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THE EFFECTS OF THERMAL RADIATION ON AIRCRAFT STRUCTURES

Part I - The M. I. T. Mark I Radiant
Heating Structural Test Facility

John C. Loria
William J. Blackstock
James W. Mar

Massachusetts Institute of Technology

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FOREWORD

This report deals with the development and application of a Radiant Heating Structural Test Facility by the Department of Aeronautical Engineering of the Massachusetts Institute of Technology on Contract Number AF 33(038)-8906, under Project Number 1350 (U) " Atomic Weapon Effects on Aircraft Systems". The work was administered under the direction of the Aircraft Laboratory, Wright Air Development Center, with Mr. F. J. Janik, Jr. acting as project engineer. This report is one of a series of such reports which will appear as component parts of WADC TR 54-384.

ABSTRACT

A high-temperature radiation source, which measures 7- by 24-inches and utilizes Globar heating elements, has been constructed at the Aeroelastic and Structures Research Laboratory, Massachusetts Institute of Technology, for the exposure of aircraft structural components to high intensity radiation on one surface. Although designed primarily for the study of the thermal effects from an atomic explosion on aircraft structures, the radiant heater can be adapted to other problems, e.g., the uniform heating of all surfaces in aerodynamic heating and the static or dynamic loading of a specimen which is subject to high intensity radiation.

The heater has a continuously variable operating temperature up to 3000°F, and at this peak temperature it delivers approximately 11.7 cal/cm^2 sec at a distance of three inches from the midplane of the source. Two hydraulic jacks provide vertical movement while the base is mounted on tracks to provide horizontal translation. A pneumatically operated injection shield insulates the model from the heat source and furnishes quick exposure to, and shutoff from the radiation. The Globar heating elements have shown a satisfactory operating lifetime.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Carl E. Reichert
for Daniel D. McKee
Colonel, USAF
Chief Aircraft Laboratory
Directorate of Laboratories

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This development program was carried out under the general supervision of Professor Raymond L. Bisplinghoff and Professor H. Guyford Stever. Also, the authors wish to express their appreciation for the cooperation and assistance of both engineering and shop personnel of the MIT Aeroelastic and Structures Research Laboratory in the design, fabrication, and installation of this facility. Finally, the authors wish to thank those whose fine workmanship is responsible for the appearance of this report. Mr. James R. Friery and Mr. George M. Falla prepared the figures. Miss Iris G. Ellis typed the manuscript.

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LIST OF COMMON SYMBOLS

q	radiant flux intensity, cal/sq. cm. sec.
t	time, sec.
A	area, sq. cm.
$\mathfrak{F}$	radiation factor defined in Ref. 11
KT	kilotons
MT	megatons
T	temperature, $^{\circ}R$
W	energy release
α	absorptivity
λ	wavelength, microns
σ	Stefan-Boltzmann constant [$0.1306(10)^{-12}$ cal/sq. cm. sec. $(^{\circ}R)^4$]

Subscripts

s	source
m	model
A	aircraft
L	laboratory

SECTION I

INTRODUCTION

An important characteristic of atomic explosions is the emission of significant thermal radiation. It has been estimated (Ref. 1) that approximately one-third of the total energy of an atomic weapon is released in the form of radiant energy. Aircraft operating in the vicinity of such an explosion may be affected by this radiant energy; these thermal effects are a subject of investigation. In the aerodynamic heating problem as well, the aircraft is faced with the problem of absorbing large quantities of heat energy. In the light of these two problems the importance of the thermo-elastic problem is evident.

If the heat energy inputs are adequately known, the thermo-elastic problem can be expressed as follows:

1. Prediction of the temperature distribution
2. Determination of the resulting structural effects.

The M. I. T. Mark I Radiant Heating Structural Test Facility has been constructed primarily to experimentally investigate the temperature distributions and effects experienced by aircraft structures which may be exposed to large amounts of thermal radiation from atomic explosions. Also, it has been used as a pilot model for the construction of a larger and more versatile test facility. This program was initiated at the Aeroelastic and Structures Research Laboratory, Massachusetts Institute of Technology, under the sponsorship of the U. S. Air Force Contract

No. AF 33(038)-8906 monitored by the Aircraft Laboratory at Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

SECTION II

THE NATURE OF THE STRUCTURAL PROBLEM

High temperatures in aircraft structures result in the following primary effects:

a. Thermal stresses are induced throughout the structure by differential expansion of separate components of the structure.

b. Strength properties of the structural materials are adversely affected.

c. Structural distortion takes place which may result in nonlinear interactions with flight loads.

Assuming an elastic structure and a known temperature distribution, the associated thermal stresses can be theoretically calculated. All structural materials, however, exhibit plastic behavior at extreme temperatures; this factor complicates the problem. Also present-day knowledge of the high-temperature properties of aircraft materials is incomplete. In addition, time becomes a very important parameter because failure at any specific plastic stress level is not instantaneous, but instead, new modes of structural behavior such as creep and creep buckling are introduced.

Ordinary flight loads caused by gusts and maneuvers are superimposed upon the stresses which result from differential thermal expansion or restraint. In the low-temperature or elastic range, these loads can be added linearly; however, in the high-temperature range the complicating factors enumerated above make this combination nonlinear.

Detailed review and consideration of the general problem areas described above indicated the need for an experimental investigation of basic aircraft structures with a laboratory radiant heater which would simulate as closely as possible the expected thermal inputs to aircraft structural components. This program would permit a controlled variation of the factors influencing basic thermal phenomena in aircraft structures without the attendent costs and complexities of full-scale testing. It is considered that analytical procedures for determining temperature distributions, losses in structural load-carrying capacity, and structural deformations can be most logically checked by utilizing models of typical aircraft structures and exposing them to the thermal radiation produced by the type of furnace described in this report.

SECTION III

REQUIREMENTS FOR HEATER SOURCE

All three basic heat transfer processes, i.e., convection, conduction and radiation, are present in aircraft temperature distribution problems. Heat entering the structure through the surface upon which radiation impinges, is transferred to distant components of the structure by conduction and escapes to the atmosphere or to interior spaces by convection or radiation. Heat transfer out of the structure by convection and radiation can be treated as additional boundary conditions to the main process of heat conduction into remote portions of the structure. Determination of temperature distributions in the structure depend, therefore, chiefly upon the solution of the heat-conduction equation in solids. This equation has a rather simple mathematical form and is classed as a parabolic differential equation. Examination of this equation discloses that mass density, specific heat, and thermal conductivity are the material properties which are important. All three properties are functions of the local temperature, but unfortunately, data concerning their variations with temperature is meager.

In order to establish the specifications for the radiant heater, it is necessary to consider those characteristics of the thermal radiation from atomic weapons which will affect the process of heat conduction into the interior of the structure. The main feature of the radiation is that it represents a boundary condition which, in turn, represents a certain rate of heat flow at the surface of the structure. It is the spacewise and timewise variations of the temperatures and the temperature gradients which are to be duplicated in the structure. This objective should be kept in mind in the following discussion.

The following characteristics will be discussed and their importance to the aircraft structural problem evaluated:

(1) Spectral quality of the radiant energy

(2) Time-history of the radiant energy

(3) Peak intensity and total radiant energy.

3.1 The Spectral Quality of the Radiant Energy

When thermal radiation impinges upon a surface, part of the energy will be reflected, part will pass through, and the remainder will be absorbed by the material. For most engineering materials, that portion of the incident radiation which passes through can be ignored. It is the part which is absorbed which must be duplicated in the laboratory. Before laboratory results can be extrapolated to field situations, however, it is also important to determine the portion which is reflected. The reflected energy and the absorbed energy depend upon the surface condition of the structure. In addition, the spectral quality of the thermal radiation is an important factor because absorptivity varies as a function of the wave length of the radiation.

A curve of the probable spectral distribution of radiant energy which results from an atomic explosion is illustrated in Fig. 3.1. This representative spectral distribution was determined from Planck's radiation distribution law for a black body by the use of an "effective" source temperature of the fireball of 10,000°R. This "effective" source temperature is a rough estimate based on information contained in Ref. 1 for the fireball temperature and atmospheric absorption effects. Since the temperature of the fireball is actually changing with time, the spectral distribution of the thermal radiation is also a function of time. Thus, this "effective" temperature actually represents only an average "effective" temperature.

A qualitative comparison between the time-varying spectral distribution of thermal energy from an actual explosion and that of a "typical" laboratory heater is indicated in Fig. 3.2. The temperature of the laboratory source is considered to be maintained constant and at a level considerably lower than the 10,000°R "effective" temperature of the fireball. Since the laboratory source is at a constant temperature the shape of the spectral distribution curve is the same at different intensity levels. This is indicated in the figure by the curves labeled t_1 through t_4 which represent an increase in intensity with time, t, effected by motion of the heater towards the model and/or the opening of a shutter mechanism. The spectral distribution of thermal energy in the case of an atomic explosion varies with time according to the fireball temperature. With increasing temperatures the energy and the wave length at which a maximum of intensity occurs shift to smaller wave lengths according to Wien's Displacement Law. This is shown in Fig. 3.2 which demonstrates this shift with increasing intensity for times, t_1 through t_4, and illustrates the difference in the spectral ranges for the atomic explosion and the typical laboratory source. An examination of Fig. 3.2 discloses the practical impossibility of duplicating the spectral distribution of radiant energy in the laboratory on any reasonable scale.

To duplicate structural behavior in the laboratory it is necessary that

$$q_L(t)_{\text{absorbed}} = q_A(t)_{\text{absorbed}} \tag{3.1}$$

where

$q_L(t)_{\text{absorbed}}$ = Heat flux absorbed by a laboratory specimen at time t.

$q_A(t)_{\text{absorbed}}$ = Heat flux absorbed by an aircraft at time t.

The heat flux which is absorbed depends, among other things, upon the spectral distribution of the heat flux, and the absorptivity, i.e.,

$$q_A(t)_{\text{absorbed}} = \int_{\lambda=0}^{\lambda=\infty} q_A(\lambda, t)_{\text{incident}} \; \alpha_A(\lambda, t)\, d\lambda \tag{3.2}$$

$$q_L(t)_{\text{absorbed}} = \int_{\lambda=0}^{\lambda=\infty} q_L(\lambda, t)_{\text{incident}} \; \alpha_L(\lambda, t)\, d\lambda \tag{3.3}$$

where

$q(\lambda, t)_{\text{incident}}$ = normal spectral irradiance incident at time t on the receiver

$\alpha(\lambda, t)$ = spectral absorptance of the irradiated surface of the receiver at time t.

and the subscripts A and L refer to the aircraft and the laboratory specimens, respectively. Thus, the requirement of equal absorption of thermal flux becomes

$$\int_{\lambda=0}^{\lambda=\infty} q_A(\lambda, t)_{\text{incident}} \; \alpha_A(\lambda, t)\, d\lambda = \int_{\lambda=0}^{\lambda=\infty} q_L(\lambda, t)_{\text{incident}} \; \alpha_L(\lambda, t)\, d\lambda \tag{3.4}$$

As already indicated, it is practically impossible to duplicate the spectral distribution of the actual thermal radiation in the laboratory, i.e.,

$$q_L(\lambda, t)_{\text{incident}} \neq q_A(\lambda, t)_{\text{incident}} \qquad (3.5)$$

The other variable in the equation, i.e., the absorptivity coefficients, $a_L(\lambda, t)$ can be controlled to a certain extent in the laboratory. Both $a_L(\lambda, t)$ and $a_A(\lambda, t)$ are indicated as being functions of time. In reality, the time variable is the result of the time variation of the thermal heat input which, in turn, causes a variation of the temperature of the surface that is receiving the radiation. It is possible to use the same type of surface finish on the laboratory specimen as on the actual aircraft, but because of the impracticability of duplicating the spectral-time-distribution of thermal radiation the spectral-time-variation of absorptivity will be different, i.e.,

$$a_L(\lambda, t) \neq a_A(\lambda, t) \qquad (3.6)$$

The time-variation of absorptivity is particularly important in the case of specimens which when exposed to thermal radiation experience the phenomena of chemical and physical surface changes. Therefore, it would be impossible to duplicate with the facility described herein the time effects of thermal radiation from an atomic explosion on such specimens as wood, fabric, or rubber, or on painted surfaces where burning, charring, blistering, or any other surface changes take place during exposure. The facility would only serve in the case of organic materials for more basic studies such as damage initiation by high intensity radiation.

Once again it should be pointed out that structural behavior under the influence of thermal radiation is to be simulated in the laboratory. If the laboratory source temperature remains constant, its spectral distribution remains unchanged and since for these studies the surface temperatures of the models are usually below values which would produce surface changes, the surface absorptivities of the structural models can be considered as constant. The requirement that

$$q_L(t)_{\text{absorbed}} = q_A(t)_{\text{absorbed}} \tag{3.7}$$

can then be met by proper choice of source temperature, source geometry relative to the model, surface treatment of the model to effect the required absorbed energy intensity, and by a proper time variation of this intensity by means of a shutter and/or movement of the heater itself.

Since the amount of power available is limited, it is usually desirable to prepare the surface in such a manner as to have maximum absorptivity. This objective can be accomplished by coating the surface with black paint or lamp black, or by anodizing the surface black. In the case of an aluminum alloy, the absorptivity might even be doubled by this method. The new absorptivity must be determined in the spectral range of the heater, and care must be exercised to ensure that no time effects are introduced by the new surface conditioning.

3.2 The Time-History of the Flux

Reference 1 contains a representative time-history of the spectrally integrated thermal energy, that is, the time-history of radiant flux, from the explosion of a 20 KT atomic weapon. This information is replotted in Fig. 3.3 using a linear ordinate and abscissa. Scaling laws, based on the hydrodynamic equations which apply to shock waves, are presented in the same reference. If the somewhat questionable assumption is made that the scaling law for time,

$$\frac{t}{t_o} = \left(\frac{W}{W_o} \right)^{1/3} \tag{3.8}$$

where

t = time,

W = energy release, and

W_o refers to the energy from a reference explosion,

applies in the case of the thermal pulse, then a significant expansion in the time scale of Fig. 3.3 occurs for high yield weapons. This assumption does have a limited basis in fact, because initially the growth of the fireball is associated with the blast wave expansion. Thus, for an atomic explosion with an energy yield of, say 10 MT, the time scale of Fig. 3.3, which is for a 20 KT burst, would be expanded by a factor of almost eight.

As stated in the previous section, the temperature of the laboratory source will remain constant because thermal inertia precludes any rapid variation of the source temperature. The time variation of the thermal flux must be obtained mechanically, by means of shutters or by movement of the heater itself. The expanded time scale for the thermal pulses from the explosion of higher yield weapons suggests that the time response requirements to simulate the pulse shape are less severe for high yields than for low yields. Actually, the maximum speed of the mechanical system for pulse simulation is the limiting factor in determining the lowest yield weapon which the laboratory source can simulate.

3.3 The Peak Intensity and the Total Radiant Energy

Peak intensity and total radiant energy are related if the thermal pulse shape is assumed to remain unchanged with yield, i.e., if it is assumed that the pulse can be scaled by a law such as that given by Eq. 3.8. If the maximum intensity is specified for a particular yield weapon, the total radiant energy is defined once the generalized pulse is known, and vice-versa.

The peak intensity represents another limitation on the conditions which laboratory sources can duplicate. If it is assumed that the total thermal energy which can be safely absorbed by a given structure is the same whether the duration of the input is 2 seconds or 40 seconds, then it is evident that the required peak intensity is less for the higher yield weapon. The validity of the total energy criterion, however, must be investigated. Nevertheless, once again the flux from a high yield weapon appears easier to simulate than that from a weapon of low yield. For a weapon with a specific yield, the peak intensity of the total energy at a specified distance from the explosion can be determined from the geometry of the pulse shape. Again, total flux absorbed is the criterion, and if the peak intensity cannot be duplicated, compensation can be achieved by increasing the absorptivity of the laboratory model.

To summarize the above considerations, the following requirements were established for the laboratory source which would be used in order to simulate structural behavior at the elevated temperatures produced by thermal inputs from an atomic explosion:

1. The heater should supply sufficient thermal flux such that a specimen could absorb energy equivalent to that which it would experience at a specified distance from the point of explosion of an atomic weapon of given size. (This requirement might dictate the proper choice of source temperature, source geometry relative to the specimen, and treatment of the specimen surface).
2. Since the temperature of the source is constant, it must be possible to vary the thermal flux with time by a shutter mechanism or by movement of the heater itself.
3. The thermal flux should be uniform over the exposed area of the specimen.

Several additional requirements, established for reasons of structural similitude, convenience, safety, and economy are listed at the beginning of Section VI; but, it is first necessary to discuss the selection of a type of heater element. This choice may, in turn, affect the approach to certain of the requirements listed in Section VI.

SECTION IV

LABORATORY SOURCES OF RADIANT ENERGY

In reference 2, the laboratory sources of radiant energy are broken down into the following four general classifications:

(A) Continuous sources of infrared radiation.

(B) Continuous sources of very high intensity radiation.

(C) Sources with continuous spectra and short pulse durations.

(D) Sources with discontinuous spectra.

Since most of the sources which fall under each of the above categories are also described in reference 2 they will only be enumerated here and some of their operating characteristics noted. References 2, 3, 4, 5 and 6 should be consulted for more detailed information about these sources. The Globar source is considered in more detail in Section V.

4.1 Brief Summary of Source Characteristics

TABLE 4.1

CONTINUOUS SOURCES OF INFRARED RADIATION

Heating Element	Operating Characteristics	
	Pulse Duration	Maximum Irradiation Intensity ($cal/cm^2/sec$)
Metallic Wire Heaters		
Nichrome	continuous	4
Kanthal	continuous	6
Globar Heating Units	continuous	11.7
Carbon Resistor Furnace	continuous	15
Selas Burner (gas-fired radiant panel)	continuous	4

TABLE 4.2

CONTINUOUS SOURCES OF VERY HIGH INTENSITY RADIATION

Heating Element	Operating Characteristics	
	Pulse Duration	Maximum Irradiation Intensity ($cal/cm^2/sec$)
Aluminum - Oxygen Furnace	continuous	30
High-Intensity Carbon Arc	continuous	300
High-Intensity Tungsten Filament Lamps	continuous	4-6
Solar Sources	continuous	600

TABLE 4.3		
SOURCES WITH CONTINUOUS SPECTRA AND SHORT PULSE DURATIONS		
Heating Element	Operating Characteristics	
	Pulse Duration (sec)	Maximum Irradiation Intensity (cal/cm^2/sec)
The Edgerton Xenon-Filled Flash Tube	0.0002	2567
The Anderson Spark	0.0001	25000
Burning Combustibles Igniting Magnesium	0.37	5
Photoflash Tubes	.003-.03	1.6

TABLE 4.4		
SOURCES WITH DISCONTINUOUS SPECTRA		
Heating Elements	Operating Characteristics	
	Pulse Variation (sec)	Maximum Irradiation Intensity (cal/cm^2/sec)
High Pressure Mercury Arc	continuous	1.35
High Pressure Xenon Arc	no data available	

4.2 Selection of Source Elements

An examination of the above tabulated characteristics indicated that a resistance-heater type of radiant source would be the most appropriate design choice to satisfy the requirements listed at the end of Section III. The resistance-type elements are adaptable to group connection which facilitates the achievement of large radiation areas, thereby providing a more uniform radiation source. Also, the simplicity of the electrical connections more easily permits mounting the elements such that the source itself can be made mobile. The fact that the radiant flux is constant in the case of the resistance-type elements is another strong argument in their favor. For the most part, the other types of sources were eliminated because they did not meet the requirements of a radiation area large enough to provide uniform irradiation, portability, or constant irradiance.

Since the highest possible operating temperatures consistent with the available power were sought, it was decided to investigate the possibilities of the refractory types of resistance heater elements because their temperature range exceeded that of metallic heating elements. Accordingly, silicon carbide electric heating elements, manufactured by the Carborundum Company under the trade name of "Globars", were ordered for testing purposes. The results of these successful tests together with a description of the Globar elements themselves are given in Section V.

SECTION V

GLOBAR HEATING ELEMENTS

5.1 Description of Globar Elements

Globar heating elements (see Fig. 5.1) are made in the form of round rods and have central heating sections of self-bonded crystals of silicon carbide between low-resistance terminals. The low-resistance ends are each equal in length to the furnace wall thickness plus an inch or an inch and a half for terminal connections.[1] These extremities of the low resistance ends are coated with aluminum to provide a suitable low-contact-resistance metallic surface for the flexible terminal straps.

The heating section of crystalline silicon carbide has a resistivity of 0.1 ohm per cubic centimeter at a temperature of 1960°F for a new element.[2] Resistance-temperature characteristics measured during various tests are included in Fig. 5.2. Available sizes of Globars range from an over-all length of 11 inches, a heating section of 4 inches in length, and a 5/16-inch diameter up to an over-all length of 111 inches, a heating section 80 inches in length and 1-3/4 inches in diameter. Tubular elements with diameters up to 2-1/8 inches and a heating section 60 inches in length are also available. For more detailed information on the Globar elements, reference 7 should be consulted.

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[1] The high resistance portion extends into the walls for one-half inch.

[2] This statement is true for the specific size of Globar mentioned but is not valid in general, i.e., a 56- by 1-inch Globar has a resistivity $\approx$ 0.0039Ω/cm^3.

5.2 Operating Characteristics

The first series of experiments were intended to furnish information concerning the capabilities, characteristics, and power requirements of Globar heating elements when operated in free air. Industrial furnaces and heaters which use Globar elements were found to be invariably of the closed-oven type operated by AC power. Almost all of the information concerning Globar heating elements dealt with these operating conditions. Only one curve, Fig. 5.3, was available for operation of these elements in free air, and it pertains to operation with AC power. Since the only source of high power which was available at the time the facility was being designed was DC power, it was necessary to establish the operating characteristics of the elements for this condition. Accordingly, such studies were undertaken.

Under ideal conditions, that is, continuous operation of an AC powered oven at temperature levels from 2300°F to 2800°F as in many industrial applications, useful element lifetimes of the order of thousands of hours are apparently being obtained. It was also established that Globar elements could be operated satisfactorily up to 3000°F when contained in a closed cavity and powered by an AC source, although the lifetime of the elements is reduced considerably. When such elements are operated in free air, however, the power required to reach and sustain operating temperatures is much greater . Furthermore, the use of a direct current source, which was the only controllable source of high power available at the initiation of this program, was expected to introduce "directional polarization" in the crystalline structure of the elements. Both of these factors, together with the fact that operation would be intermittent and would probably induce thermal shocks in the elements, pointed to a lifetime expectancy for the elements of the order of hours. As a matter of fact, the employment of the Globar elements in such operation was seriously discouraged, and it was predicted that the lifetime of the elements would be no more than an hour or two at the most. Fortunately, these predictions proved erroneous, and the Globars showed lifetimes sufficiently long to warrant their use in experimental tests of the nature intended herein. A suggested partial compensation for the "polarizing effect" by periodic reversal of the input polarity proved unnecessary because there was no discernible effect on the temperature gradient or the lifetime of the elements.

A preliminary heater, the Model A, with inside dimensions of seven by four inches was constructed for evaluation of the Globar elements (see Fig. 5.1). This furnace was constructed of Babcock and Wilcox K-28 firebricks and was designed so that one, two, or three Globars could be incorporated. Power was supplied to this heater from an 87 KW DC motor-generator.

The Globar heating elements used in the Model A heater, as well as the susbsequent Mark I heater, which will be discussed later, had the following dimensions and physical characteristics:

Over-all Length	19 inches
Effective Heating Length	8 inches
Diameter	7/16 of an inch
Nominal Radiating Surface	10.77 square inches
Nominal Resistance	2.139 ohms

5.3 Power Requirements

Power was supplied to the Model A heater in small steps over time increments long enough to avoid damage to the elements due to volumetric expansion. The critical region of volumetric expansion extended from 600°F to 800°F, and particular care was taken in passing through this region. From temperature levels which were discernible with a Leeds and Northrup optical pyrometer, the temperatures were monitored and recorded at each power setting. The results obtained from a series of runs are shown in Fig. 5.4 in terms of power density loadings (watts per square inch of effective radiating surface) versus temperature for a single element and for three elements connected in series or in parallel. As indicated in this figure, the power per element required to effect a given temperature is greater for a single element than for elements in a group. In the latter case, each element receives radiation from the adjoining element, and the power requirement per element is thereby reduced somewhat.

Two types of resistance changes were anticipated with the use of the Globar heating elements, namely, a variation in resistance with temperature changes and an increase in resistance of the element with time at constant temperature. The variation of resistance with temperature which is shown in Fig. 5.2, represents a mean curve of percentage resistance change as a function of temperature in the range 1500°F to 3000°F. A curve from reference 7 is also included for comparison. The experimental curve of Fig. 5.2 indicates a nearly constant percentage resistance change with temperature in this region; it should be pointed out, however, that this curve is based upon the examination of a relatively small number of elements. Consequently, the results may not be entirely consistent with data taken over a larger sampling.

Under ideal operating conditions, and hence for long lifetimes, Globar elements have experienced resistance increases as high as 400%. At the outset of this investigation, similar changes over much shorter lifetimes were anticipated, but in practice the maximum increase in resistance of the elements with use at a specified temperature was no more than 10%.

5.4 The Spectral Quality

The wave lengths over which the Globars radiate energy is confined almost entirely to the infrared region (see Fig. 5.5). As discussed previously, this does not duplicate the spectrum which is covered by the thermal radiation from an atomic weapon. The treatment of the radiated surface to gain the proper absorptivity must, however, take into account the nature of the Globar spectrum.

SECTION VI

DESIGN AND CONSTRUCTION OF THE MARK I HEATER

In addition to the flux level and time variation requirements discussed in Section III, the design of Mark I heater had to satisfy the following requirements:

(1) The source area should be large enough to accomodate structural specimens.

(2) The heater and its components should be both rugged and portable, and permit both vertical and horizontal translation.

(3) The geometry of the heater should permit external loading of the structural specimens.

(4) The effective lifetime of the source and its components should be economically and operationally practical.

(5) The component parts of the heater should not be of such a nature as to preclude repair or replacement.

(6) The heater should not be hazardous either in its manner of operation or in any by-product of its operation such as gases, high voltage arcs, etc. If such hazards should exist, however, the serviceability of the heater should not be impeded by the addition of protective devices.

(7) The heater should be available for operation in a relatively short time.

(8) The cost of operation should not be unreasonable.

In addition to these requirements and the information obtained on the operating characteristics of the Model A heater, the following considerations also influenced the design of the Mark I heater:

(a) The power available

(b) The floor space required

(c) The expense and availability of requisite components

(d) The number of operators required.

The Mark I contains 20 Globar elements which are spaced 1.15 inches between centers giving a radiation area of 7- by 24-inches. Electrically, the elements are connected as ten parallel connections of two elements in series. As can be seen in Fig. 6.3, the heater is mounted on a trolley which permits horizontal movement of the heater; hence, the heater can be brought up to temperature at a location remote from the test specimen. Vertical movement of the heater on the trolley is accomplished by means of the two hydraulic cylinders shown in the same figure. Both horizontal and vertical motions are manually controlled, and as a result the time variation of the flux can be controlled only qualitatively. The usefulness of the heater, however, is not impaired to any large extent since the behavior of structural models can be investigated in many cases without an exact duplication of the thermal pulse; in fact, in many experiments,pulse simulation itself is not required.

An auxiliary device, a radiation shield, was developed to permit the rapid exposure of the radiation to the model. The shield, which may be thought of as a one piece shutter, is a 1/4-inch thick steel plate with over-all dimensions of

30- by 18-inches. As shown in Fig. 6.2, this shield is mounted on a trolley in such a manner that its elevation is adjustable. Pneumatic cylinders, which are mounted on the base of the trolley, are employed for rapid injection and ejection of the shield between the model and the heater. The sequence of operations for irradiating a specimen is as follows:

(1) Cover the surface to be exposed with the shield.

(2) Move the heater under the shield.

(3) Eject the shield.

(4) Inject the shield at the end of the desired exposure time.

(5) Move the heater to a position remote from the model.

This sequence of operations is shown in Fig. 6.3. The time for injection or ejection of the shield is of the order of a fraction of a second.

As part of the furnace development program, the Mark I heater was modified to incorporate a silicon carbide slab which is 2- by 6- by 24-inches, the distance from the plane of the Globars to the silicon carbide slab (which now becomes the reflecting surface of the heater) was the same as that to the refractory bottom which existed before the slab was incorporated. The primary purpose of the slab is to store energy and, thus, to slow down the cooling rate of the heater after the power has been cut off. The slab also makes the heat source more uniform and, hence, more nearly the ideal plane source.

SECTION VII

THE RADIATION FIELD OF THE MARK I

The specification of the field of radiation emanating from the heater requires a knowledge of the thermal flux at each point in the region which surrounds the heater. The net radiant-interchange between the source and the model surface due to the combined mechanism of direct radiation and reradiation from the refractory surfaces, together with allowance for the emissivities of the source and model surface may be expressed in the form (see Ref. 11)

$$\frac{q}{A} = \mathcal{F}\sigma \left(T_s^4 - T_m^4\right) \text{ cal/ sq. cm. sec.}$$

where σ = Stefan-Boltzmann constant [0. 1306(10)$^{-12}$ cal/sq cm sec ($^{\circ}$R)^4]

T_s = Source temperature

T_m = Model surface temperature

$\mathcal{F}$ = Factor which takes account of shape and relative orientation of the source and model surface, reradiation from the refractory surfaces, and the emissivities of both the source and receiver.

Reference 11 should be consulted for the determination of the factor $\mathcal{F}$ and application of the above equation.

For a target which is oriented so that the incident radiation is normal to its surface and which is centrally located above the plane of the Globars, a net flux of approximately 11.7 cal/cm^2 sec is possible at the maximum Globar temperature of 3000°F. This radiation, however, is not uniform across the heater. Radiation pattern studies were made using circular-foil radiometers (Ref. 10), and total thermal energy received was measured with a silver-disk calorimeter (Ref. 12). Results of these studies are shown in Figs. 7.1, 7.2 and 7.3. Examination of the curves shows that the flux at a constant distance above the plane of the Globars is not uniform. This nonuniformity is due to the convergence effect which exists because the source is of finite size and is located a finite distance from the target. Thus, a target located at a point above the center of the furnace is closer to a larger number of Globars than a target located over an edge of the furnace. The chordwise and spanwise variations in flux can, of course, be taken into account.

Two other factors which are of interest and importance in the use of the heater are (a) the effects of convection and (b) the time rate of change of the flux, that is, the decay rate after the power has been cut.

Heat transfer by forced convection is not an important factor for the Mark I, but heat transfer by free convection is important in at least two ways. First, free or natural convection from the radiating plane reduces the fraction of energy input available as thermal radiation. This loss or reduction in efficiency due to free convection varies as the 4/3 power of the temperature difference between the source and the ambient air. At 2800°F these losses represent approximately 9% of the total energy input when the plane of the source is horizontal and facing upward. Since the output of the source is proportional to the fourth power of this temperature difference, the percentage loss by free convection will consequently be less for higher source temperatures. Reference 12 indicates that this free convection loss is roughly 28% greater than that which would exist if the source were in a vertical plane and roughly twice that for the case if the source were horizontal, facing downward.

The convective-heat-transfer characteristics will also be affected by the presence of a parallel plane to an extent which is dependent upon the distance of separation between the two planes. McAdams (Ref. 11) indicates that the values of the convective heat loss from a vertical radiating plane are not affected by the presence of a target surface representing a parallel plane if it is more than 2 cm. away from the radiating plane. In the present case where the source is horizontal, facing upward, and the model surface is in a parallel plane above it, the values of the convective heat loss from the radiating plane will most certainly be affected, particularly since the spacing between these planes is usually quite small. A decrease in the free-convection loss might be expected in this case as the model heats up because of the fact that there is less reason for any convection as the air above the source becomes heated in the region bounded by these two planes. Convective heat transfer between the source plane and the model surface is another factor which should be taken into account.

An investigation of the transient temperature decay of the Globars in the Mark I when the power was cut off revealed that the initial decay rate was of the order of 140°F per second in free air. Thus, the flux, which is proportional to the fourth power of the temperature, drops very rapidly, With the addition of a silicon carbide slab as a heat storage element, the maximum decay rate was found to be approximately 20°F per second. The measurement of the drop in temperature was recorded with an optical pyrometer. Results of a series of tests are given in Fig. 7.4.

SECTION VIII

SUMMARY

The operating characteristics of the Mark I high-temperature radiant heater measuring seven inches by twenty-four inches and employing Globar heating elements are summarized in the present section. Although designed specifically for application in the testing of aircraft structural models exposed to high intensity radiation on one surface in order to study the effects of thermal radiation from an atomic explosion on aircraft structures, its application to other problems is quite extensive. For example, laboratory work on the aerodynamic heating problem could be accomplished by the construction of an identical upper heater unit, which with little modification, would provide uniform irradiation on all surfaces of a structural model. The design of the Mark I heater also permits static or dynamic loading of the structural model while under the influence of high-intensity thermal radiation.

The complete Mark I radiant heating structural test facility consists of

(1) The Mark I heater source mounted on two hydraulic jacks which provide vertical movement and a base which is mounted on tracks to provide horizontal movement(see Fig. 6.3).

(2) A pneumatically operated shielding plate which serves to shield the model from the source (see Fig. 6.3).

(3) The test bed for mounting the aircraft structural models (see Fig. 6.3).

This report describes the Mark I heater source, its mode of operation, and its application as a radiant heating structural test facility. The most important features of the continuous infrared radiation source are as follows:

(1) Operating temperatures: continuous at any temperature level up to 3000°F in free air or as a closed unit.

(2) Power requirements: approximately 300 watts per square inch of radiating area of the Globar elements for 3000°F. A total of approximately 65 KW for the 7-inch by 24-inch Mark I source in free air at 3000°F. Power supply employed is an 87 KW DC motor-generator unit.

(3) Energy received by the models at three inches above the center of the source; at 3000°F, approximately 11.7 cal/cm^2sec.

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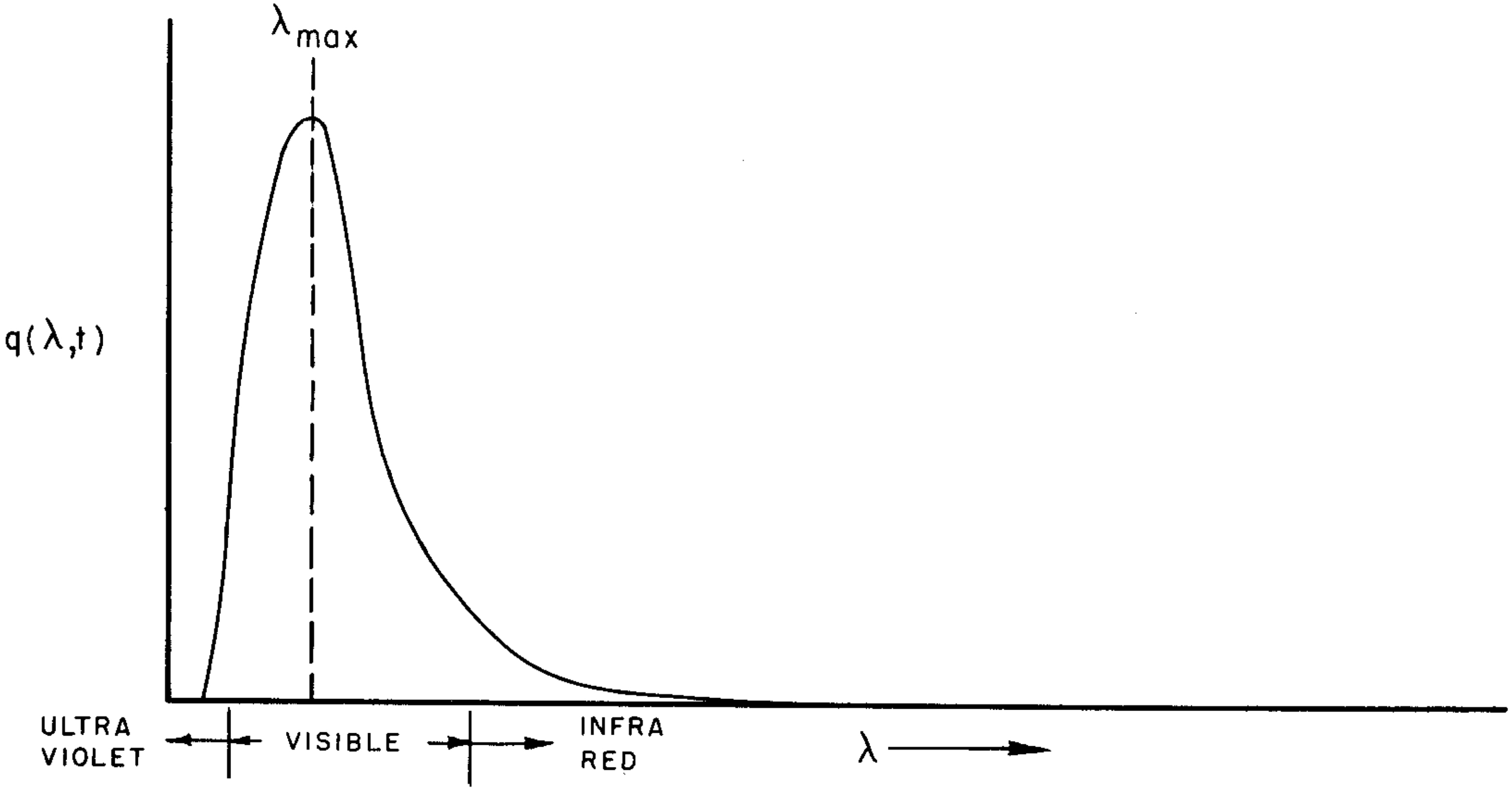


FIG. 3.1 QUALITATIVE SPECTRAL DISTRIBUTION OF RADIANT ENERGY FOR A SOURCE AT 10,000 °R

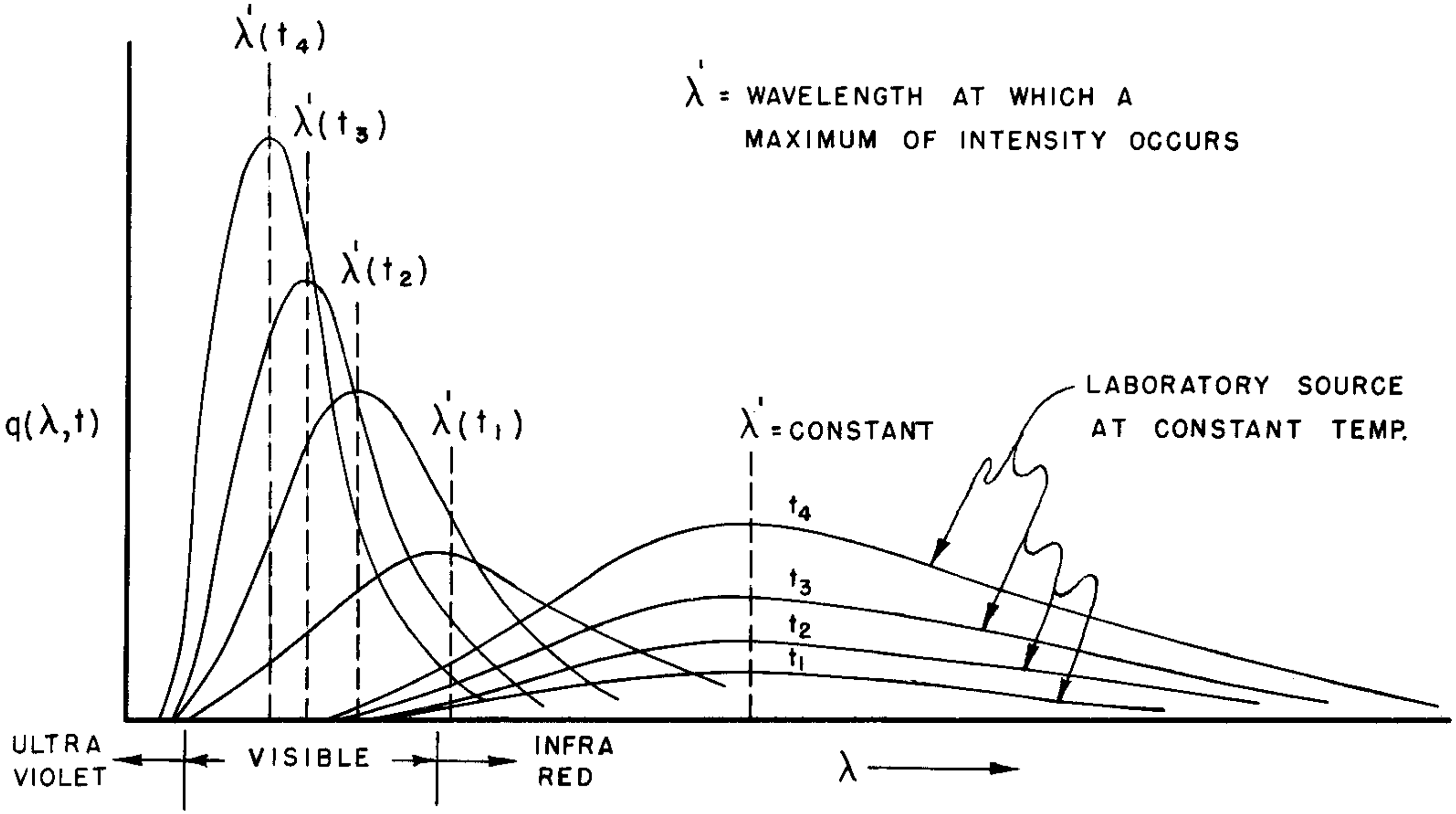


FIG. 3.2 A QUALITATIVE COMPARISON BETWEEN THE TIME VARYING SPECTRAL DISTRIBUTION OF THERMAL ENERGY FROM AN ATOMIC EXPLOSION AND THAT OF A TYPICAL LABORATORY SOURCE

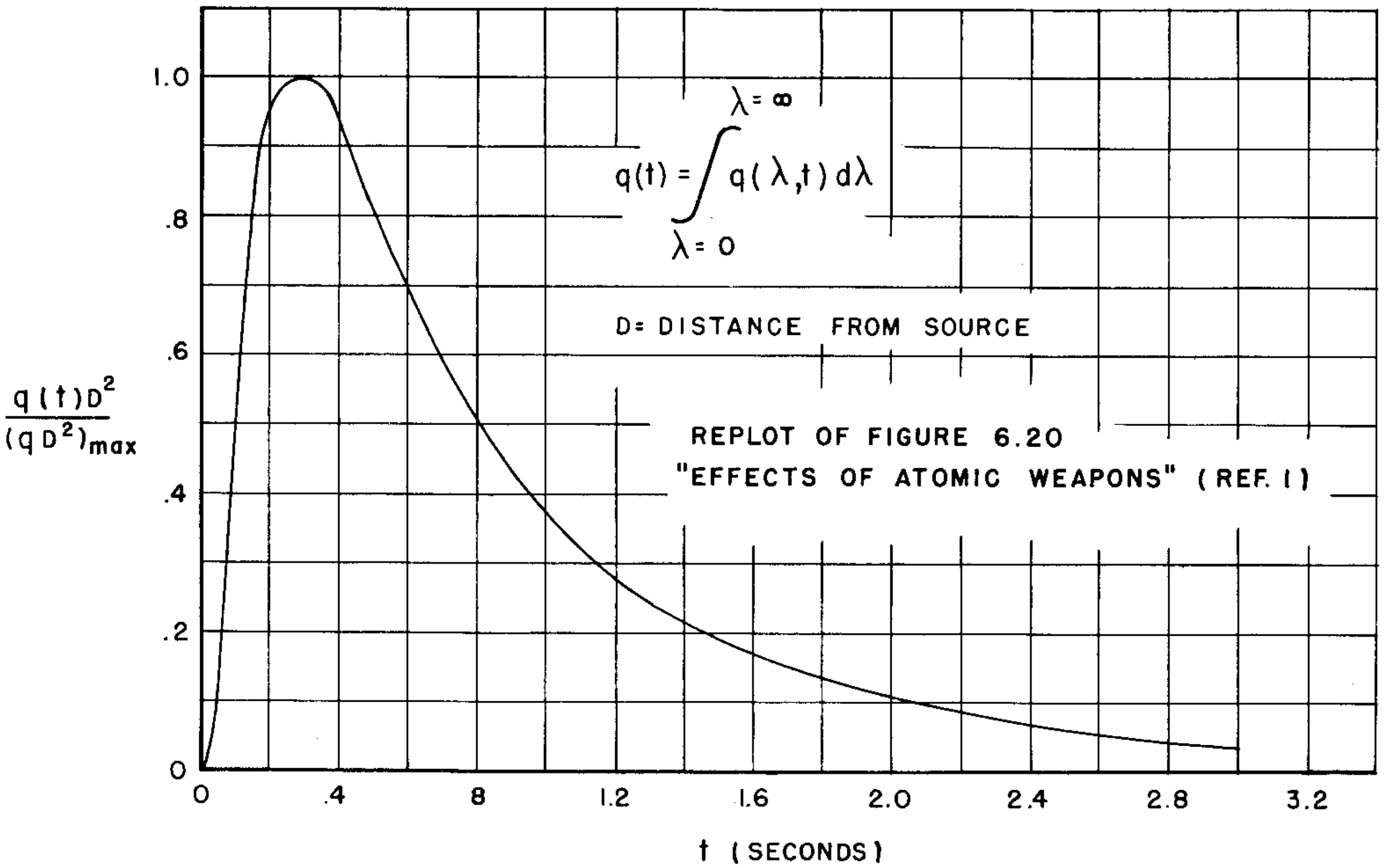


FIG. 3.3 NON-DIMENSIONAL SPECTRALLY INTEGRATED THERMAL ENERGY VERSUS TIME FOR A 20KT ATOMIC WEAPON

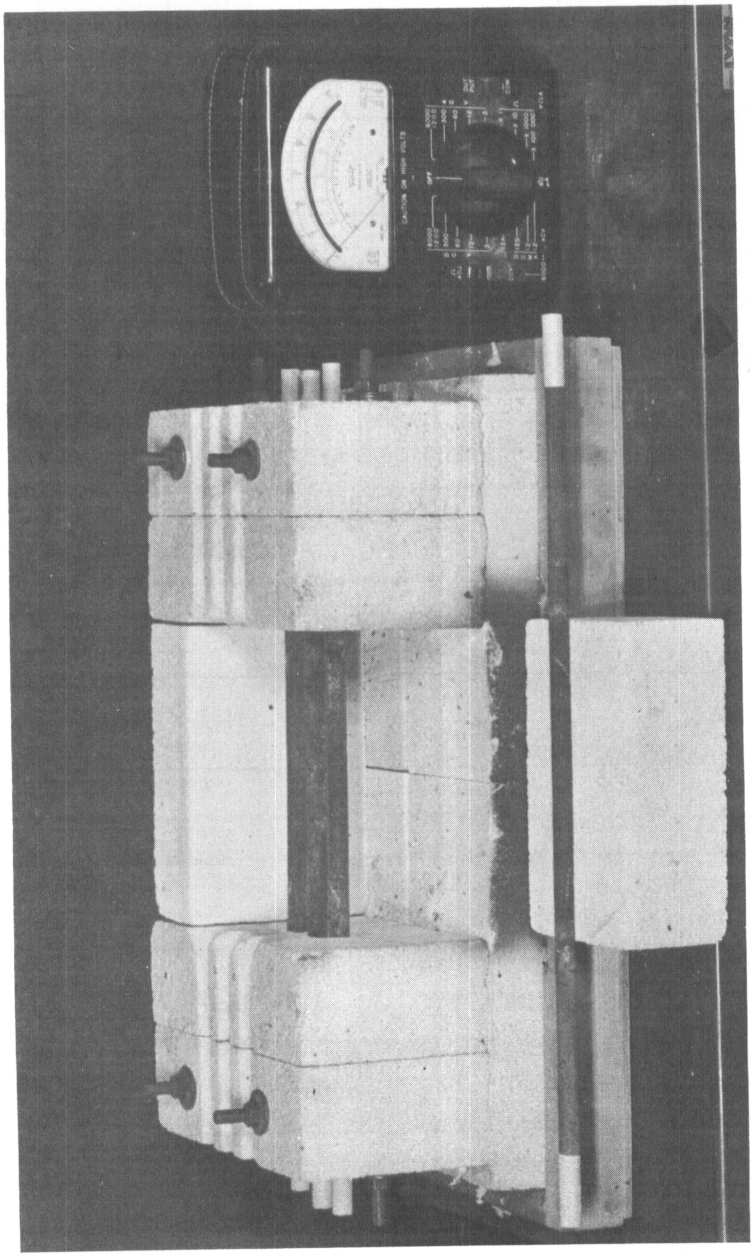


FIG. 5.1 MODEL A HEATER

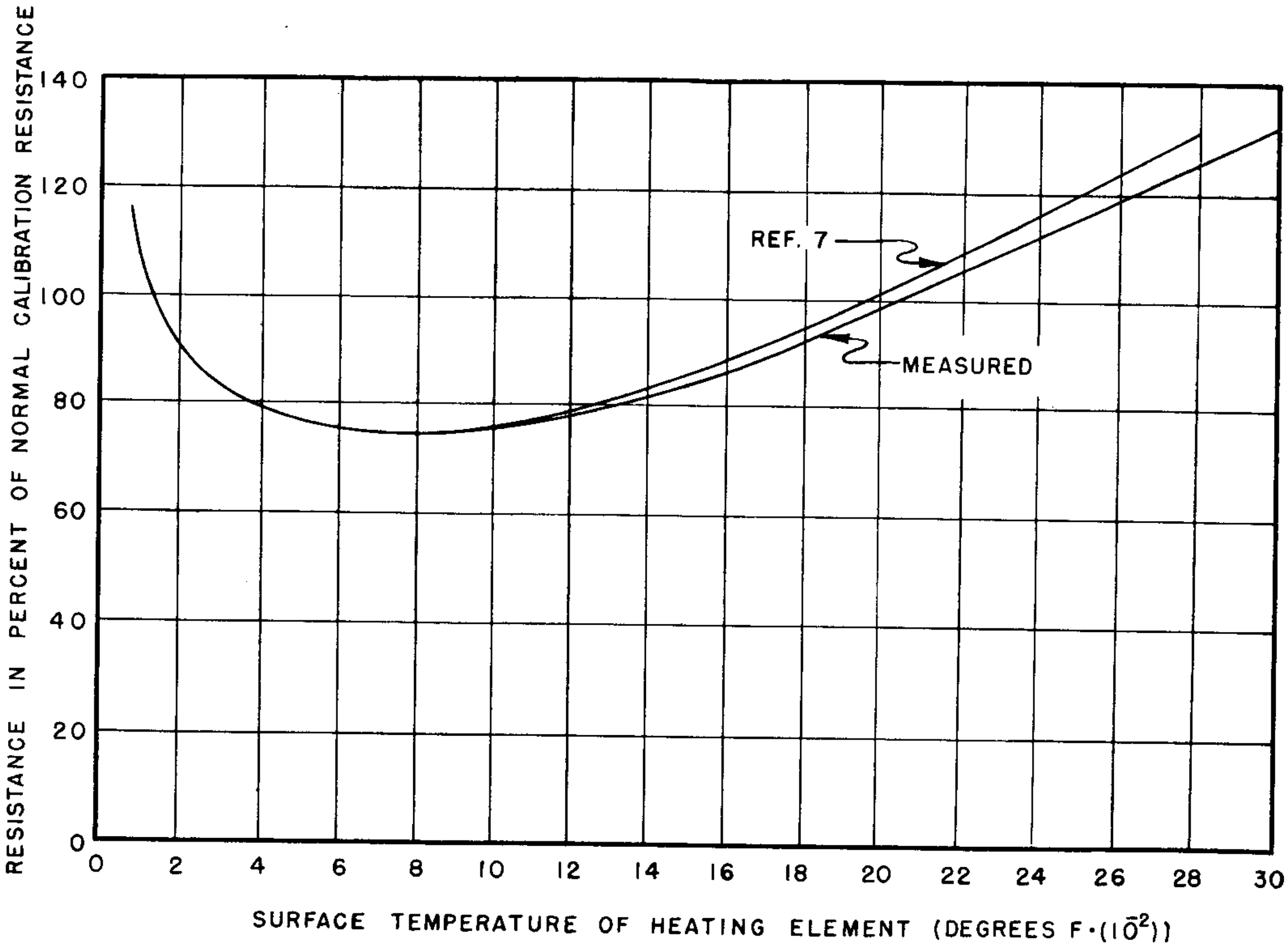


FIG. 5.2 GLOBAR RESISTANCE IN PERCENT OF NORMAL CALIBRATION RESISTANCE VERSUS SURFACE TEMPERATURE OF HEATING ELEMENTS.

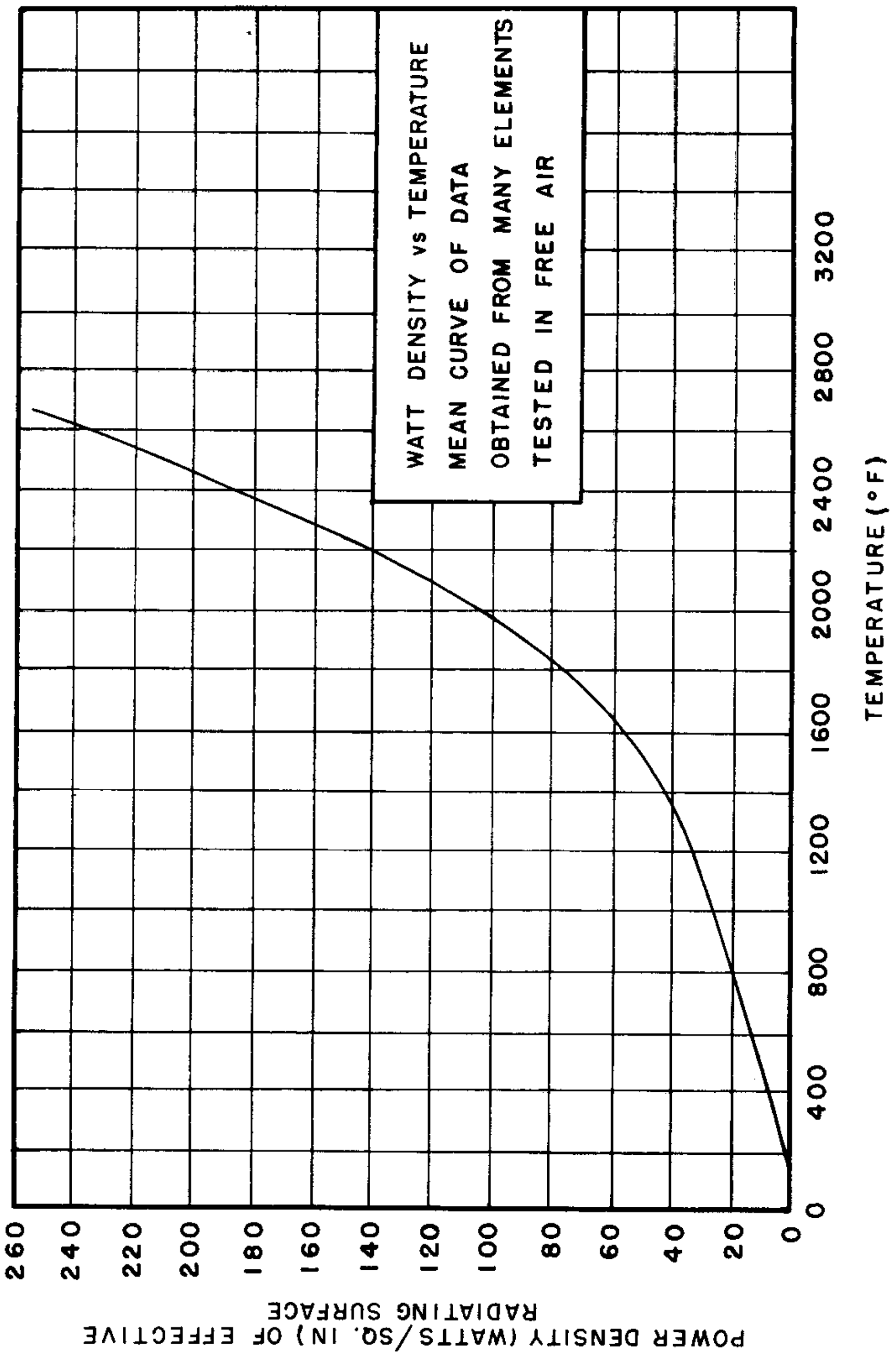


FIG. 5.3 MEAN CURVE OF WATT DENSITY VERSUS TEMPERATURE FOR GLOBARS OPERATED IN FREE AIR

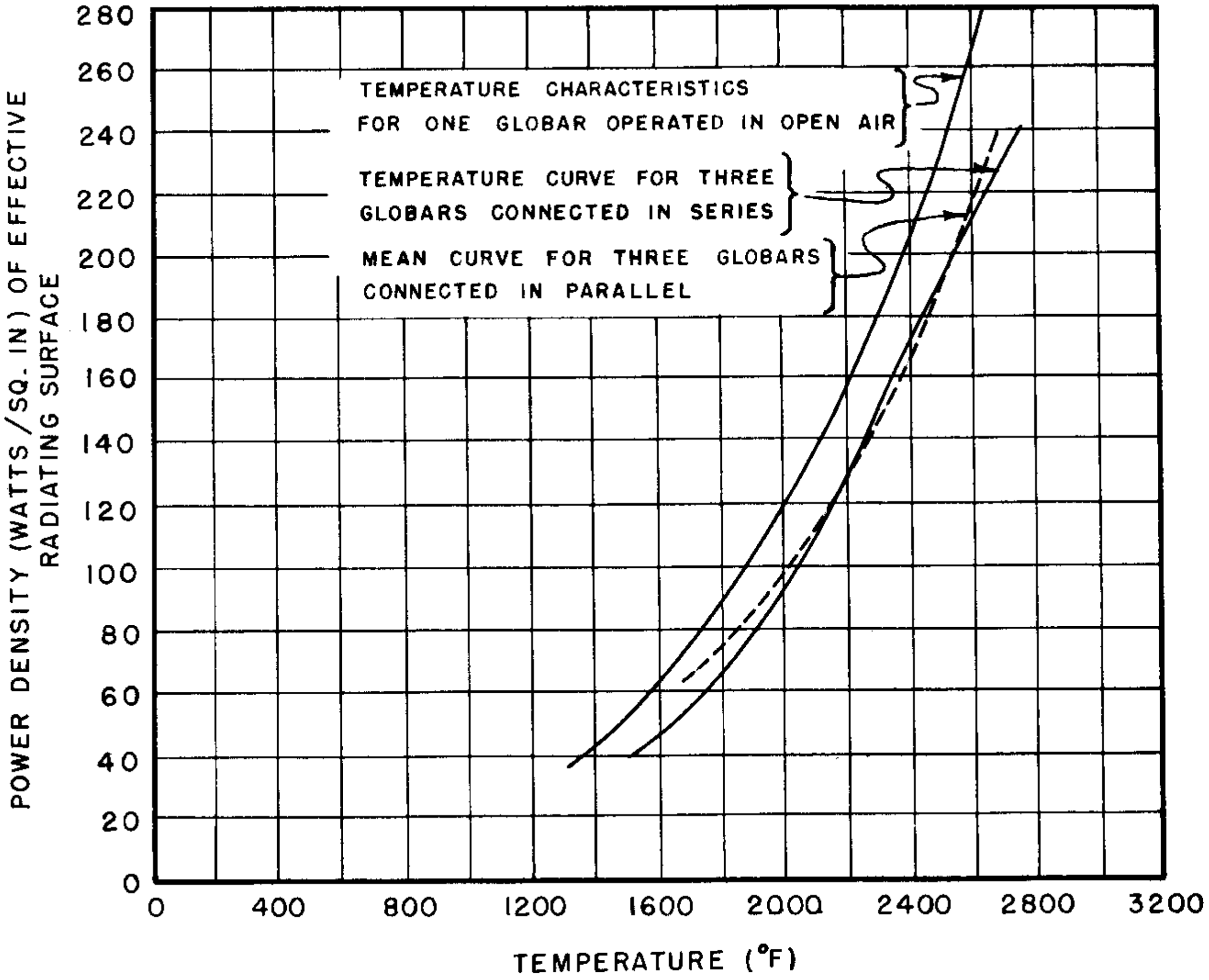


FIG. 5.4 WATT DENSITY LOADINGS FOR VARIOUS GLOBAR CONFIGURATIONS

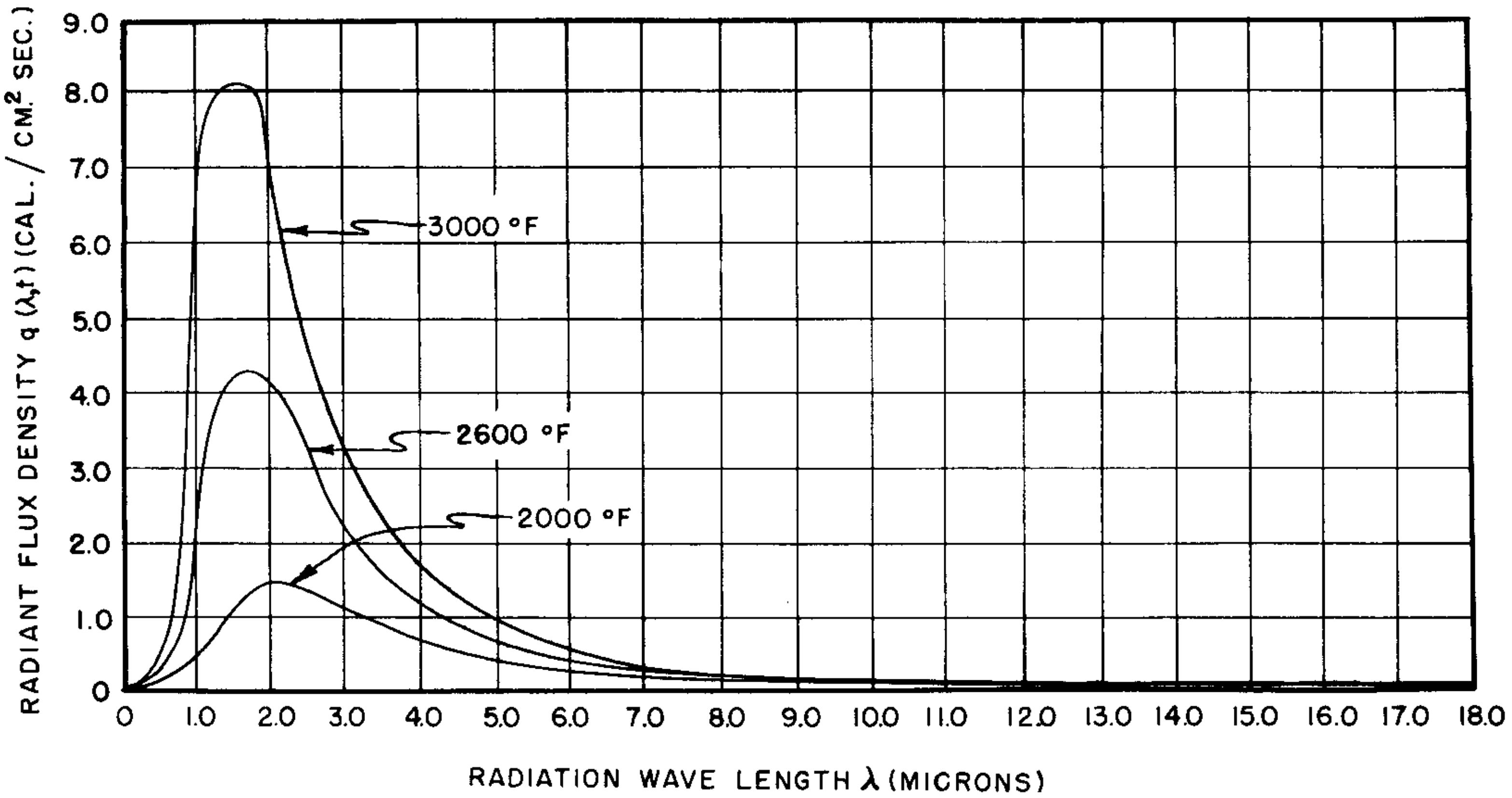


FIG. 5.5 THEORETICAL RADIANT FLUX DENSITY VERSUS WAVE LENGTH

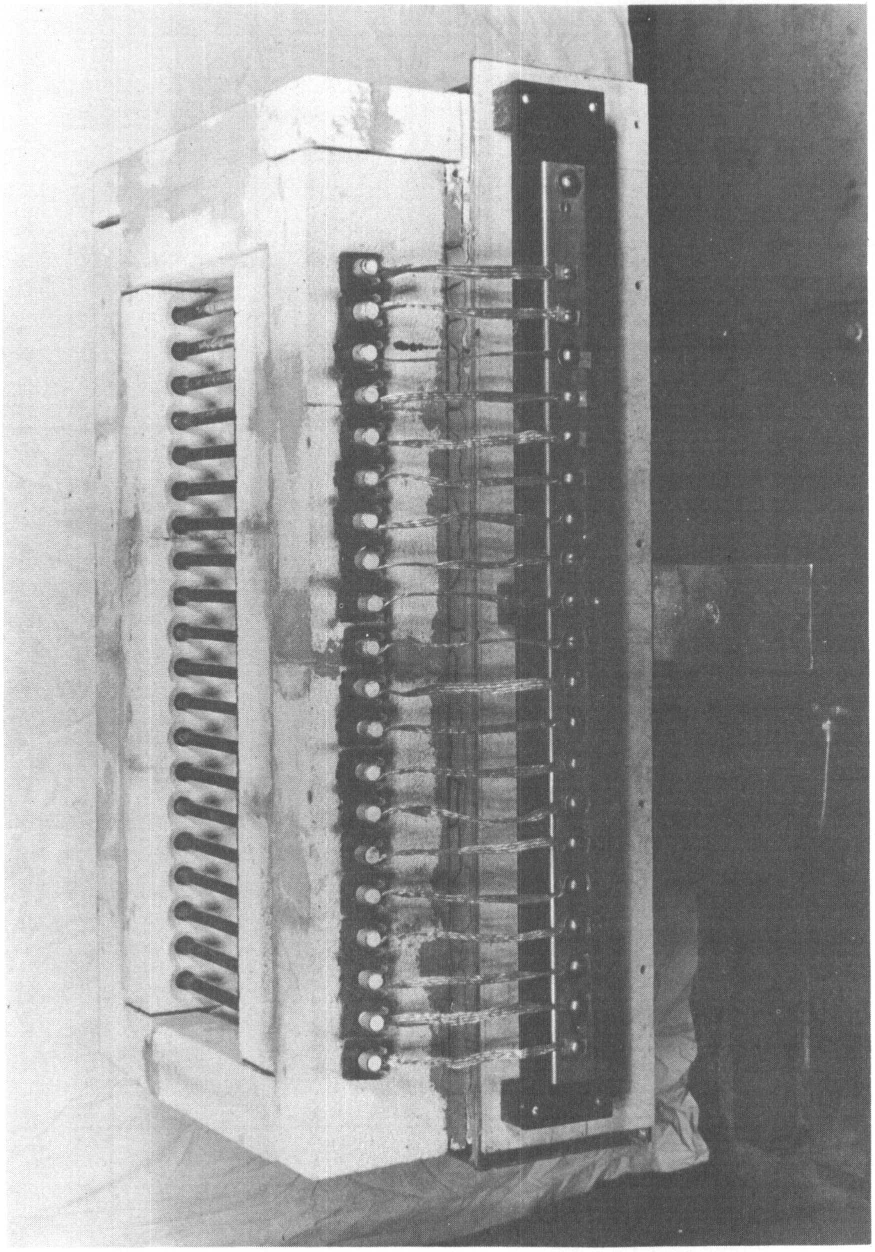


FIG. 6.1 MARK I HEATER

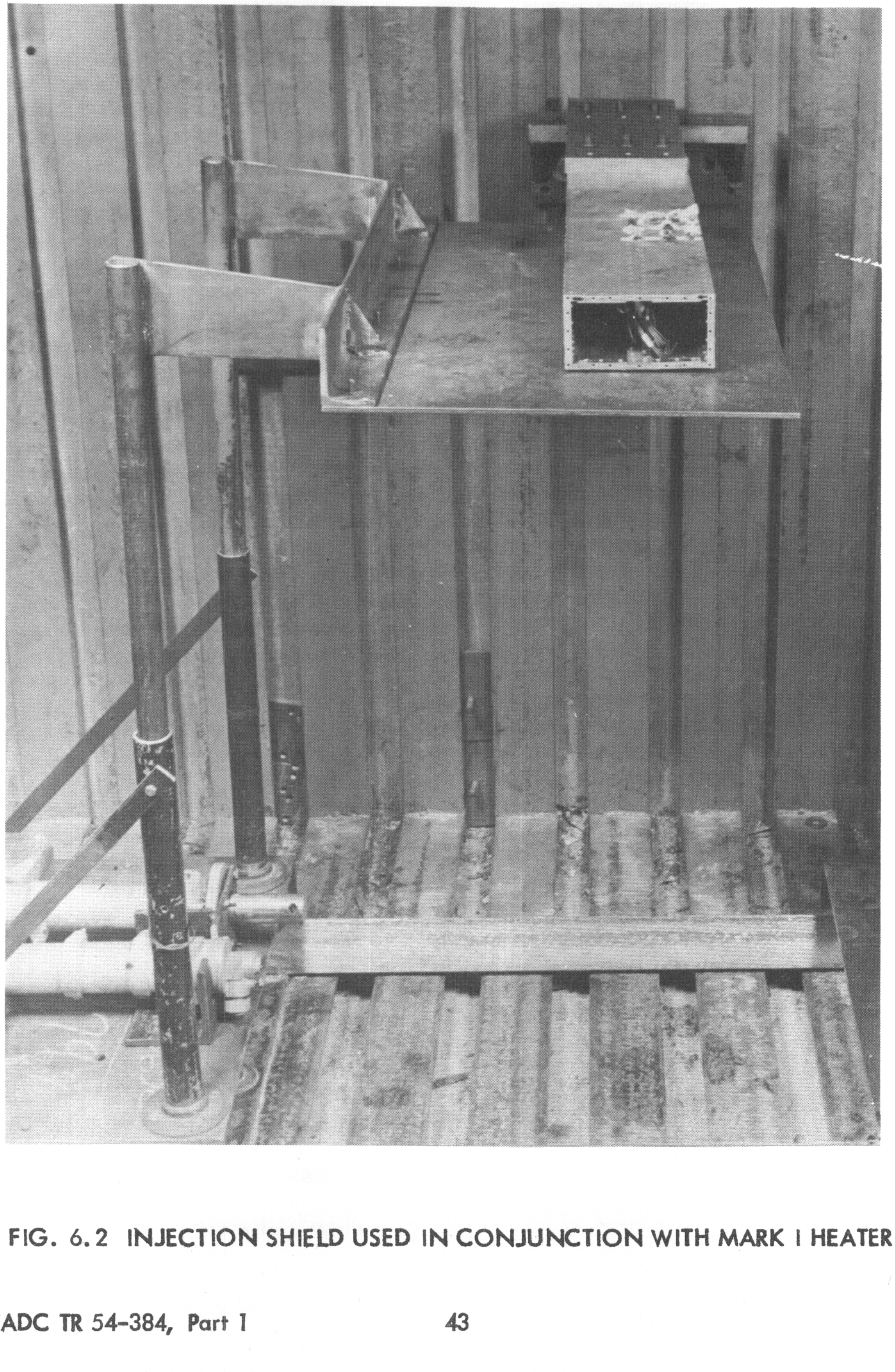
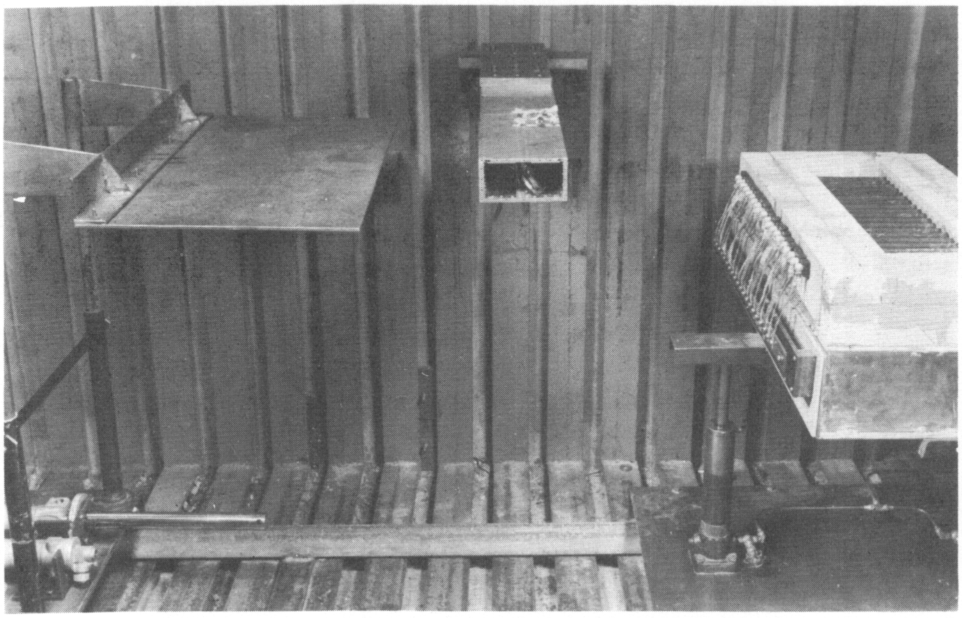


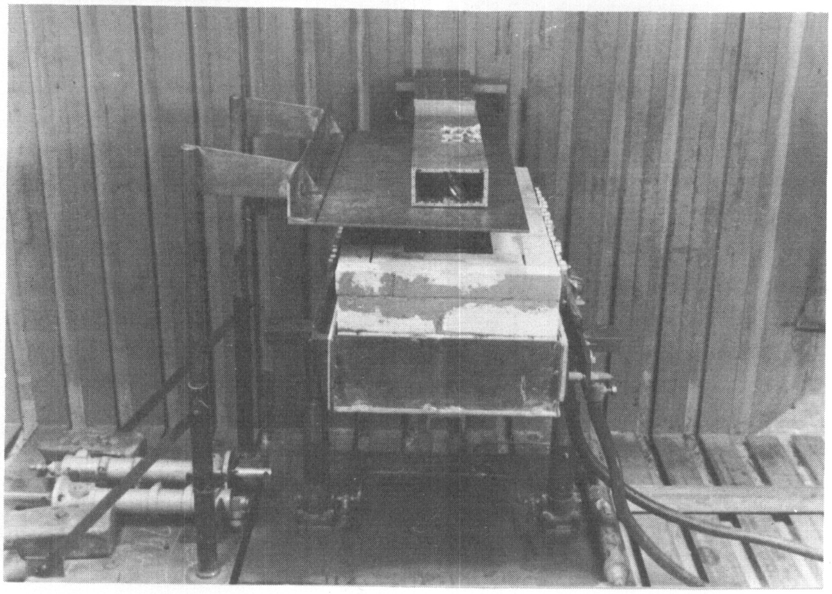
FIG. 6.2 INJECTION SHIELD USED IN CONJUNCTION WITH MARK I HEATER



(a) Pretest Configuration

(b) Shield is Injected

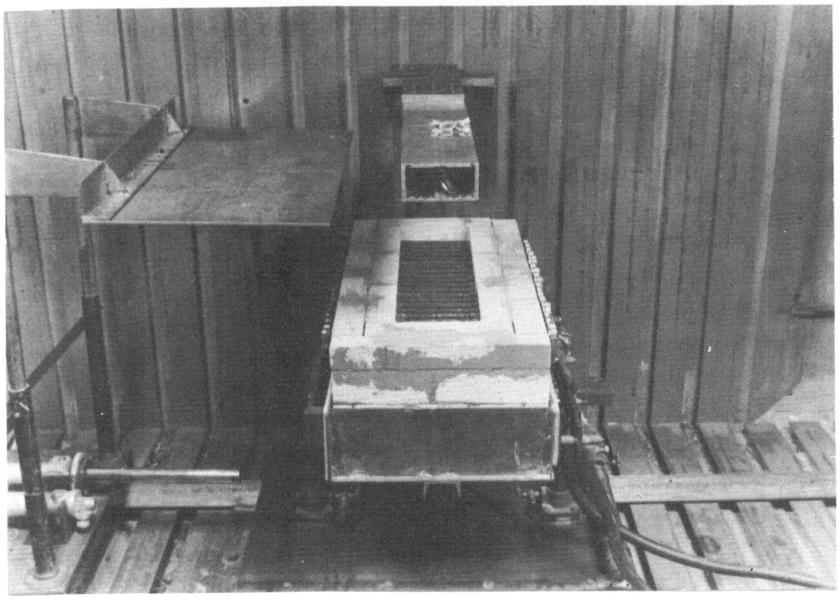
FIG. 6.3 SEQUENCE OF OPERATIONS



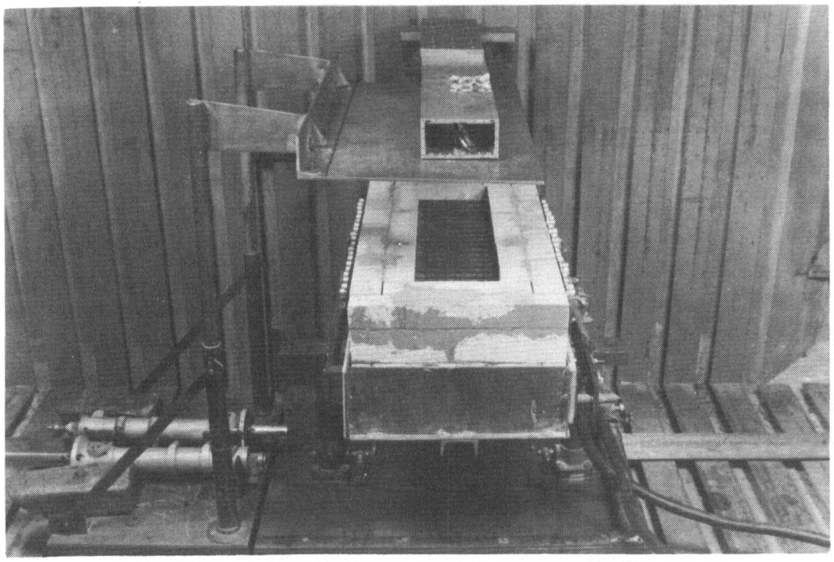
(c) Source is Introduced

(d) Shield is Ejected

FIG. 6.3 (Cont'd) SEQUENCE OF OPERATIONS



(e) Source Moves Down and Away From Specimen



(f) Shield is Re-injected

FIG. 6.3 (Concluded) SEQUENCE OF OPERATIONS

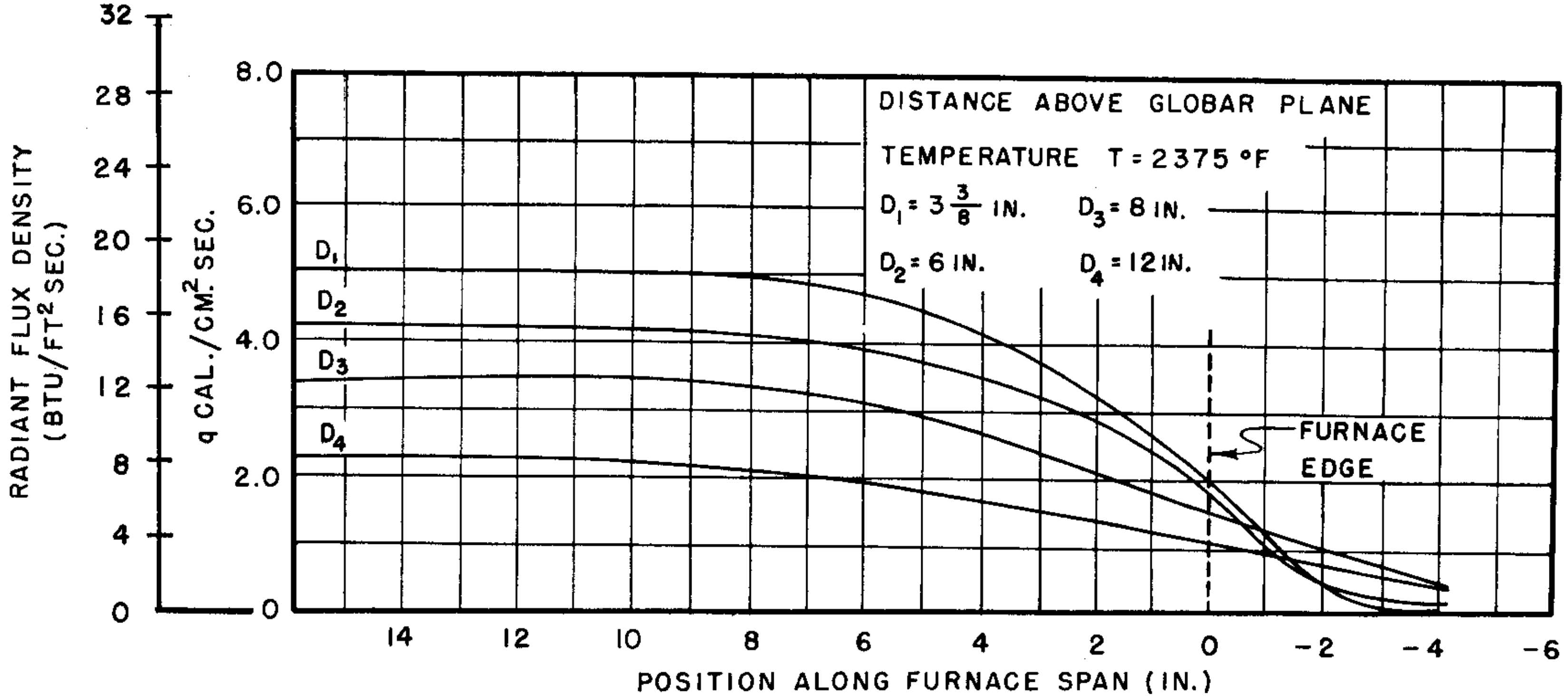


FIG. 7.1 SPANWISE VARIATION IN RADIANT FLUX DENSITY ALONG MID-CHORD FOR VARIOUS ELEVATIONS, WITH TEMPERATURE HELD CONSTANT

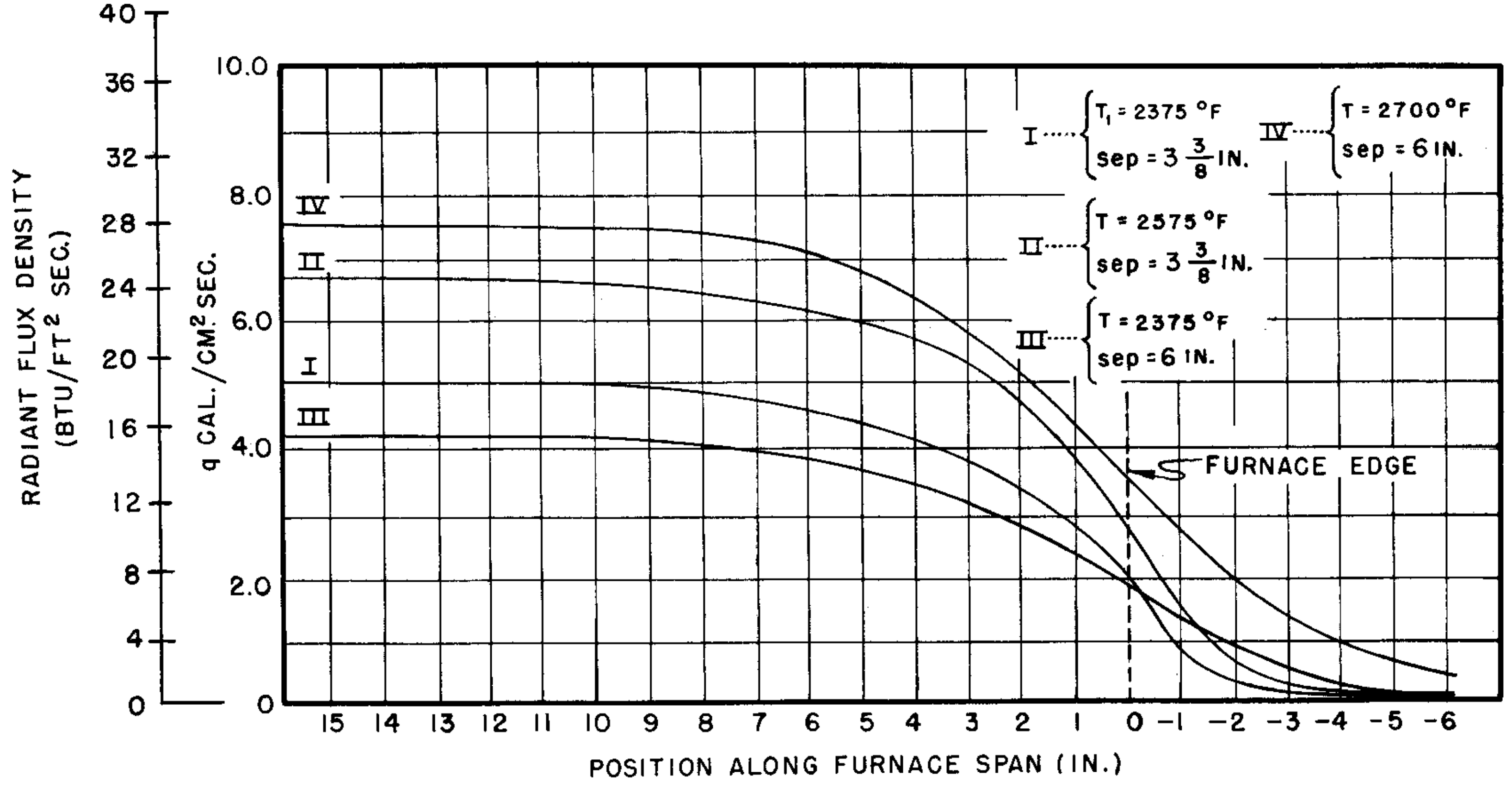


FIG. 7.2 SPANWISE VARIATION IN RADIANT FLUX DENSITY ALONG MID-CHORD FOR VARIOUS TEMPERATURES, WITH CONSTANT SEPARATION

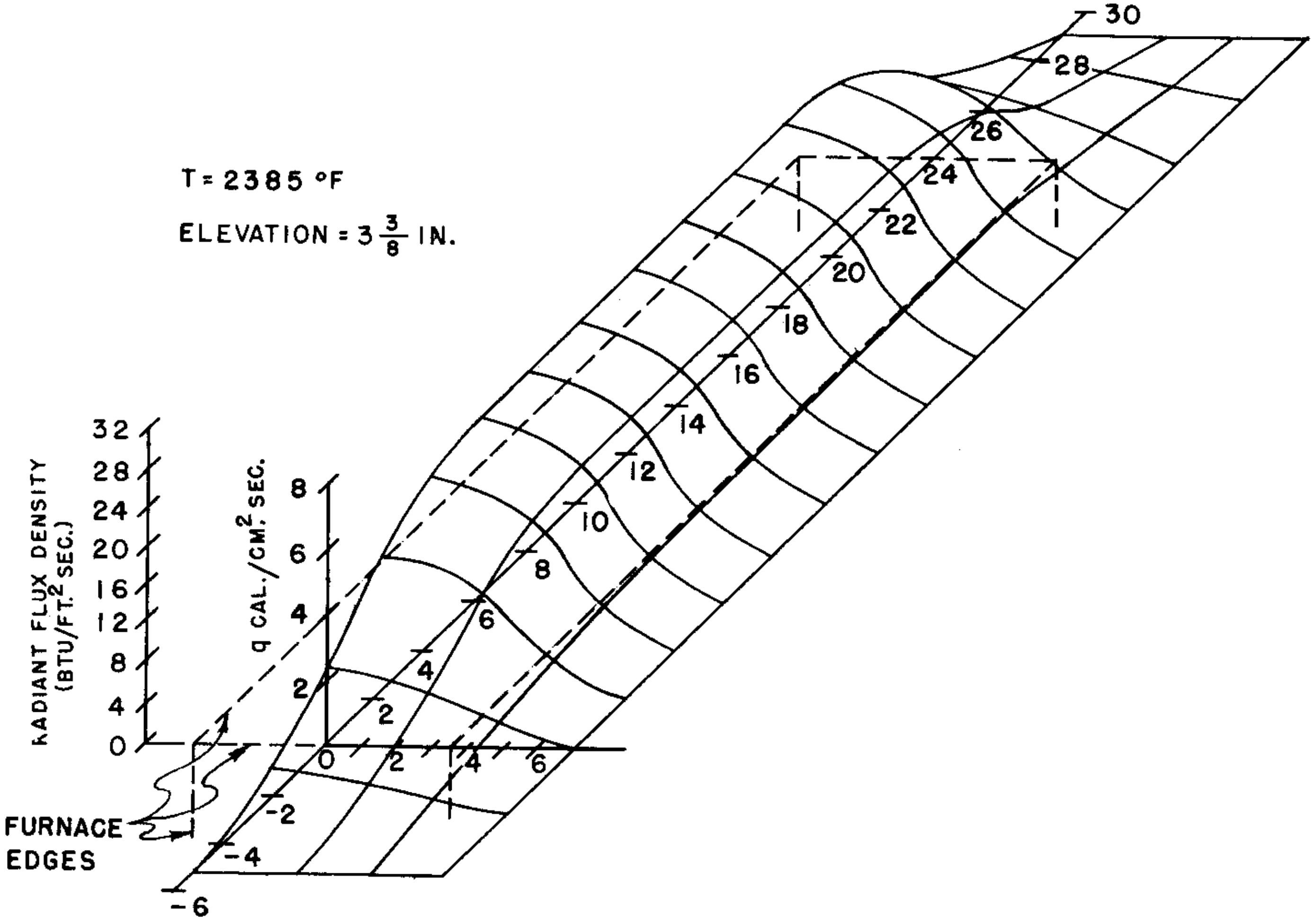


FIG. 7.3 VARIATION IN FLUX DENSITY FIELD AS FUNCTION OF POSITION AT A FIXED HEIGHT ABOVE THE GLOBAR PLANE.

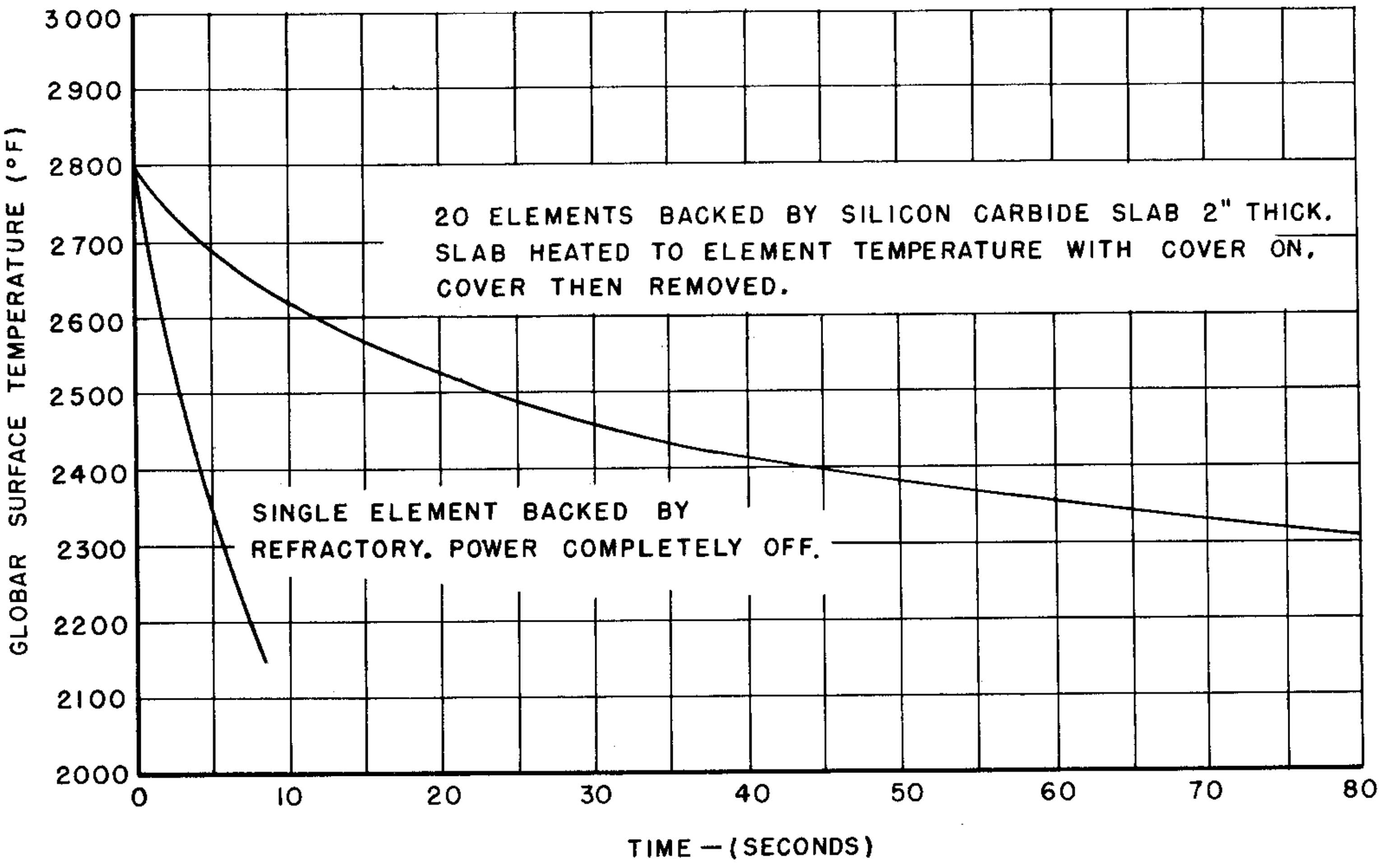


FIG. 7.4 DECAY TIME OF GLOBAR HEATER