain threshold and would be dangerous for unprotected humans. The effects on buildings and other structures may also be significant.

Current Navy specifications [1] would place the crane shield 22.5 ft away from the burner centerline or 4.5 ft from the edge of the fireplace (figure 2). In turn, the crane centerline would be 3 ft from the radiation shield. Using the cylindrical radiator assumption with a diameter equal to either the longest dimension or the equivalent circle diameter locates the crane shield within the fire area. In this case, the parallelpiped shape would be a more appropriate representation of the flame to target (the crane and its shield) geometry. If the fire area is assumed to have a rectangular base with dimensions of 52 ft by 36 ft and the flames are 12 ft high, the heat flux reaching the crane shield would be approximately 19000 Btu/hr ft^2 assuming the fire radiates 40 percent of its total energy release. This flux is over six times the maximum amount recommended for equipment exposure [25]. The radiation enhancement produced by the wind will be an even more important consideration in the development of protection for the crane. When the wind is blowing in the direction of the crane and shield, it may force the flame into contact with the crane shield. This will greatly increase the thermal exposure to the crane shield and ultimately to the crane itself.

4. SUMMARY

Most of the results from this analysis of the radiation effects of the 19F4 have been presented in the form of graphs. These graphs may be used to determine the radiation fluxes at locations and for conditions not explicitly mentioned in this study. The target objects of primary concern are the instructor's tower and the facility crane. The analysis (assuming $\chi = 0.4$) indicates that the instructor's tower will be exposed to a radiation flux of between 700 and 2200 Btu/hr ft^2. The crane radiation shield could receive a radiation flux in excess of 19000 Btu/hr ft^2. In fact, the hot gases of the flame may impinge on the crane shield, increasing the heat transfer and the resulting total heat flux to the crane.

The specifications [1] for the design of the 19F4 trainer state that the trainer shall not be operated when the prevailing winds are in the direction of the crane. Even in the presence of no wind, the crane radiation shield will be subjected to a substantial radiation heat flux. The resulting effect on the crane itself will depend on the effectiveness of the crane shield. This radiation shield must be capable of withstanding large radiation heat fluxes and direct flame impingement. If possible, the trainer should only be operated when there is a wind blowing away from the crane. In addition, the instructor's tower should be located in the same general direction as the crane. When the wind is blowing away from the crane, it will also be blowing away from the instructor's tower. This will minimize the radiation fluxes to both structures.

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TABLE 1. Properties of Propane

ΔH_c	$= 20000\ Btu/lb_m$
ρ_v	$= 0.1098\ lb_m/ft^3$

TABLE 2. Properties of Ambient Air

k	$= 0.015\ Btu/hr\ ft\ °F$
c_p	$= 0.24\ Btu/lb_m\ °F$
ρ_a	$= 0.06867\ lb_m/ft^3$
ν_a	$= 1.6878 \times 10^{-4}\ ft^2/s$

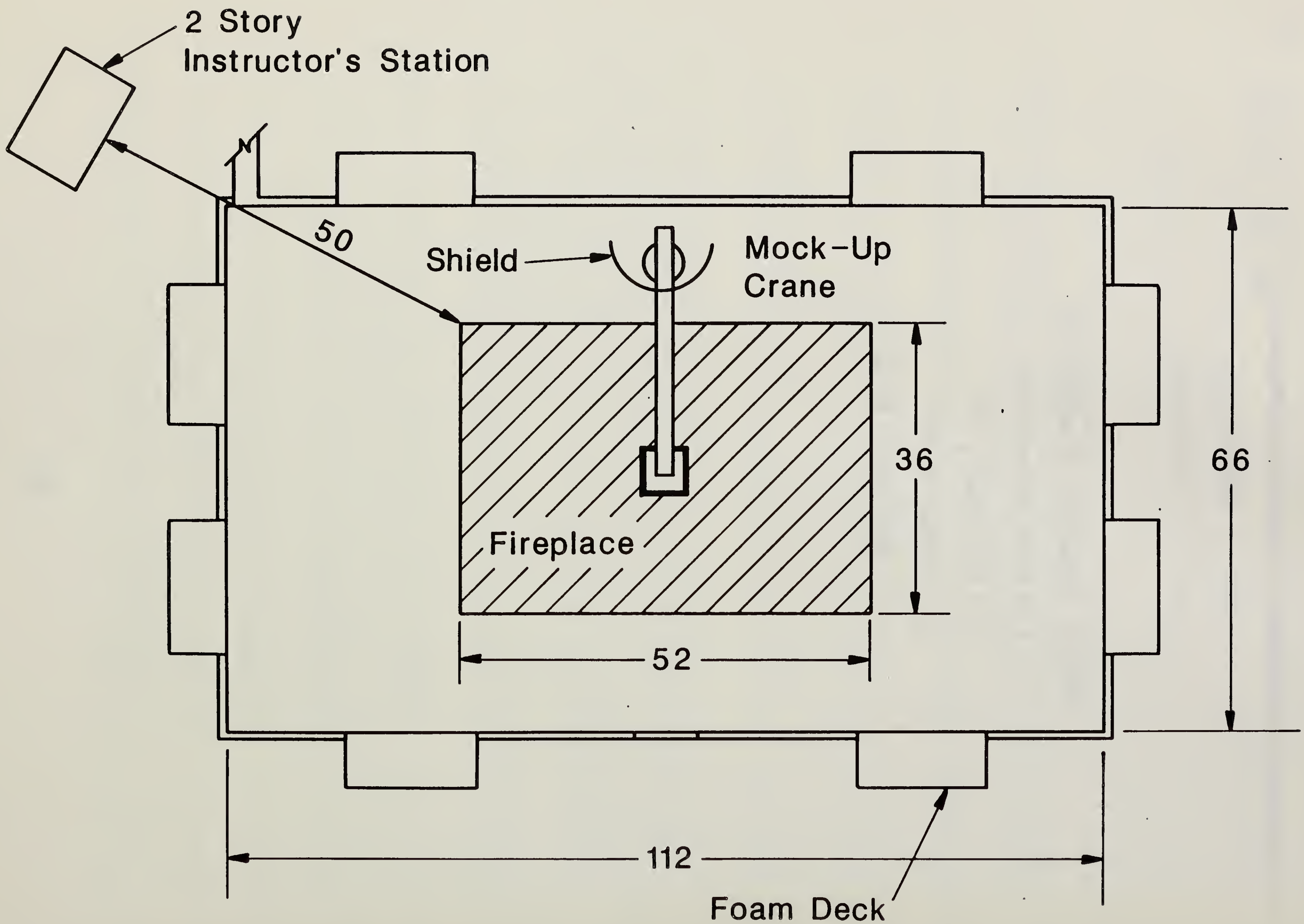

Figure 1. Plan view of 19F4 trainer facility (all dimensions in feet)

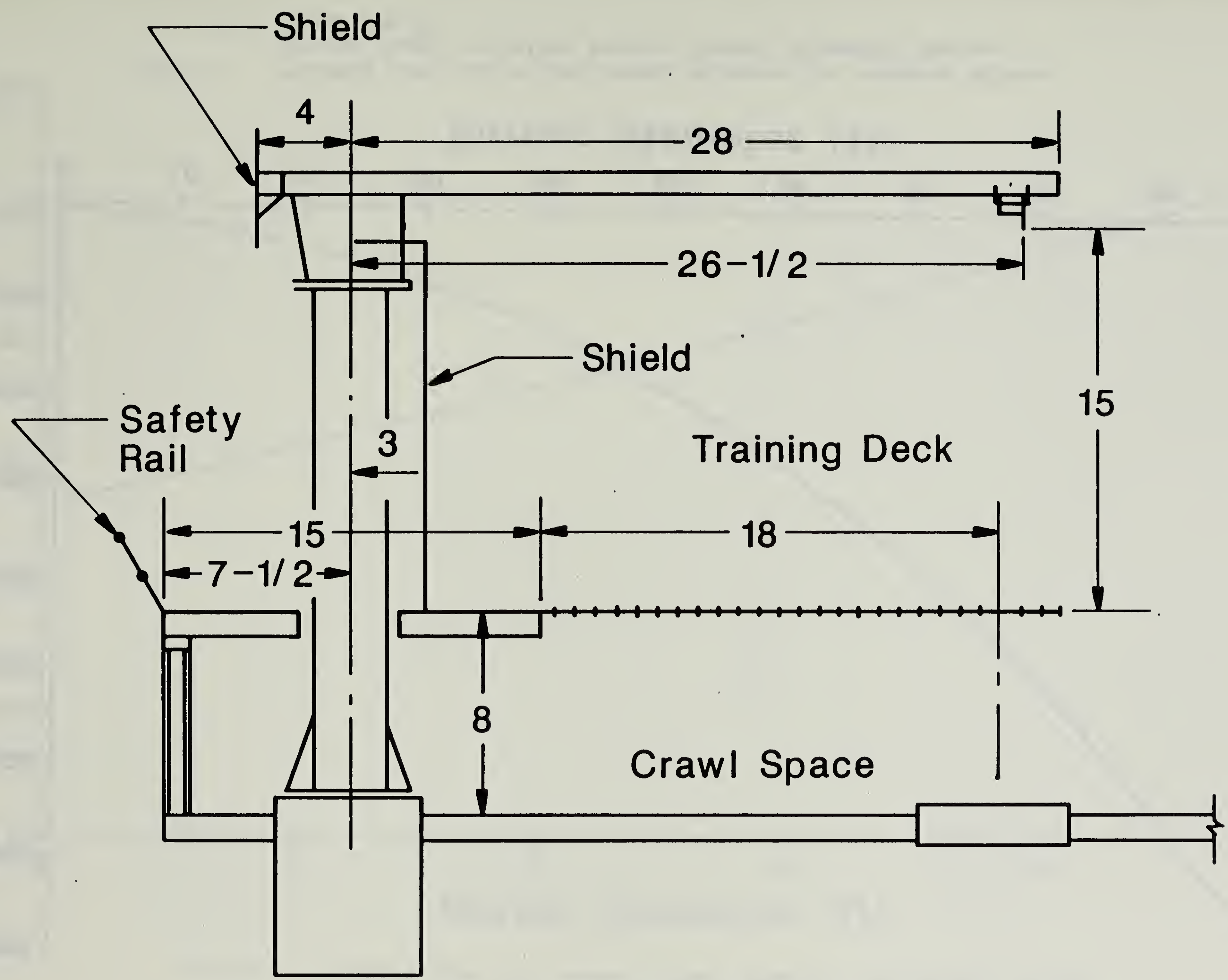

Figure 2. Elevation view of 19F4 trainer facility (all dimensions in feet)

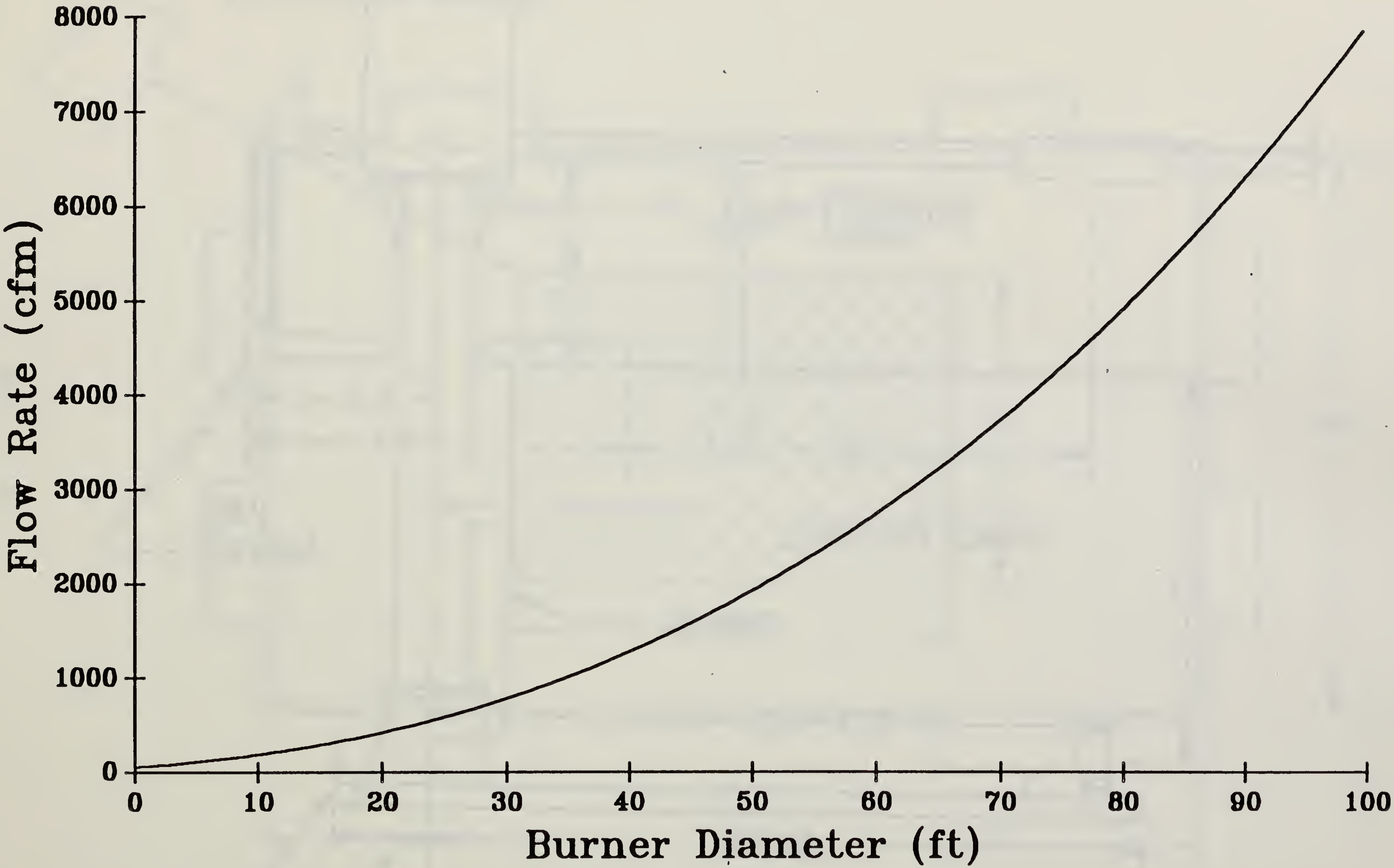

Figure 3. Maximum flow rate versus burner diameter for buoyancy driven, 16 foot high, turbulent propane flames (diameters between 0 and 100 ft)

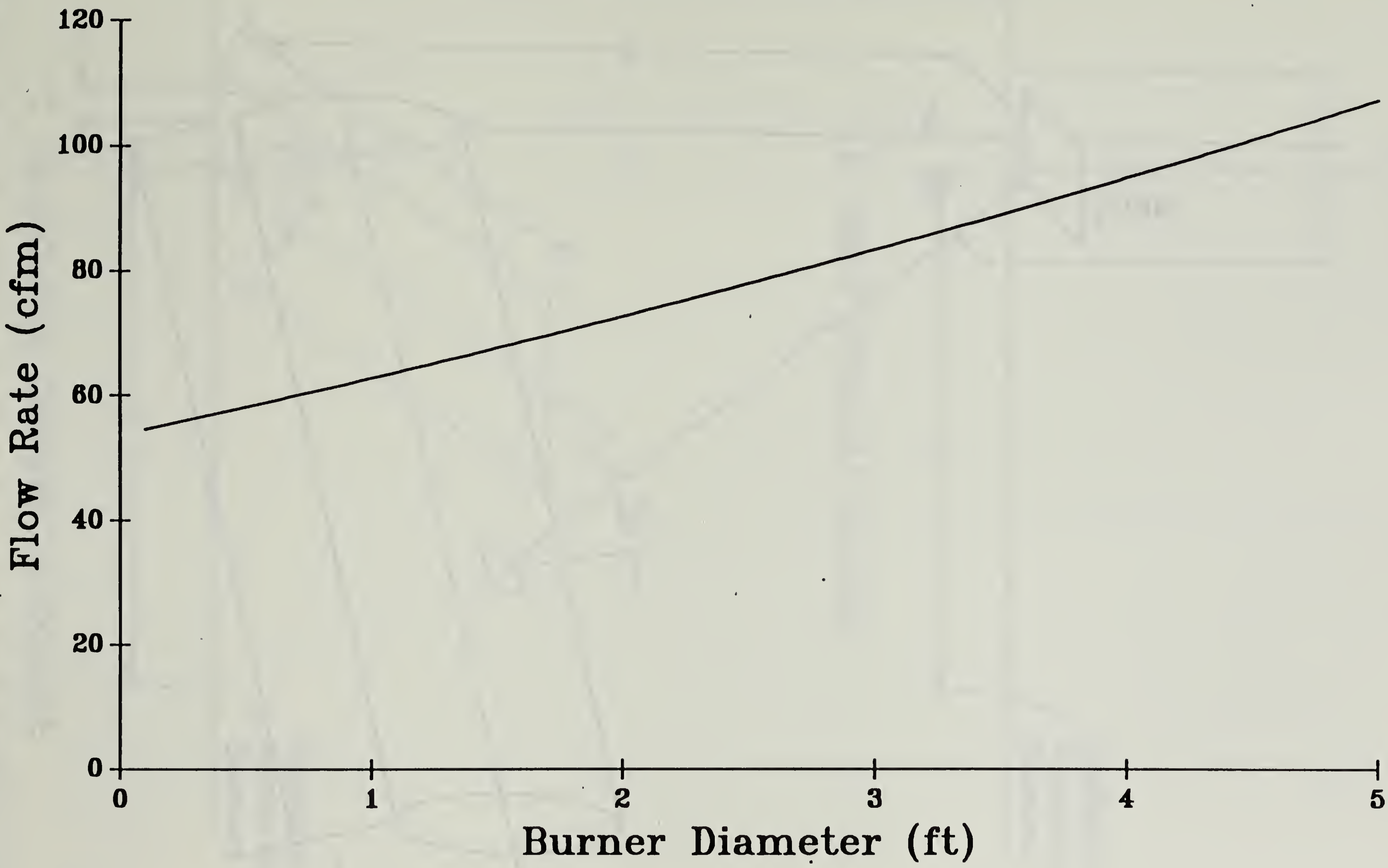

Figure 4. Maximum flow rate versus burner diameter for buoyancy driven, 16 foot high, turbulent propane flames (diameters between 0 and 5 ft)

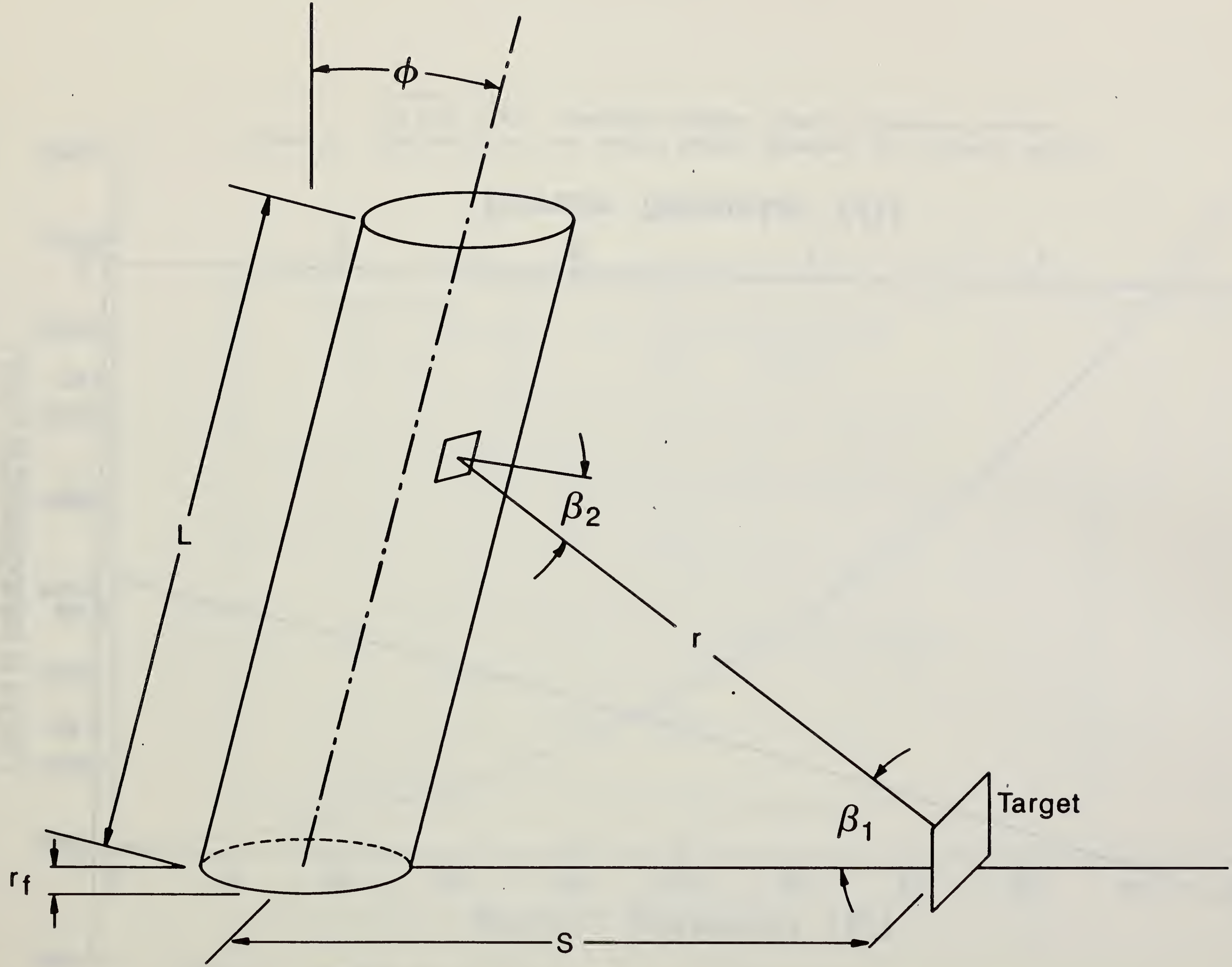

Figure 5. Geometry used for calculation of view factors

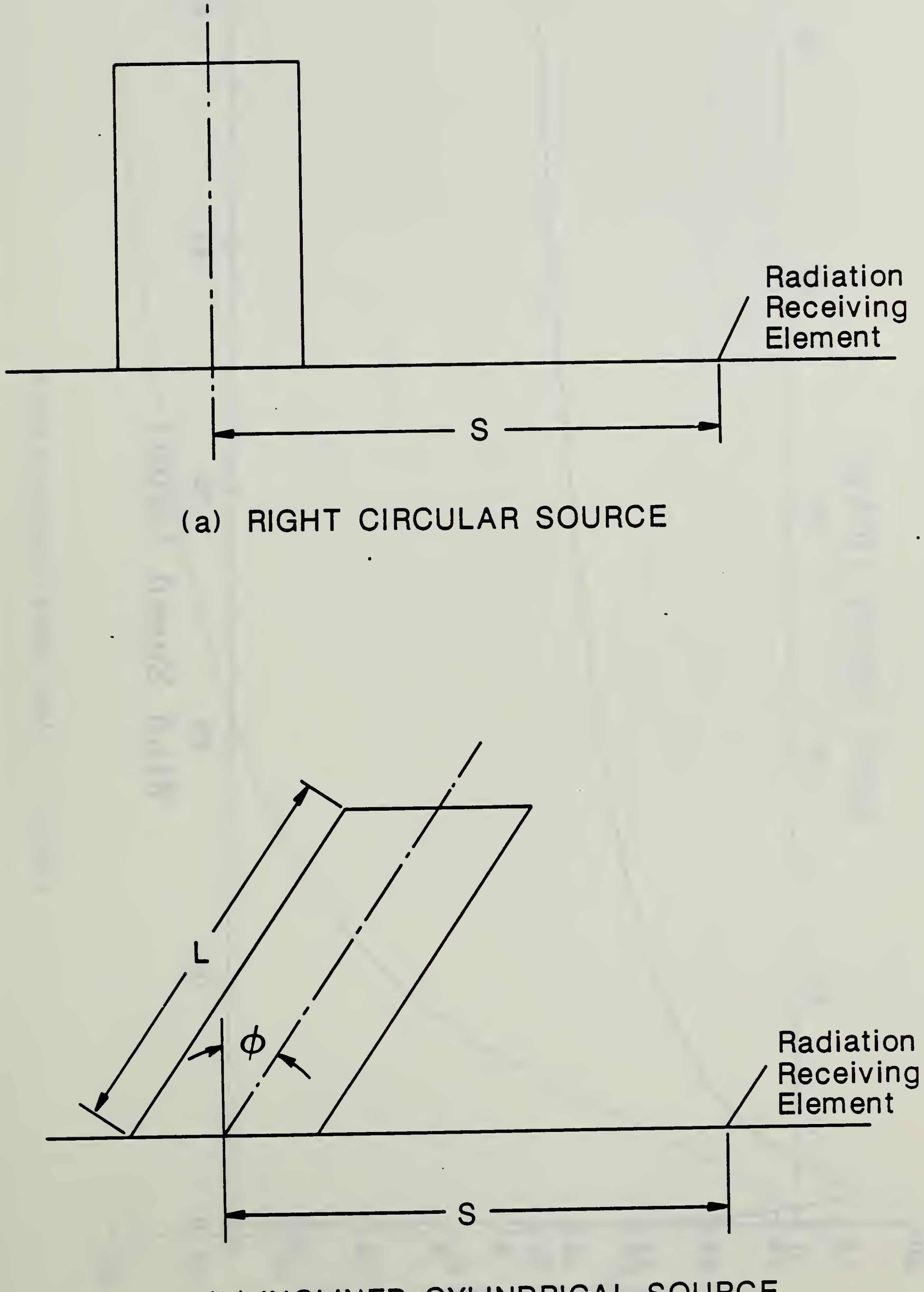

Figure 6. Geometric configuration for calculating view factors for right circular and inclined cylindrical sources

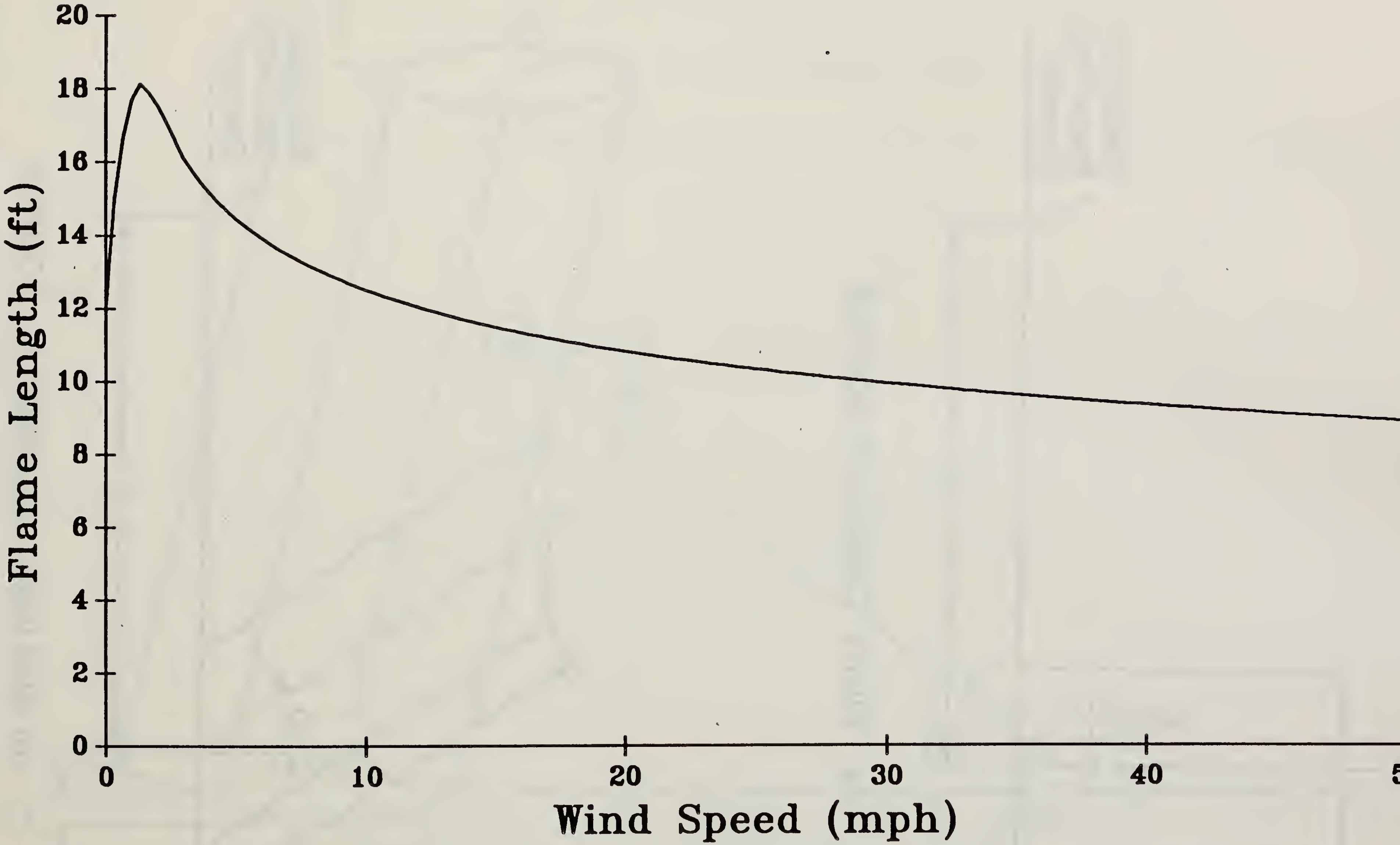

Figure 7. Flame length versus wind speed

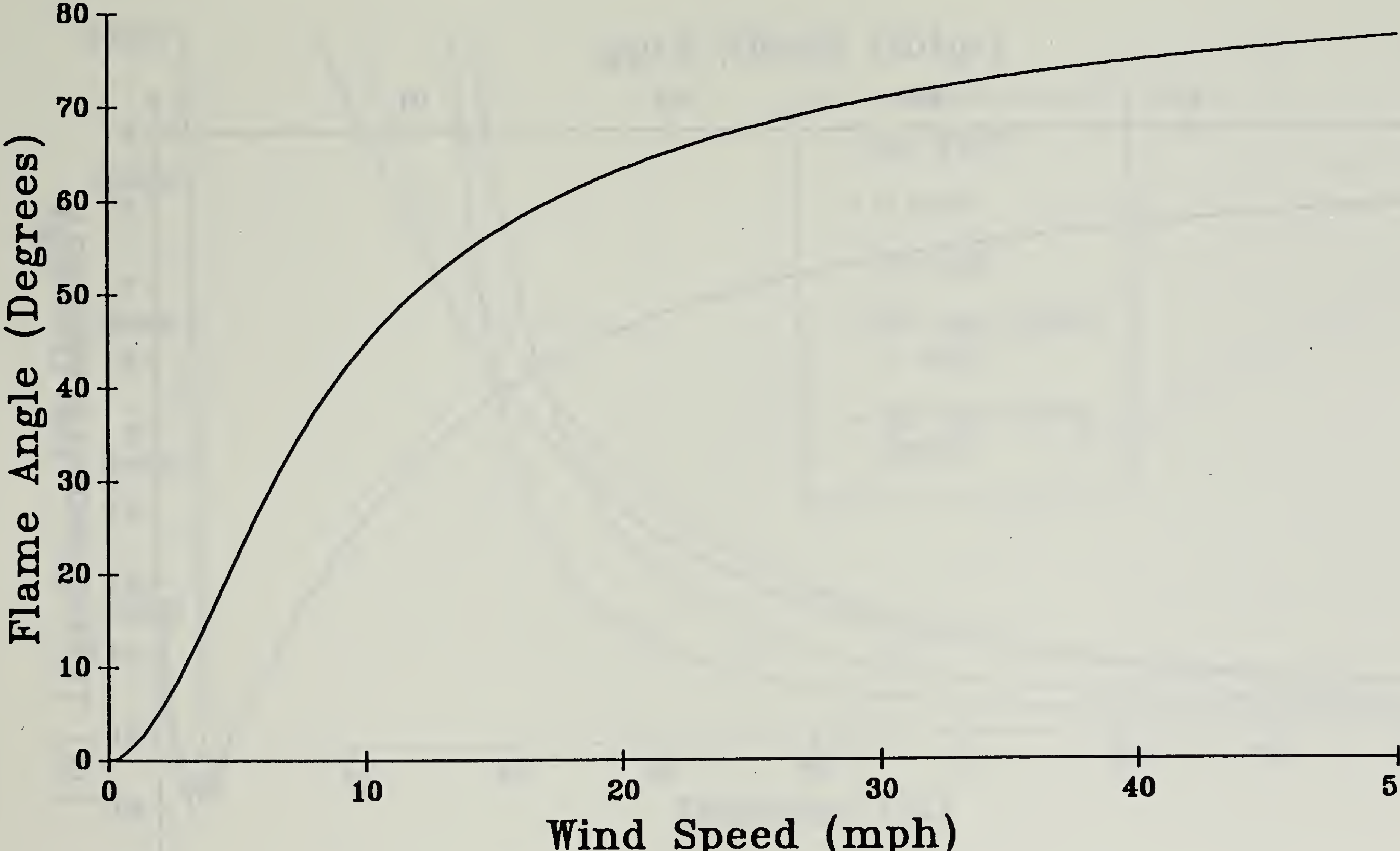

Figure 8. Flame angle of tilt versus wind speed

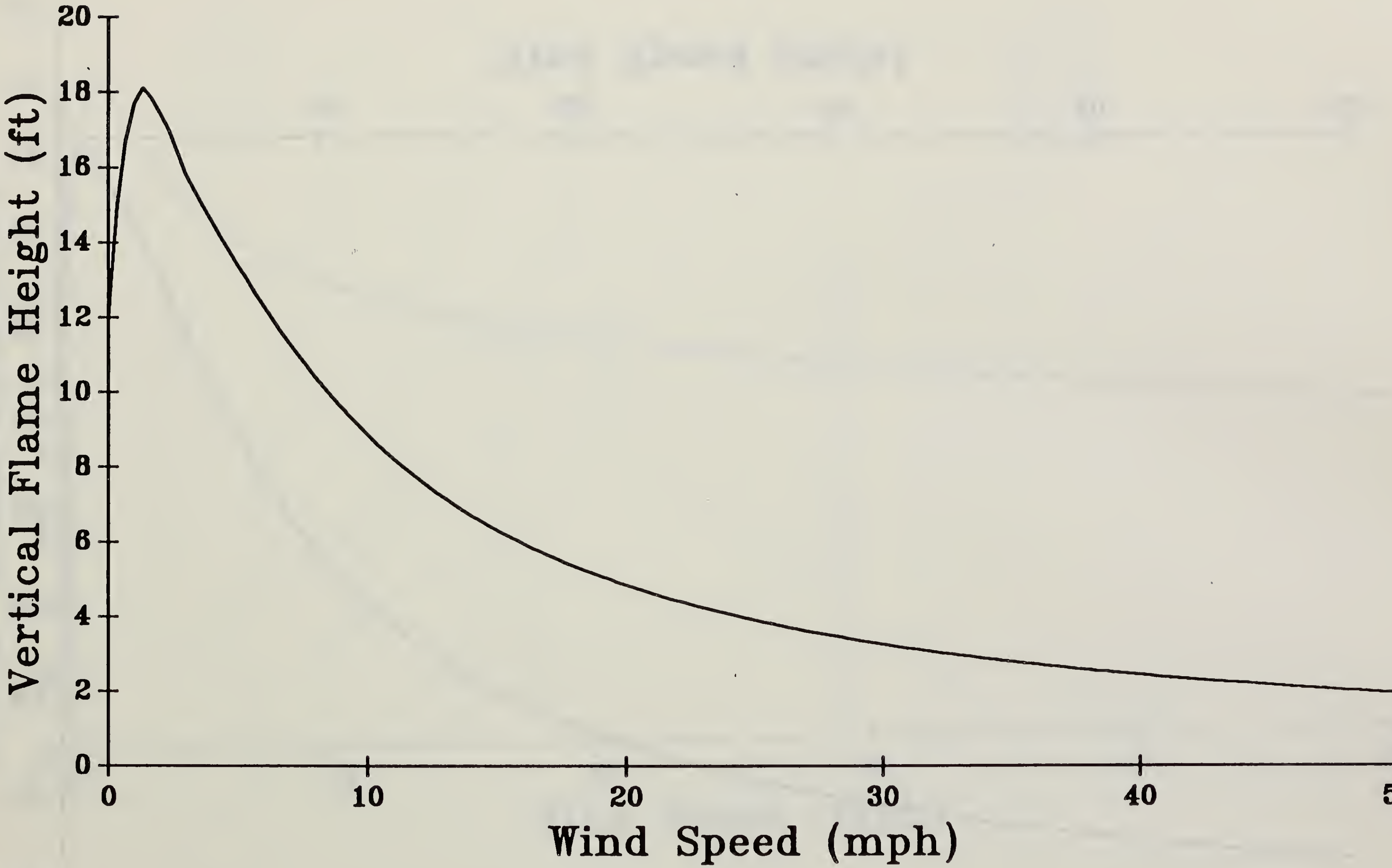

Figure 9. Flame height above horizontal versus wind speed

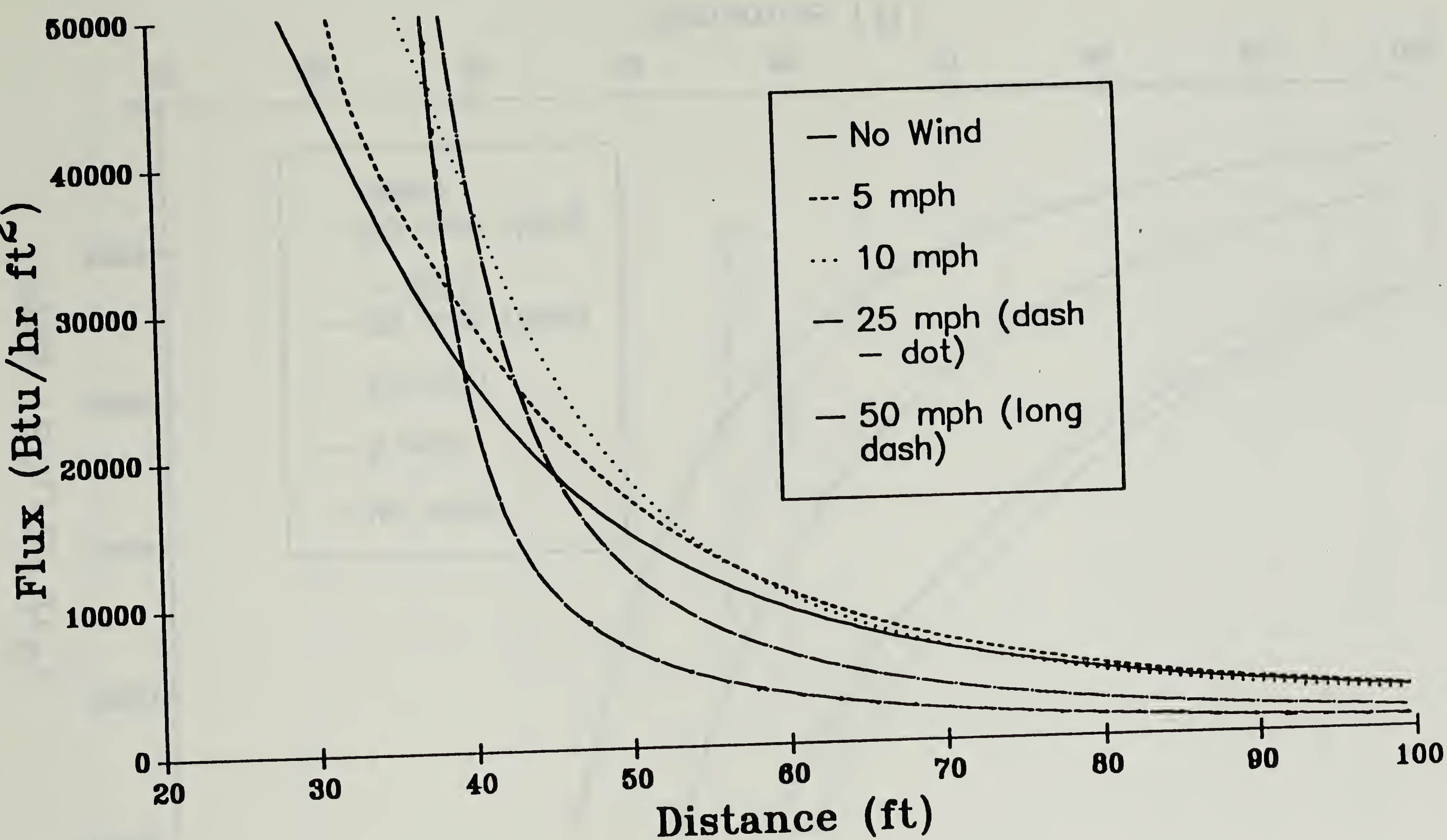

Figure 10. Radiation flux versus distance from burner centerline for wind speeds of 0, 5, 10, 25, and 50 mph

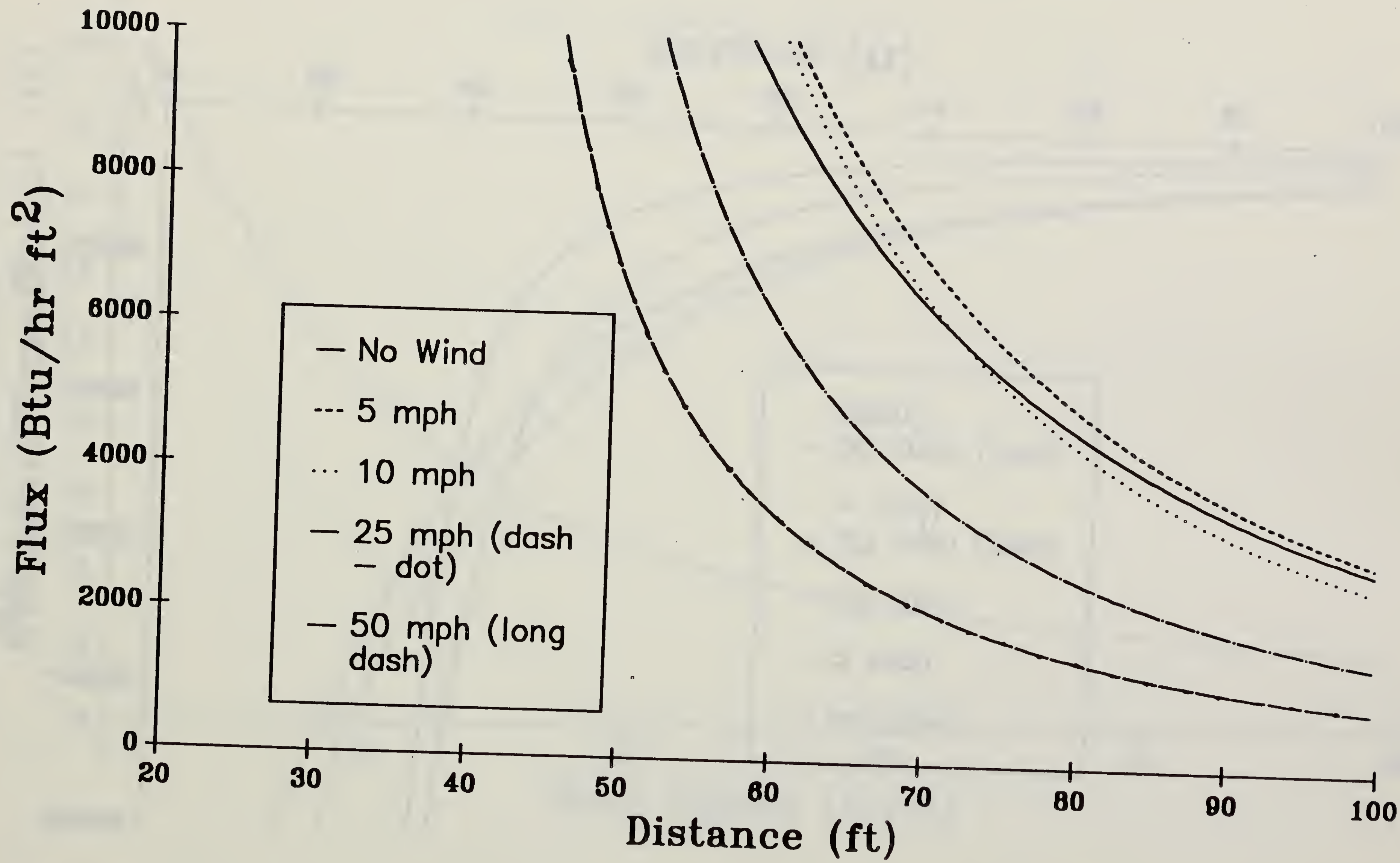

Figure 11. Radiation flux versus distance from burner centerline for wind speeds of 0, 5, 10, 25, and 50 mph

APPENDIX A

Flame Temperature Calculations

As part of an effort to validate the use of equation (6) for estimating radiation heat fluxes to targets, a modified form of the equation was used to calculate radiation flame temperatures. The flame temperatures, calculated using equation (8), were compared to data obtained by researchers using propane and PMMA fuels. Specifically, radiation flame temperatures were calculated for and compared to data obtained by Orloff [1][1] from studies of flames generated by burning PMMA.

The general form of the equation used to estimate flame temperature is

$$T_f = \left[\frac{\chi \, \Delta H_c \, \dot{m}'' \, A_{fire}}{\epsilon \, \sigma \, A_{flame\ surface}} \right]^{1/4} \qquad \text{(A-1)}$$

where $\dot{m}''$ - mass burning rate per unit area of the fire source,

ΔH_c - the heat of combustion of the fuel,

ϵ - emissivity of the flame,

σ - Stefan-Boltzmann constant (1.71×10^{-9} Btu/hr ft^2 R^4),

χ - the fraction of the fire's energy which is radiated,

A_{fire} - the area of the base of the fire, and

$A_{flame\ surface}$ - the surface area of the flame envelope.

---

1 Numbers in brackets refer to literature references at the end of this appendix.

For the analysis of Orloff's data [1], the PMMA flames are assumed to have a conical shape. The equations for the area of the base of a cone, the surface area of a cone, and the volume of a cone, respectively are:

$$A_{base} = (1/4)\ \pi\ d^2 \tag{A-2}$$

$$A_{surface} = (1/2)\ \pi\ d\ \sqrt{(1/4)d^2 + L^2} \tag{A-3}$$

$$V = (1/12)\ \pi\ L\ d^2 \tag{A-4}$$

where d - diameter of the base of the cone and

L - height of the cone (flames).

The PMMA flames studied by Orloff were not optically thick and did not represent black bodies. The assumption of unity for emissivity, ϵ, (used throughout the rest of this paper) would lead to gross errors in the calculated flame temperatures. Therefore, the first step in calculating flame temperatures is to calculate the effective emissivity of Orloff's PMMA flames. The emissivity can be expressed in terms of a gray absorption-emission coefficient, k, and the flame geometry. Orloff [1] provides the following equation for estimating flame emissivity

$$\epsilon = 1 - \exp\ (-\eta k V_f / A_p) \tag{A-5}$$

where η - an adjustable parameter,

k - the gray absorption-emission coefficient,

V_f - the radiating gas volume, and

A_p - the projected area of the flames.

As part of his analysis, Orloff determined an average absorption-emission coefficient, $\bar{k}_f$, for his PMMA flames. This average value of 0.47 ft^{-1} will be used for the k in equation (A-5). Orloff recommends a value of 0.95 for η (the adjustable parameter). The projected area, A_p, refers to the effective area that is "seen" by the target. For a target viewing flames with a conical shape, the projected area would be an isosceles triangle with a base width equal to the diameter of the fire area and a height equal to the flame height. In equation form, this is

$$A_p = (1/2)\ d\ L \qquad (A\text{-}6)$$

Using equation (A-4) for the radiating gas volume together with equation (A-6) yields the following ratio of flame volume to projected area

$$V_f/A_p = \pi d/6 \qquad (A\text{-}7)$$

From Orloff's data [1], the diameter of the burning area used for a number of tests was 1.25 ft. The effective flame emissivity is, from equation (A-5), equal to 0.25. This emissivity value agrees reasonable well with a value of 0.26 quoted by de Ris [2] for PMMA flames.

The next step in calculating radiation flame temperatures is evaluating the flame base area, A_{fire}, to flame surface area, $A_{flame\ surface}$, ratio. In this analysis which assumes the flames have a cone-like shape, the flame surface area is equal to the surface area of a cone (equation (A-3)) plus the area of the cone base (equation (A-2)). The flame base area is equal to the area of the base of the cone (equation (A-2)). From Orloff's data [1], the average flame height appears to be about three times the burner radius or three-halves times the burner diameter. The ratio of flame base area to flame surface area is $(\sqrt{10} - 1)/9$. Also from Orloff's data [1], the heat of combustion for PMMA is 11590 Btu/lb_m.

Equation (A-1) may be re-written in the following form:

$$T_f = \left[\frac{\Delta H_c \ A_{fire}}{\epsilon \ \sigma \ A_{flame\ surface}} \right]^{1/4} \left[\chi \ \dot{m}'' \right]^{1/4} \qquad \text{(A-8)}$$

Substituting the available data into equation (A-8) yields

$$T_f = 12374.6 \ (\chi \ \dot{m}'')^{1/4} \qquad \text{(A-9)}$$

Equation (A-9) will be used to calculate the flame temperature for PMMA flames at various burning rates.

By changing the distance between the fuel surface and the container lip, Orloff was able to vary the PMMA burning rate while maintaining the same burner diameter. The burning rate ranged from a low of 0.002 lb_m/ft^2 s at a zero surface to lip distance to a maximum of about 0.0036 lb_m/ft^2 s for a surface to lip distance of 2 in. There was a slight decrease in burning rate as the surface to lip distance increased above 2.4 in. Orloff estimated the radiation fraction, χ, to be from 0.32 at the zero distance to 0.42 for the 3 in. distance. The radiation flame temperatures calculated using equation (A-9) and Orloff's data are summarized below

Lip Size (in.)	Burning Rate (lb_m/ft^2 s)	χ	Flame Temperature (R)
0	0.0020	0.32	1968
0.49	0.0030	0.37	2259
1.95	0.0036	0.40	2411

These values differ from Orloff's average radiation flame temperature of 2270 R by a maximum of about 13 percent. Given the gross assumptions made in order to complete this analysis, this is very good agreement.

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APPENDIX B

Source Code for Radiation Heat Flux

and Configuration Factor Computer Program

```
      PROGRAM FLUX
C
C ***********************************************************************
C *   This program calculates the heat fluxes received by targets at    *
C *   user-specified distances from a fire.  The program accounts for  *
C *   the effect of wind on the flame size and shape.  The flame is    *
C *   assumed to be cylindrical in shape.                               *
C ***********************************************************************
C
C ***********************************************************************
C *                 LISTING OF IMPORTANT VARIABLES                      *
C ***********************************************************************
C
C ***********************************************************************
C     ASUR    -  Surface area of the flame
C     BETA    -  Angle of inclination of the target
C     CHI     -  Fraction of the energy release lost as radiation
C     D       -  Diameter of the fire (meters)
C     DM      -  Diameter of the fire (feet)
C     EMISS   -  Emissivity of the flame
C     F       -  Actual view factor for flame to target
C     FH      -  Horizontal portion of view factor
C     FLGTH   -  Flame length (meters)
C     FLGTHF  -  Flame length (feet)
C     FM      -  Maximum view factor for flame to target
C     FV      -  Vertical portion of view factor
C     G       -  Acceleration of gravity
C     H       -  Vertical height of the flames (meters)
C     HM      -  Vertical height of the flames (feet)
C     HC      -  Heat of combustion of the fuel
C     HLGTH   -  Vertical height of the flames (meters)
C     HLGTHF  -  Vertical height of the flames (feet)
C     HR      -  Flame height to radius ratio
C     MDOT    -  Mass flow rate of fuel
C     MDOTAF  -  Mass flow rate of fuel per unit burner area
C     ND      -  Number of distances for flux calculations
C     NRING   -  Number of rings used for view factor
C     NSECT   -  Number of sections used for view factor
C     NW      -  Maximum number of wind speeds
C     NWIND   -  Actual number of wind speeds
C     QDOT    -  Flux received at a given target
C     R       -  Radius of burn area
C     RHOA    -  Density of air
C     RHOF    -  Density of fuel vapors
C     S       -  Dimensionless distance to target
C     THETA   -  Angle of inclination of the flame
C     TRANS   -  Transmissivity of the atmosphere
C     TRGDIF  -  Distance from flame to target (feet)
C     TRGDIS  -  Distance from flame to target (meters)
C     VDOT    -  Volume flow rate of fuel
C     VISC    -  Viscosity of air
C     WNDSM   -  Wind speed (meters per second)
```

```
C     WNDSPD -  Wind speed (miles per hour)
C     Z      -  Height of the target above the ground
C ***********************************************************************
C
      PARAMETER (NW=10,ND=200)
      DIMENSION WNDSPD(NW),WNDSM(NW)
      DIMENSION QDOT(NW)
      REAL MDOT,MDOTAF
      DATA G,SIGMA / 9.8,5.67E-11 /
      DATA RHOA,VISC / 1.1,2.0E-5 /
      PI = 4.*ATAN(1.)
      PHI = 0.0
      NRING = 10
      NSECT = 20
C
C     Open the output files and enter the data.
C
      OPEN (7,FILE='A:FLHGHT.RES',STATUS='UNKNOWN')
      OPEN (8,FILE='A:FLUX.RES',STATUS='UNKNOWN')
      WRITE (6,1000)
      READ (5,*) RHOF,HC
      RHOF = 16.018*RHOF
      HC = 2.326*HC
      WRITE (6,1010)
      READ (5,*) EMISS,TRANS
      WRITE (6,1020)
      READ (5,*) VDOT,DM,HM
      VDOT = 0.0283*VDOT
      D = 0.3048*DM
      H = 0.3048*HM
      MDOT = VDOT*RHOF
      MDOTAF = MDOT/(PI*D**2/4.)
      WRITE (6,1030)
      READ (5,*) CHI
      WRITE (6,1040)
      READ (5,*) BETA
      WRITE (6,1050)
      READ (5,*) Z
      WRITE (6,1060)
      READ (5,*) NWIND
      WRITE (6,1070) NWIND
      READ (5,*) (WNDSPD(I),I=1,NWIND)
      DO 10 I = 1, NWIND
         WNDSM(I) = WNDSPD(I)*(1./3600.)*5280.*0.3048
   10 CONTINUE
C
C ***********************************************************************
C                               CALCULATIONS
C ***********************************************************************
C
      R = D/2.
      HR = H/R
```

```
      TRGDIF = DM/2.+0.5
C
C     Begin loop to calculate flux at each distance from the fire.
C
   20 CONTINUE
      TRGDIS = TRGDIF*0.3048
      S = TRGDIS/R
      DIS = TRGDIS
C
C     Begin loop to determine the effect of each wind speed on the
C     size and shape of the flame.
C
      DO 30 I = 1, NWIND
         IF (WNDSM(I).LE.0.0) THEN
C
C     Calculate view factor.
C
            A = (HR**2+S**2+1.)/(2.*S)
            B = (1.+S**2)/(2.*S)
            TN1 = ATAN(SQRT(((B+1.)*(S-1.))/((B-1.)*(S+1.))))
            TN2 = ATAN(SQRT(((A+1.)*(S-1.))/((A-1.)*(S+1.))))
            FH = (1./PI)*(((B-(1./S))/(SQRT(B**2-1.)))*TN1-(((A-(1./S))/
     *         (SQRT(A**2-1.)))*TN2))
            TN3 = ATAN(HR/SQRT(S**2-1.))
            TN4 = ATAN(SQRT((S-1.)/(S+1.)))
            FV = (1./PI)*(1./S*TN3-(HR/S)*(TN4-(A/(SQRT(A**2-1.)))*TN2))
            FM = SQRT(FH**2+FV**2)
C
C     Calculate the flame surface area and the heat flux.
C
            ASUR = PI*D*H
            QDOT(I) = EMISS*TRANS*FV*CHI*MDOT*HC/ASUR
            FLGTHF = H/0.3048
            THET = 0.0
            WRITE (7,*) WNDSPD(I),FLGTHF,THET
         ELSE
C
C     Calculate the flame angle of tilt, flame length, and view
C     factor.
C
            CALL ANGLE (D,WNDSM(I),RHOA,VISC,G,RHOF,THETA)
            THET = THETA*180./PI
            CALL FLMEXT (D,WNDSM(I),RHOA,G,RHOF,MDOTAF,HRR,FLGTH)
            CALL VIEW (D,FLGTH,THET,DIS,Z,PHI,BETA,NRING,NSECT,FM,FH,FV,
     *         F)
C
C     Calculate the flame surface area and the heat flux.
C
            ASUR = PI*D*FLGTH
            QDOT(I) = EMISS*TRANS*FV*CHI*MDOT*HC/ASUR
            HLGTH = FLGTH*COS(THETA)
            FLGTHF = FLGTH/0.3048
```

```
          HLGTHF = HLGTH/0.3048
C
C     Write results to the appropriate files.
C
          WRITE (7,*) WNDSPD(I),FLGTHF,THET,HLGTHF
        ENDIF
   30 CONTINUE
      DO 40 J = 1, NWIND
        QDOT(J) = QDOT(J)*317.
   40 CONTINUE
      WRITE (8,1080) TRGDIF,(QDOT(J),J=1,NWIND)
      TRGDIF = TRGDIF+1.
      IF (TRGDIF.LE.100.) GO TO 20
      STOP
C
C
 1000 FORMAT (' Enter the Density of the Fuel Vapors (lb/ft**3) and '/
     *   '        Its Heat of Combustion (Btu/lb).'/)
 1010 FORMAT (' Enter the Flame Emissivity and '/
     *   '        the Transmissivity of the Atmosphere.'/)
 1020 FORMAT (' Enter the Volume Flow Rate of the Fuel (ft**3/s)'/
     *   '        the Diameter of the Fire Area (ft) and'/
     *   '        the Vertical Flame Height (ft). '/)
 1030 FORMAT (' Enter the Fraction of the Total Heat Release Rate that/
     *   '        is Lost as Radiation from the Flame.'/)
 1040 FORMAT (' Enter the Angle of Inclination of the Target to the ',
     *   'Horizontal.'/)
 1050 FORMAT (' Enter the Height of the Targets.'/)
 1060 FORMAT (' Enter the Number of Wind Speeds to be examined (6) ')
 1070 FORMAT (' Enter the Wind Speeds (mph) up to ',I1/)
 1080 FORMAT (6(1X,F8.2))
C
      END
      SUBROUTINE ANGLE (D,WNDSPM,RHOA,VISC,G,RHOF,THETA)
C
C ***********************************************************************
C *   Calculates the flame angle of tilt due to the wind.              *
C ***********************************************************************
C
      RE = D*WNDSPM*RHOA/VISC
      FR = WNDSPM**2/(D*G)
      X = 3.3*RE**0.07*FR**0.8*(RHOF/RHOA)**(-0.6)
      A = SQRT(1.+4.*X**2)
      B = 2.*X/(A+1.)
      THETA = ASIN(B)
      RETURN
C
      END
      SUBROUTINE FLMEXT (D,WNDSPM,RHOA,G,RHOF,MDOTAF,HRR,FLGTH)
C
C ***********************************************************************
C *   Calculates the wind influenced flame length.                      *
```

```
C ***********************************************************************
C
      REAL MDOTAF
      A = MDOTAF/(RHOA*(SQRT(D*G)))
      B = WNDSPM/((G*MDOTAF*D/RHOF)**(1./3.))
      IF (B.LE.1.0) B = 1.0
      HD = 55.*A**0.67*B**(-0.21)
      HRR = 2.*HD
      FLGTH = HD*D
      RETURN
C
      END
      SUBROUTINE VIEW (D,FLEN,ALPHA,DIST,Z,PHI,THETA,NRING,NSECT,FMAX,FH
     *   ,FV,F)
C
C ***********************************************************************
C *   Computes the view factor from a differential element to the fire *
C *   by numerically summing elements of the fire shape.                *
C ***********************************************************************
C
      DIMENSION FACTR(3)
      PI = 4.*ATAN(1.)
      TWOPI = 2.*PI
      DBASE = 1.
      H = FLEN/D
      S = DIST/D
      Z1 = Z/D
      PHII = PHI*PI/180.
      AL = ALPHA*PI/180.
      THET = THETA*PI/180.
      SA = SIN(AL)
      CA = COS(AL)
      X1 = S*COS(PHII)
      Y1 = -S*SIN(PHII)
      RING = FLOAT(NRING)
      SECT = FLOAT(NSECT)
      ASUBD = PI*H*DBASE/(RING*SECT)
      DELH = H/RING
      RBASE = DBASE/2.
      DO 80 ICASE = 1, 3
         GO TO (10,20,30), ICASE
   10    RN1X = 0.
         RN1Y = 0.
         RN1Z = 1.
         GO TO 40
C
   20    RN1X = -1.*COS(PHII)
         RN1Y = SIN(PHII)
         RN1Z = 0.
         GO TO 40
C
   30    RN1X = -1.*COS(PHII)*SIN(THET)
```

```
      RN1Y = 1.*SIN(PHII)*SIN(THET)
      RN1Z = COS(THET)
40    FNITE = 0.
      DO 70 I = 1, NRING
         RI = FLOAT(I)
         DO 70 J = 1, NSECT
            RJ = FLOAT(J)
            BETAJ = (RJ-1.)*TWOPI/SECT
            SB = SIN(BETAJ)
            CB = COS(BETAJ)
            X2 = (RI-0.5)*DELH*SA+RBASE*CB
            Y2 = RBASE*SB
            Z2 = (RI-0.5)*DELH*CA
            RLEN = SQRT(CA**2+SA**2*CB**2)
            RN2X = CA*CB/RLEN
            RN2Y = SB*CA/RLEN
            RN2Z = -CB*SA/RLEN
            RIJ = SQRT((X2-X1)**2+(Y2-Y1)**2+(Z2-Z1)**2)
            VX = (X2-X1)/RIJ
            VY = (Y2-Y1)/RIJ
            VZ = (Z2-Z1)/RIJ
            COST1 = VX*RN1X+VY*RN1Y+VZ*RN1Z
            IF (COST1) 70 , 70 , 50
50          COST2 = -VX*RN2X-VY*RN2Y-VZ*RN2Z
            IF (COST2) 70 , 70 , 60
60          X = D*RIJ
            DF = COST1*COST2/RIJ**2
            FNITE = FNITE+DF
70    CONTINUE
      FACTR(ICASE) = ASUBD*FNITE/PI
80 CONTINUE
   FMAX = SQRT(FACTR(1)**2+FACTR(2)**2)
   FH = FACTR(1)
   FV = FACTR(2)
   F = FACTR(3)
   RETURN
C
   END
```

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report presents an analysis of the thermal radiation produced by flames from the U.S. Navy 19F4 Fire Fighter Training facility. The 19F4 facility is used to simulate airplane crash fires on aircraft carrier flight decks and aircraft carrying ships. A simple methodology for calculating radiative heat transfer to targets is developed from a review of available literature. Of particular importance is the influence of wind on flame size and shape, the calculation procedure accounts for this effect. The radiation heat fluxes at various distances from the trainer are presented in the form of graphs. The fluxes received by a crane and the 19F4 instructor's tower adjacent to the facility are calculated and shown to be substantial under certain conditions. Recommendations for placement of the crane and the instructor's tower are provided.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

aircraft carriers; aircraft fires; crash fires; fire fighting training; flame height; flame radiation; radiation heat flux; radiative heat transfer; thermal radiation; training devices; wind effects

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