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# EXPERIMENTAL DETERMINATION OF THE MAXIMUM SAFE THERMAL RADIATION LOADS FOR A FIGHTER-BOMBER COCKPIT

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**EXPERIMENTAL DETERMINATION OF THE MAXIMUM SAFE  
THERMAL RADIATION LOADS FOR A  
FIGHTER-BOMBER COCKPIT**

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## FOREWORD

The experiment reported here was accomplished by personnel of the Air Force Flight Dynamics Laboratory, Research and Technology Division, and Aerospace Medical Research Laboratories, Aerospace Medical Division. Personnel from the Air Force Flight Dynamics Laboratory worked under Project 1350, Task 135004; personnel from the Aerospace Medical Research Laboratories worked under Project 7222, Task 722204. The research was initiated March 1961 and completed January 1962.

This report was originally prepared informally for limited distribution as Flight Dynamics Laboratory Technical Memorandum, No. ASRMDS-TM-63-4. Because of the continued interest it has been decided to republish it in a form allowing a broader initial distribution and subsequent availability in the Department of Defense scientific and technical information structure.

This technical report has been reviewed and is approved.

WAYNE H. McCANDLESS  
Technical Director  
Biomedical Laboratory

## ABSTRACT

The maximum thermal radiation load to which the cockpit of a fighter-bomber may be safely subjected was determined experimentally. Fighter-bombers delivering nuclear weapons under cloud conditions may encounter these thermal radiation loads. A static F-100C cockpit was the test vehicle and four human subjects dressed in full flying equipment were exposed in it to thermal pulses simulating those of nuclear detonations. An unprotected cockpit and pilot can be safely subjected to a range from 3 to 5 cal/cm<sup>2</sup> if the yield of the weapon is approximately one megaton. This limit assumes adequate protection for the pilot's eyes. Materials in an unoccupied, unprotected cockpit will smoke profusely and char (but not flame) under a load of approximately 10 cal/cm<sup>2</sup>. Partial cracks will form in the plexiglass canopy under an absorbed load of approximately 11 cal/cm<sup>2</sup>.

## TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
I. INTRODUCTION . . . . .	1
II. EXPERIMENTAL APPROACH . . . . .	2
General Procedure . . . . .	2
Thermal Radiation Simulation. . . . .	3
Cockpit. . . . .	4
Instrumentation . . . . .	5
III. PRESENTATION OF DATA. . . . .	7
General. . . . .	7
Basic Data . . . . .	7
Additional Data . . . . .	16
IV. CONCLUSIONS . . . . .	18
V. RECOMMENDATIONS FOR PROTECTION PRIOR TO WEAPON DELIVERY . . . . .	19
APPENDIX I. EXPERIMENTAL PROCEDURE AND DATA ACQUISITION . . . . .	21
APPENDIX II. NUCLEAR DETONATION SIMULATOR SERIES . . . . .	34
REFERENCES. . . . .	35

## LIST OF ILLUSTRATIONS

<u>FIGURE NO.</u>	<u>PAGE</u>
1 General External View of Experimental Apparatus, Subject in Cockpit. Reflector and Canopy Up . . . . .	4
2 Static Aircraft Assembly, Canopy Closed, Reflector in Position for Thermal Exposure. . . . .	5

LIST OF ILLUSTRATIONS (Cont'd)

<u>FIGURE NO.</u>		<u>PAGE</u>
3	Calorimeter, Left, Radiometer, Right, Skin Simulant with Flight Suit Material Covering in Center. This Sensor Assembly at Level of Stick Grip . . . . .	6
4	Smoke from Electrical Insulation at Peak Exposure. View is Forward from Headrest . . . . .	11
5	Dissipation of Smoke from Electrical Insulation Near End of Thermal Pulse. View is Forward from Headrest . . . . .	11
6	Smoke from Maps and Charts Placed in Aircraft Seat. View is Forward from Headrest . . . . .	12
7	General Smoking of Indeterminate Origin. View is from Instrument Panel toward Headrest . . . . .	12
8	Early Canopy Deterioration. Concentrated External Cracking . . . . .	14
9	Deterioration of Canopy. Generalized Longitudinal Cracking . . . . .	15
10	Experimental Hood in Protective Position . . . . .	16
11	Absorption Characteristics of Plexiglass . . . . .	17
12	Idealized Thermal Radiation Pulse . . . . .	21
13	Infrared Lamps in Reflector, View is Upward from Aircraft . . . . .	23
14	Voltage Characteristics for G. E. T-3 Tubular Quartz Infrared Lamps. . . . .	24
15	Thermal Pulse Shape Correlation, $t_{max} = 1.0$ sec. . . . .	27
16	Thermal Pulse Shape Correlation, $t_{max} = 1.5$ sec. . . . .	27

LIST OF ILLUSTRATIONS (Cont'd)

<u>FIGURE NO.</u>		<u>PAGE</u>
17	Thermal Pulse Shape Correlation, $t_{\max} = 2.0$ sec. . . . .	28
18	Plexiglass Absorption vs Peak Lamp Wattage. . . . .	30
19	Atmospheric Transmission of Infrared Radiation (Sea Level) (Ref 4) . . . . .	30
20	Integrated Radiometer and Corrected Calorimeter Curves . . . . .	33

LIST OF TABLES

<u>TABLE NO.</u>		<u>PAGE</u>
I.	Human Subject Exposures . . . . .	8
II.	Response of Cockpit Components. . . . .	10
III.	Wavelength Intervals Characterized by Their Com- monly Accepted Identifying Names . . . . .	31
IV.	Fractional Black-Body Irradiance for Five Tempera- tures Contained within the Wavelength Intervals of Table III . . . . .	31
V.	Integrated Radiometer/Corrected Calorimeter Values. . . . .	32

## SECTION I

### INTRODUCTION

When an airplane delivers a nuclear weapon from a low-altitude approach and then escapes at a low altitude, it will encounter conditions that are different from those of high-altitude delivery and escape. If there are heavy cloud conditions in the target area, the cockpit of the airplane may be exposed to significant amounts of thermal radiation from the delivered weapon. To assure the safety of the delivering aircraft and the pilot and to assure a minimum sacrifice in accuracy of weapon-delivery, we must determine the maximum thermal load to which both cockpit and pilot can be safely subjected.

High-intensity thermal radiation loads in the cockpit can occur during delivery under heavy cloud conditions, one of the worst conditions being the fairly common one in which there is total overcast over a snow covered terrain. In this experiment we did not concern ourselves with where and under what conditions the cockpit would receive the maximum safe load, since this is a function of cloud-terrain conditions and airplane-burst geometry. We were concerned only with determining the maximum safe load for the cockpit and pilot.

One method of determining maximum safe load is to expose all of the cockpit materials in separate, carefully controlled exposures and then integrate the results of the separate exposures into a specification for hazardous thermal radiation loading. This approach, although logical and sound, is complex and requires extensive and precise correlation to assure that all factors have been properly considered.

In the experiment reported here, a "brute-strength" procedure was used to complement the detailed approach and to establish a rough estimate of the maximum thermal radiation to which an operational fighter-bomber cockpit and pilot can be safely subjected. This experiment involved exposing a real cockpit and pilot to increasing levels of thermal radiation loads until a limit response was obtained.

The brute-strength procedure required a massive electrical power handling and control capability, and an actual cockpit; in this experiment a Class 26 (salvage) F-100C aircraft. The necessary electrical power handling and control capability became available during October 1961 (a previous attempt (ref 1) at conducting the experiment had been suspended until there were full-scale facilities) and the experiment was completed by mid-January 1962. Some of the results obtained before the first attempt was discontinued

were used in making estimates of the maximum thermal loads a pilot could tolerate (ref 1). Only the second series of experiments is reported here. The text of this report is limited to the results obtained.

There are two appendices. The first gives a detailed discussion of the experimental setup, the data acquisition techniques and data reduction, and the analysis techniques projected in the main text. The second appendix describes a special application of the experimental apparatus that served to orient a selected group of operational pilots to the hazards of thermal radiation in the cockpit.

The primary objective of the experiment was to determine the maximum load of thermal radiation to which an operational cockpit and a pilot can be safely subjected. The following configurations were studied:

- Unoccupied, unprotected cockpit
- Occupied, unprotected cockpit
- Unoccupied, protected cockpit
- Occupied, protected cockpit

The second objective was to describe the response of cockpit components and establish the safe limit.

The third objective was to investigate the effect of varying the yield of the weapon since this may affect the tolerable limit. With larger yields the time-energy relation is changed.

## SECTION II

### EXPERIMENTAL APPROACH

#### GENERAL PROCEDURE

The entire cockpit and its components were exposed to massive thermal radiation loads of increasing intensity until individual components reached their limit. Limits were real and extrapolations were avoided. A non-limiting response, from either cockpit component or pilot, was that which indicated the component was affected, but still operational, or a response which indicated the pilot was aware of thermal radiation loads, but still capable of functioning as a pilot. The limit response occurred when the subject felt that exposure to a greater level of thermal energy would produce intolerable hazard, pain, or injury.

During the first experiments, thermal radiation intensity was low enough to assure that no hazard existed, then intensity was increased in small increments until a limit response was obtained. This procedure was repeated for each configuration. When a nonlimiting response, such as charring of insulation on exposed wiring, was obtained, the pertinent data were recorded and then the component concerned was protected by covering it with aluminum foil to prevent cumulative effects from masking the primary responses. This procedure was a compromise because its use assumed that a more severe response of the damaged item would not be classified as a limiting response.

#### THERMAL RADIATION SIMULATION

Thermal radiation was simulated by duplicating an idealized thermal radiation curve. In this curve (fig. 15, p 27 ) irradiation (rate of energy delivery) is plotted versus time and the curve is normalized with respect to both peak intensity (determined by the range from the burst) and time to rise to peak intensity (determined by the weapon yield). By duplicating this pulse shape, while maintaining the capability to vary the peak intensity and time to rise to peak intensity independently, any combination of weapon yield and intensity could be simulated within the capability of the power supply and control equipment.

The angular variation of the thermal radiation field of an actual detonation, incident on the cockpit, was not known precisely. Therefore, a generalized input was devised. The incident flux was made as constant as possible over the entire canopy. Although this is not what actually occurs, it was considered to be accurate enough for an experiment designed to give only generalizations.

The laboratory thermal radiation failed in two ways to simulate the real input received by an aircraft delivering a nuclear weapon: in the spectrum of the thermal radiation and in the geometry of the input. The laboratory source radiated at a varying, but always lower temperature than the aircraft would receive from a real weapon. This puts a larger percentage of the laboratory energy in the infrared region of the spectrum. The geometric breakdown in the simulation occurred for two reasons. In an actual delivery, the intensity of the radiation field will vary by only a negligible amount over the distance from the top to the bottom of the cockpit (neglecting shielding effects of the airplane). However, because of the proximity of the laboratory source of radiation, the variation is not negligible in this experiment. Since the experimental setup could not precisely simulate the spectrum of the thermal radiation or the actual geometry of a delivering aircraft, the results obtained in the laboratory experiment had to be correlated with actual conditions and the correlation analyzed. Procedures for the correlation and analysis are described in the data reduction and analysis section of appendix I.

## COCKPIT

A salvaged F-100C provided the cockpit (fig. 1). Except for some of the radio controls, which had already been removed, the cockpit was complete. It was not specially cleaned and no repairs were made since it was thought that this would be a reasonable simulation of an operational cockpit. For some experiments a skin simulant was used in lieu of a human subject (fig. 3, p 6). In the others human subjects were tested wearing the complete summer flying clothing and personal equipment of an Air Force tactical pilot (fig. 2).

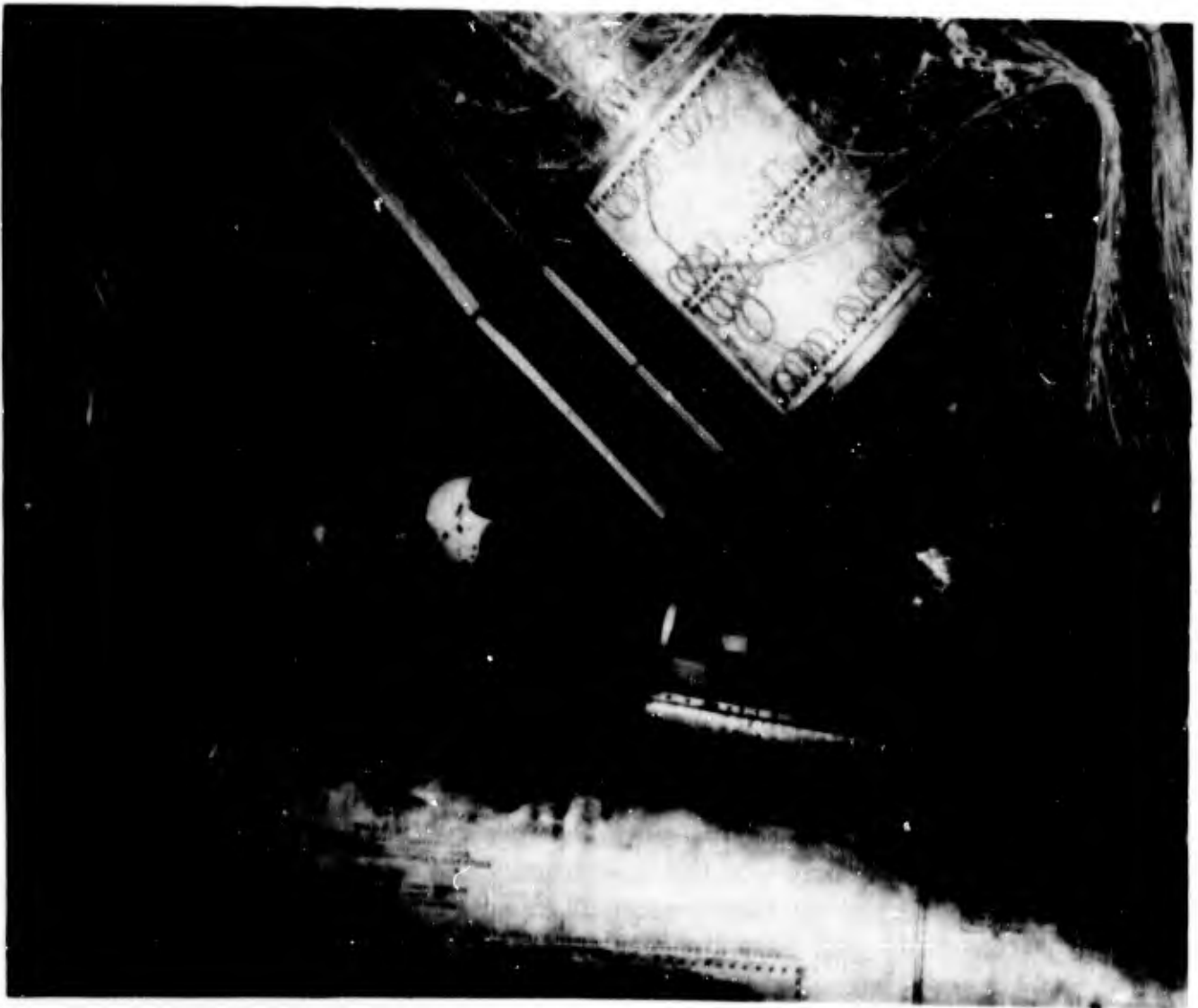


Figure 1. General External View of Experimental Apparatus, Subject in Cockpit. Reflector and Canopy Up.



Figure 2. Static Aircraft Assembly, Canopy Closed, Reflector in Position for Thermal Exposure.

## INSTRUMENTATION

### Cockpit

The cockpit was instrumented with eight radiometers to measure the rate of delivery of energy, and eight calorimeters to indicate the total energy delivered. Radiometers and calorimeters were paired and these pairs were spaced appropriately over the interior and exterior of the cockpit. Because of the variations in the energy received at various points in the cockpit due to the geometry, the value of correlating laboratory data with that of an actual detonation depends upon having measured the input at the precise point where a response occurred. Still and motion pictures taken during the experiment were used as an aid in analyzing results.

### Pilot

When human subjects were used, thermocouples sensed four skin temperatures (forehead, chin, shoulder, and knee) and the rectal temperature.

A continuous electrocardiogram was recorded. In consultation with vision specialists, it was decided that having the subject close his eyes during the exposure would adequately prevent injury from the unknown effects of the diffuse thermal and visual energy of the experiment.

During experiments considered beyond the tolerance of human subjects, a simulant for human skin placed on a block of Beetle-silica was exposed (fig. 3). A copper-constantan thermocouple imbedded to a depth of 0.05 cm in the simulant measured the temperature (appendix I).

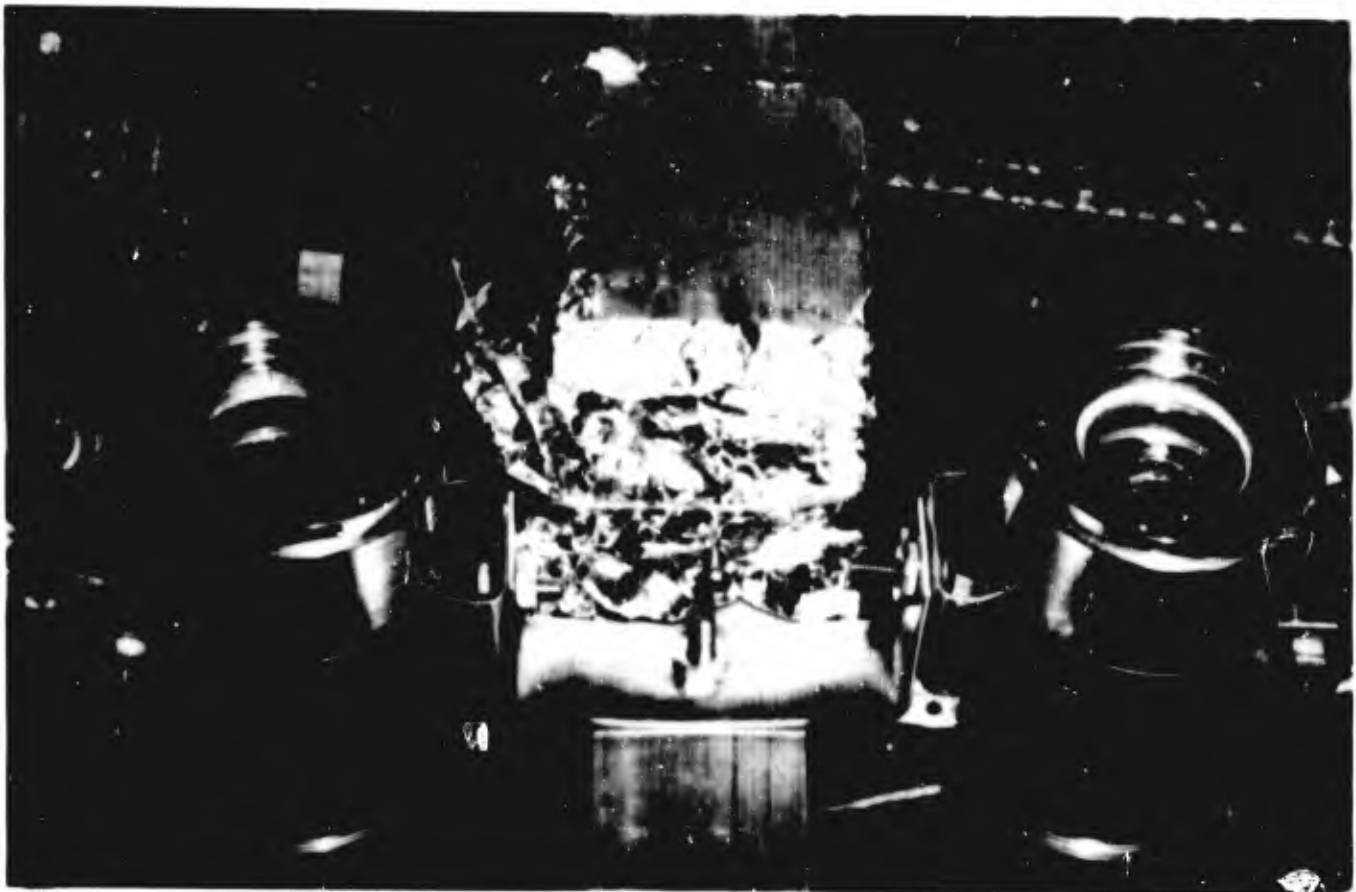


Figure 3. Calorimeter, Left, Radiometer, Right, Skin Simulant with Flight Suit Material Covering in Center. This Sensor Assembly at Level of Stick Grip.

## SECTION III

### PRESENTATION OF DATA

#### GENERAL

Data obtained during the experiment have been divided into two types: basic data and additional data. The basic data consist of measured loads of thermal radiation (energy received and time during which the energy was delivered) at which specific responses were obtained from the cockpit. The additional data serve to limit the validity of the basic data.

#### BASIC DATA

##### Unprotected and Occupied Configuration

Smoke from the headrest was the only response obtained from the cockpit at load levels within the pilot's tolerance. Therefore, we are concerned only with the response of the pilot in this configuration. Because the subject closed his eyes, the data are applicable to the operational situation only when the pilot's eyes have been properly protected.

Four human subjects, dressed in complete summer flying equipment, were exposed in a series of experiments during which the radiation loads were progressively increased until each subject said that he had reached the limit that had been specified as "distinct" but not "intolerable" pain. Each subject completed the entire series before the next subject began. No subject saw other experiments before he participated. No subject knew the load levels to which any other subject had been exposed. Appendix I contains more complete descriptions of the pilot's exposures.

The following data describe the exposures in which the human subjects participated. All of the exposures simulated a 1 megaton yield with a time to peak energy ( $t_{\max}$ ) of 1 second.

TABLE I  
HUMAN SUBJECT EXPOSURES

Exposure Number	Energy (cal/cm <sup>2</sup> )	Position	Subjects
1	1.4 1.0	Head Hands	—
2	2.1 1.3	Head Hands	—
3	2.5 1.6	Head Hands	—
4	2.9 1.9	Head Hands	A and B
5	3.2 2.0	Head Hands	D
6	3.5 2.2	Head Hands	C

---

NOTE: Loads specified are the energies crossing horizontal planes, located at head and hand positions. Load level on the forehead will vary from the head position load level because of the vertical orientation of the forehead.

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The subjects always reported two hot spots—the bare forehead (protected only by a lowered visor) and the portion of the knee that was under only a single layer of tautly stretched summer flying suit. One subject had the collar of his flying suit under his flight jacket, thereby exposing a small portion of the bare neck that became a hot spot.

Subject A wore brown leather summer flying gloves through exposure level 3. On exposure level 3, the surface of the gloves seared and caused some pain at the hands.

After A's experience, the leather flying gloves were discarded and the wool winter inserts were worn without the brown leather outer gloves. This change reduced the hand response from pain to merely hot. Subsequent subjects made all of their runs wearing only the wool inserts.

Since there were variations in the load levels at which the subjects reported they had reached the prescribed limit of "distinct pain," subject A made an additional series of runs at load levels 3, 4, 5, and 6. An irregularity caused the attempted run at load level 5 to duplicate the run at level 4 and the subject went directly to level 6. Level 6 was extremely uncomfortable and the pain on the knee distinct enough that the knee was moved involuntarily during the pulse and the subject cringed, jerking his head forward and down. We could only deduce that either the response of subject C to exposure level 6 was less than the response of subject A, or subject C's interpretation of the limit criteria varied significantly from subject A's interpretation.

No attempt was made to evaluate the responses for larger yield simulations (longer  $t_{\max}$ ), and smaller yield simulation was limited too severely by the power rise time of the tungsten lamps to make an evaluation possible.

Table I constitutes the basic data--the rough estimate of thermal radiation loads to which an unprotected, occupied cockpit may be safely exposed.

#### Unprotected and Unoccupied Configuration

The data consist of responses of cockpit components and the thermal radiation loads that produced the responses. Exposures simulated 1 megaton ( $t_{\max} = 1.0$  sec) until peak power was used, 2 megaton (1.5 sec) until peak power was used, and finally 4 megaton devices (2.0 sec) until the limit response was obtained. No variation with yield (time of irradiation) was examined because of equipment limitations.

The response data obtained from the canopy and the response data from the interior of the cockpit are presented separately because of the correlation problems associated with the response data of the canopy.

The data obtained from the interior of the cockpit are straightforward. First, there was the load level at which vulnerable materials (red leatherette headrest and black rubber insulated wire) began to respond; then, less vulnerable items began to respond as the load levels were increased. Finally, a load level was obtained at which a plentiful and less vulnerable item (such as the black paint in the cockpit) began to respond. This point (the response of a plentiful and durable item) was defined as a limit load level.

Table II lists critical materials within the cockpit and the load levels at which they responded. The load levels are those levels measured by the instruments closest to the responding item. Table II also presents the  $t_{\max}$  associated with the run in which the response was obtained.

TABLE II  
RESPONSE OF COCKPIT COMPONENTS

Component	Load Level (cal/cm <sup>2</sup> )	$t_{\max}$ sec
Headrest (red leatherette)	2.1	1.0
Black rubber electrical insulation	2.5	1.0
Leather case (located back of headrest)	4.6	1.0
Tape for electrical wires	5.5	1.0
Plastic electrical insulation	5.2	1.5
Material of indeterminate origin (general, slight smoking)	6.2	2.0
White cloth electrical insulation, canvas scalars for air flow hoses, and paint on air pressure regulator label	10.4	1.0

All of the responses in table II involved smoking and charring, although some items that smoked profusely did not char severely. At no time did any of the cockpit components flame. The lack of ignition is to be noted since the cockpit was quite dirty from use. Although the crudity of our methods does not allow direct correlation, these figures compare reasonably with published data (ref 3). Maps, K2B summer flying suit material, winter flying suit material, and manila folder material were mounted on a piece of aluminum and also exposed. At a load level of 6.5 cal/cm<sup>2</sup> with a  $t_{\max}$  of 1.5 seconds, all of these materials charred slightly and the map sample ignited. Figures 4 - 7 show the smoking that occurred from various components.



Figure 4. Smoke from Electrical Insulation at Peak Exposure.  
View is Forward from Headrest.



Figure 5. Dissipation of Smoke from Electrical Insulation  
Near End of Thermal Pulse. View is Forward  
from Headrest.

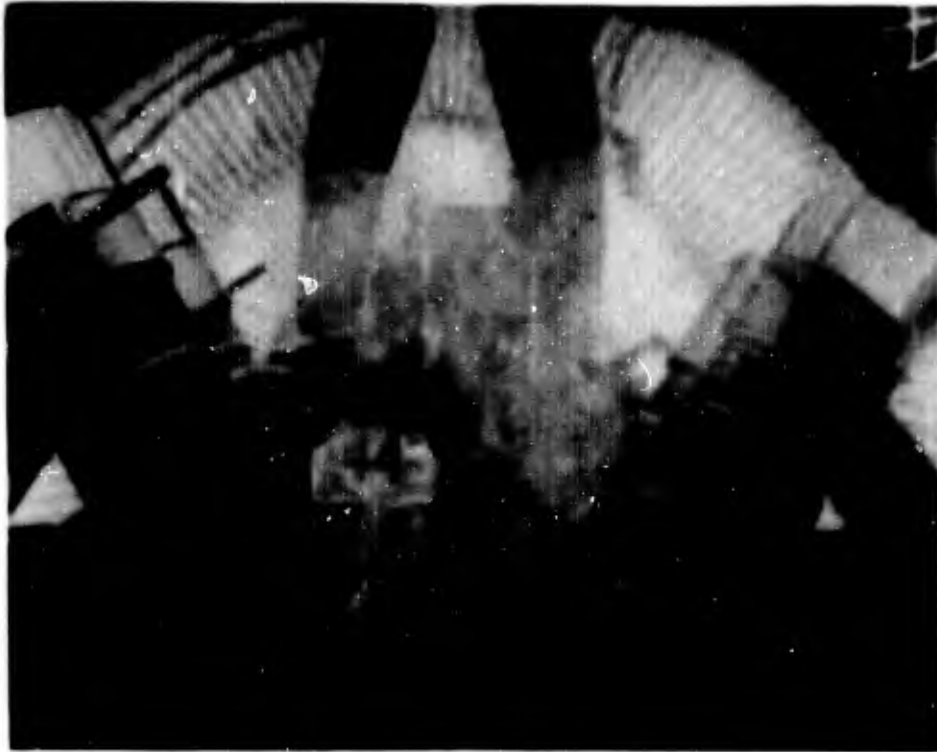


Figure 6. Smoke from Maps and Charts Placed in Aircraft Seat.  
View is Forward from Headrest.

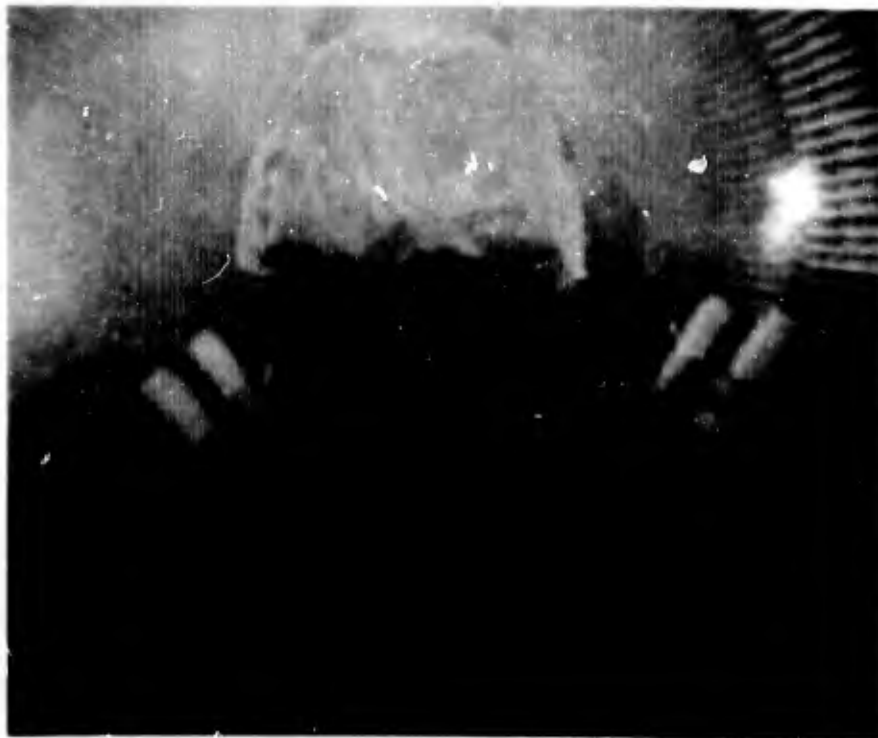


Figure 7. General Smoking of Indeterminate Origin.  
View is from Instrument Panel toward Headrest.

Three shortcomings of the simulation must be evaluated separately before a safe limit for a canopy can be specified:

Lack of airflow over the canopy

The infrared absorption bands in the plexiglass when coupled with a laboratory source having a high proportion of infrared

Lack of cockpit pressurization

The canopy response to the simulated flash is stated without regard for these shortcomings.

The compound that sealed the plexiglass to the aluminum frame of the canopy smoked easily and profusely. When this occurred during the early part of the thermal radiation pulse, it blackened a portion of the plexiglass and caused damage shown in fig. 8. In actual flight it would be very difficult for the products of combustion to collect on the plexiglass in such a manner.

Long longitudinal cracks developed in the plexiglass. These cracks began at the outer surface and continued approximately halfway through the plexiglass canopy (fig. 9). These cracks occurred with an applied load of  $11 \text{ cal/cm}^2$  delivered with a  $t_{\text{max}}$  of 2.0 seconds. The spectral absorption of the plexiglass was accounted for as described in appendix I.

#### Protected Unoccupied Configuration

The protected but unoccupied configuration was exposed only once. The protection was a prototype aluminized thermal protective hood made for the experiment (fig. 10). With the hood installed, the cockpit was subjected to approximately  $10 \text{ cal/cm}^2$ , with a  $t_{\text{max}}$  of 2.0 seconds, measured between hood and canopy. The threads of the hood, which would be protected in production models, smoked profusely and charred badly. Radiometers and calorimeters showed that no thermal radiation penetrated the hood.

#### Protected and Occupied Configuration

The protected and occupied configuration was not exposed since there was no thermal radiation load in the cockpit when the hood was used.



Figure 4. Left: Antenna; Right: Antenna; Middle: Antenna; Right: Antenna



Figure 1. Generalized low-resolution image.

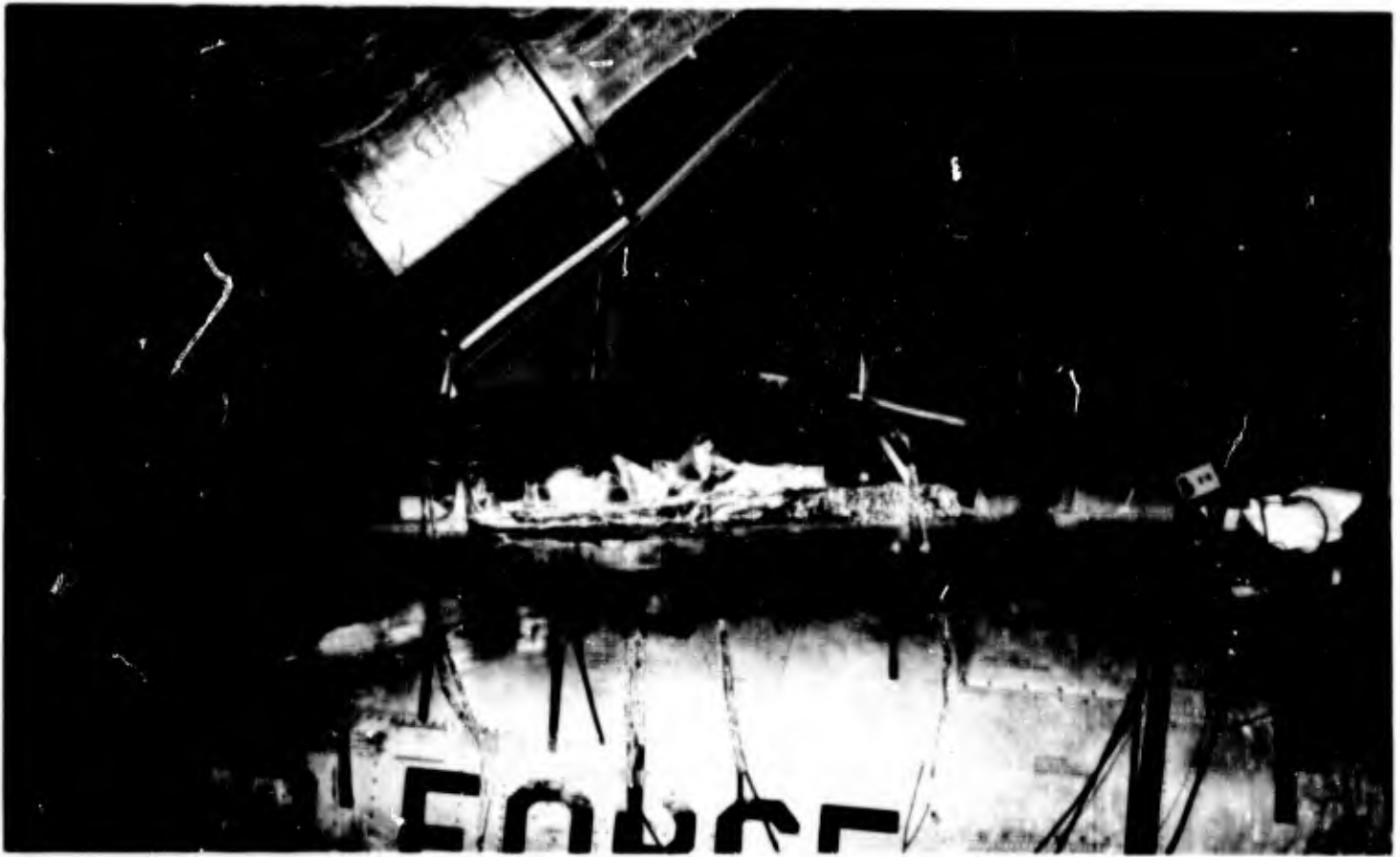


Figure 10. Experimental Hood in Protective Position.

#### ADDITIONAL DATA

##### Infrared Absorption Bands in Plexiglass

Infrared absorption bands were measured inside and outside the cockpit. Figure 11 shows a curve that indicates approximately how much of the incident energy was absorbed by the plexiglass. In the actual delivery of a weapon, the atmosphere (water vapor and carbon dioxide) would remove a large portion of the energy of the wave length absorbed by the plexiglass. Additionally, the source of temperature of an actual detonation would be higher than the source of temperature in the laboratory so a smaller portion of the incident energy would be absorbed in an actual delivery than in the laboratory. For these reasons and the shortcomings of the simulation (vide supra) correlation of the canopy responses in the laboratory with those which might occur in the field could only be a hazardous guess.

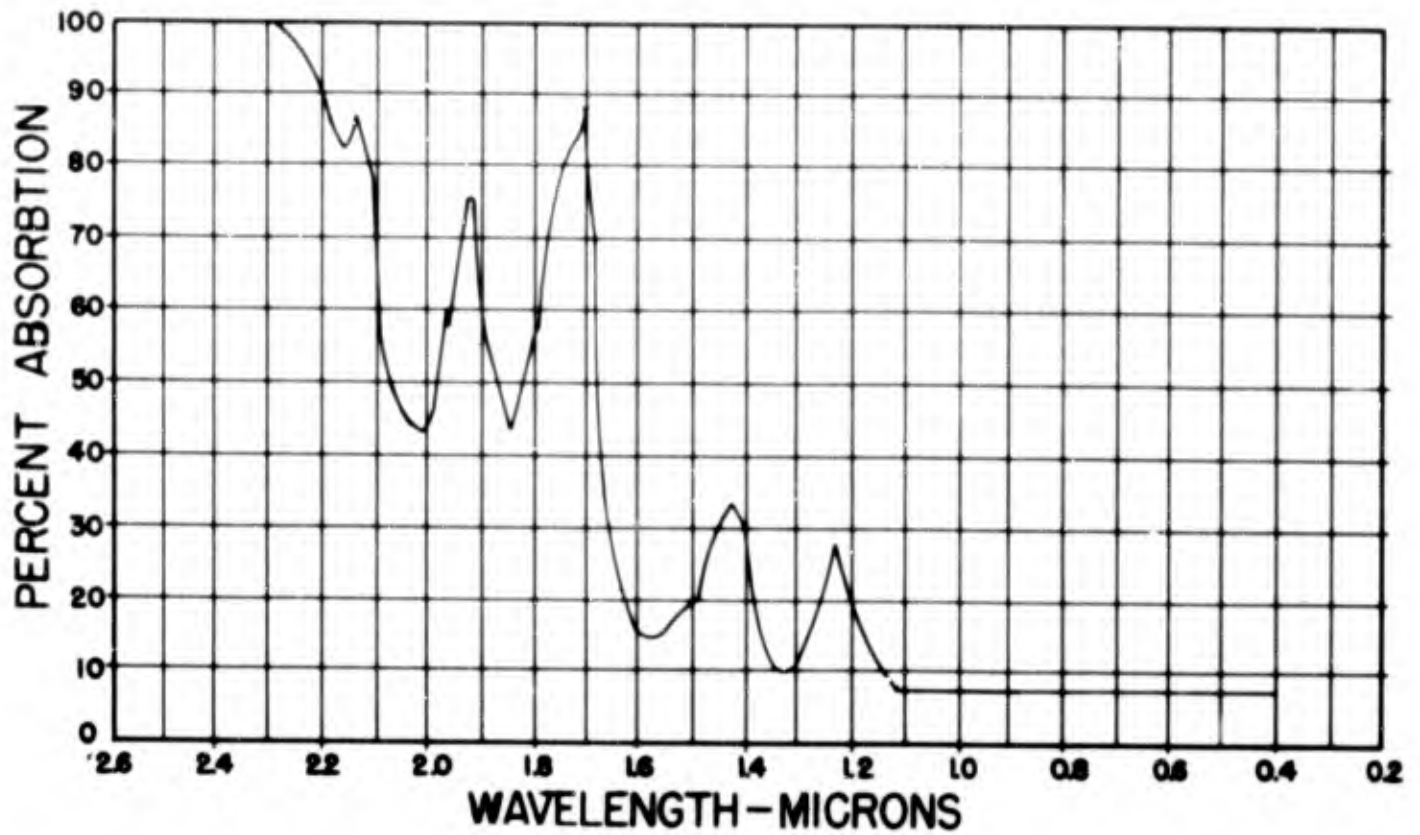


Figure 11. Absorption Characteristics of Plexiglass

#### Instrument Correction

The assumption of isotropic angular distribution of energy, used in correcting the instruments from  $1\pi$  to a  $2\pi$  acceptance angle, is not precisely true for either the laboratory experiment or for the actual delivery situation. Energy from the reflector was assumed to vary from isotropic by  $\pm 5$  percent. This variation and the geometrical variations produced one of the inherent inaccuracies in the experiment.

During an actual delivery, more energy will be reflected from clouds nearer to the burst than the airplane. Smaller amounts of energy will be reflected from clouds beyond the airplane. Equidistant clouds on either side of the airplane will reflect equal amounts of energy. Thus the field distribution of energy is not likely to be isotropic. However, we don't think that the assumption of isotropic distribution in the laboratory affects the data significantly.

## Summary

The reader is cautioned against unqualified application of the data to the field situation. The limitations imposed by cockpit components and the human pilot remain fixed. The amount of energy striking the cockpit in the field situation is a variable determined by atmospheric and cloud characteristics and the geometrical relationship of detonation, aircraft and clouds. This experiment shows what might be expected to occur in an occupied fighter-bomber cockpit in an idealized situation. Cumulative effects have been prevented by protecting vulnerable components as their vulnerability became apparent. The pilot is the most vulnerable component since he is the most vulnerable. The degree of vulnerability of components has been determined. A reflective or opaque shield, such as the experimental hood, can prevent injury to all cockpit contents.

## SECTION IV

### CONCLUSIONS

Although a slight response was obtained from some cockpit components at load levels the pilot tolerated, the limiting response was that of the pilot in the unprotected occupied configuration. The maximum thermal radiation load to which an unprotected manned operational cockpit may be safely subjected is 3 - 5 cal/cm<sup>2</sup> measured inside the cockpit at head level and applied in a time equal to that of a 1 megaton yield. This assumes the pilot's eyes are adequately protected from the relatively unknown effects of intense diffuse thermal radiation and the helmet visor is lowered. This limit is based on the subjective responses of four human subjects. No injury occurred but distinct pain was endured. This is a startling experience and an uninformed pilot might have feelings of panic even when exposed to physiologically safe levels. However, a pilot who has been told what he may encounter, ie, the intense brightness of the flash, distinct pain, smoke in cockpit, should accept the load with nothing more than discomfort and perform his assigned mission adequately.

Standard brown leather flying gloves were seared at 1.6 cal/cm<sup>2</sup>. This may produce pain on the skin beneath and produces a strange sensation as the gloves shrink. At the higher loadings, items other than the pilot's gloves begin to respond by charring slightly and the pain responses of the pilot may be intense enough to cause involuntary movements. Under such conditions control of the aircraft may be difficult. Thermal radiation loads greater than the 3 - 5 cal/cm<sup>2</sup> range, delivered in the time of a 1-megaton yield, should not be imposed unless supplementary protective equipment is used.

If the pilot were individually protected in some manner, charring and smoking of cockpit components would occur at 6 - 8 cal/cm<sup>2</sup>, delivered with a 4-megaton time period increasing in severity at levels of 10 cal/cm<sup>2</sup>, delivered with a 1-megaton time period. Higher levels would be hazardous due to the probability of a cockpit fire. Even with protective clothing the pilot still might be the limiting factor.

When the whole cockpit was protected by a hood, 10 cal/cm<sup>2</sup> with a 4-megaton time delivery period did not cause significant cockpit damage, although traces of smoke were detected. Thus, some sort of shield will be the only effective protective measure against extreme thermal radiation intensities.

Techniques are available (ref 4) for predicting the thermal radiation loads that will be encountered during escape from a low altitude nuclear weapon delivery in various atmospheric conditions. With the knowledge of acceptable safe thermal radiation loadings and information about where these loads will be encountered, an evaluation of the thermal radiation hazard can be made. This evaluation can then be used by operational planners to determine the degree of acceptable risk and the necessary escape maneuver.

## SECTION V

### RECOMMENDATIONS FOR PROTECTION PRIOR TO WEAPON DELIVERY

1. Pilots should be thoroughly briefed on possible responses, ie, intense visible flash of seconds duration, smoke in cockpit, distinct but bearable pain. If loads specified in this report are not exceeded the mission can be accomplished safely.

2. Vulnerable cockpit components should be protected. A cockpit fire may terminate an otherwise successful mission.

a. Dark leather flying gloves should not be worn. Less vulnerable materials could be substituted.

b. The mirror should be turned so flash will not be reflected into pilot's eyes.

c. Dark colored objects of low thermal capacity (wires, papers, etc) should be protected by shielding with aluminum foil or substitute.

d. Adhesive tapes should be avoided since adhesive compounds may ignite.

3. The eyes should be protected from intense flash by shading or with special visors or goggles.

4. If thermal radiation loads are to exceed safe unprotected limits, a reflective or opaque hood capable of protecting the entire cockpit should be considered.

## APPENDIX I

### EXPERIMENTAL PROCEDURE AND DATA ACQUISITION

#### EXPERIMENTAL APPARATUS

##### Power Supply

A public utilities company provided the electrical power supply through 3-phase 69,000-volt lines rated at 60 megawatts. At peak loads, the lamps drew approximately 6 megawatts (6000 kilowatts) of electrical power.

##### Power Programing and Control

A single function generator drove fifteen 580-kilowatt ignitron-controlled power channels. Due to nonlinearity of the system, calibrations were made and programs corrected until the measured output from the lamps was a close approximation (fig. 12) of the thermal radiation pulse of a nuclear device.

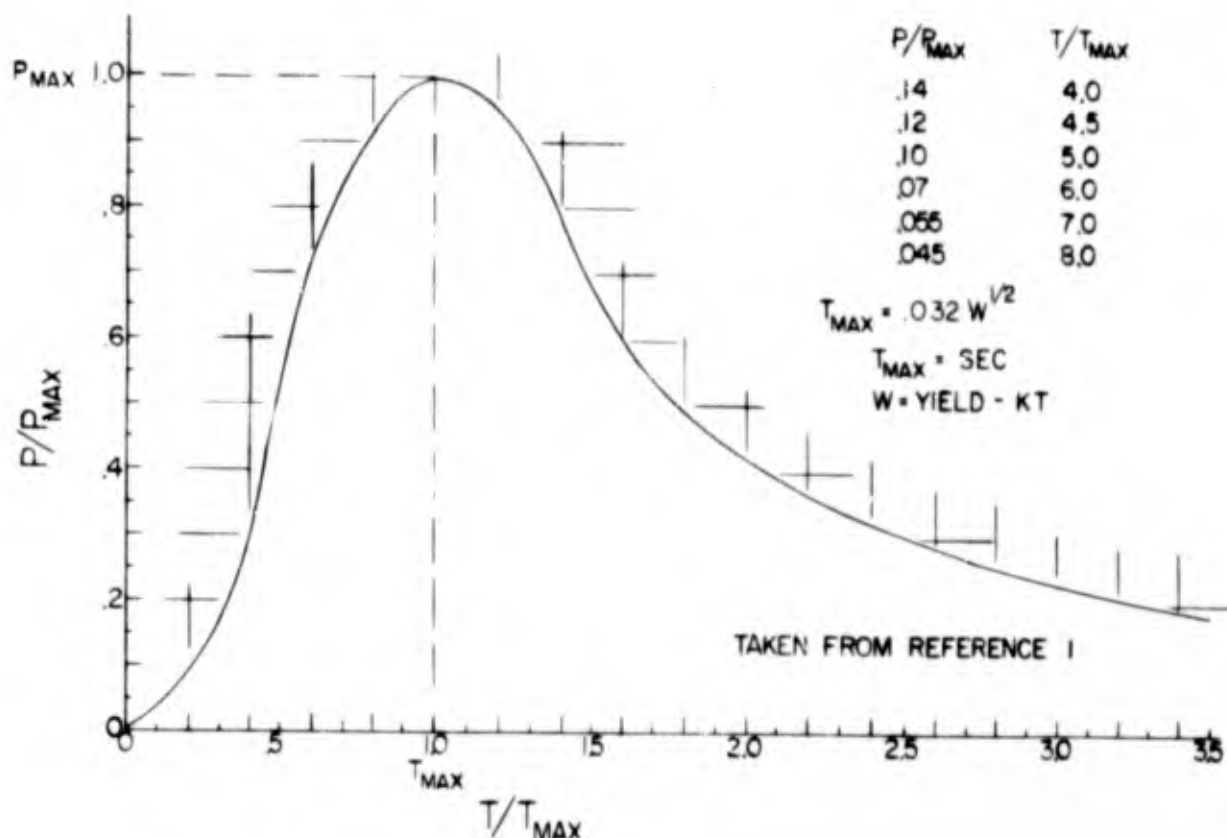


Figure 12. Idealized Thermal Radiation Pulse.

With this power control and programming arrangement it was possible to simulate any combination of weapon yield (time) and range from the burst (peak intensity) within the power limitations of the equipment.

### Thermal Radiation Source

One thousand, 2000-watt tubular quartz General Electric T-3 infrared lamps (ref 5) were mounted in an aluminum reflector large enough to cover the entire cockpit (fig. 13). The lamps were placed approximately 18 inches from the canopy at all points. The power-versus-voltage curve and the color temperature (effective black body radiating temperature) versus voltage curve are presented in fig. 14. Note that the 2000 watts occur at 240 volts, which is the rated voltage. At 100% overvoltage (480 volts) the power output is 5800 watts. This wattage to each of 1000 lamps totals approximately 6 megawatts of power. These lamps require approximately 1 second to rise to peak power (5800 watts). If rise times of less than 1 second were desired, the peak power available was limited by the maximum slope of the exponential power-rise curve. For rise times greater than 1 second, the peak power of the lamps was available. If 100% overvoltage was exceeded, the failure rate of the lamps became unacceptable and explosive failure occurred frequently.

### Cockpit

The test airplane had been flown extensively before storing. Deterioration of the cockpit or its cleanliness did not seem to be significantly different from that of an airplane in daily use. Since different cockpit configurations exist, it was necessary to note specifically what failed and use this information to predict the response of other cockpits. Components in the test cockpit were standard items.

Several standard canopies were used. Each was  $\frac{19}{64}$ -inch-thick plexiglass. A B5 cabin pressure rise tester provided normal airflow through the cockpit and gave an indication of the smoke-dissipating capability of the air conditioning system.

Twenty-eight volt DC power was supplied to the aircraft from an external source and all components in the cockpit were under power during the exposures. The cockpit was not pressurized.

A thermal radiation hood was constructed from an aluminized fabric (Specification MIL-C-27347-USAF) to the standard fittings of the F-100 thermal hood.

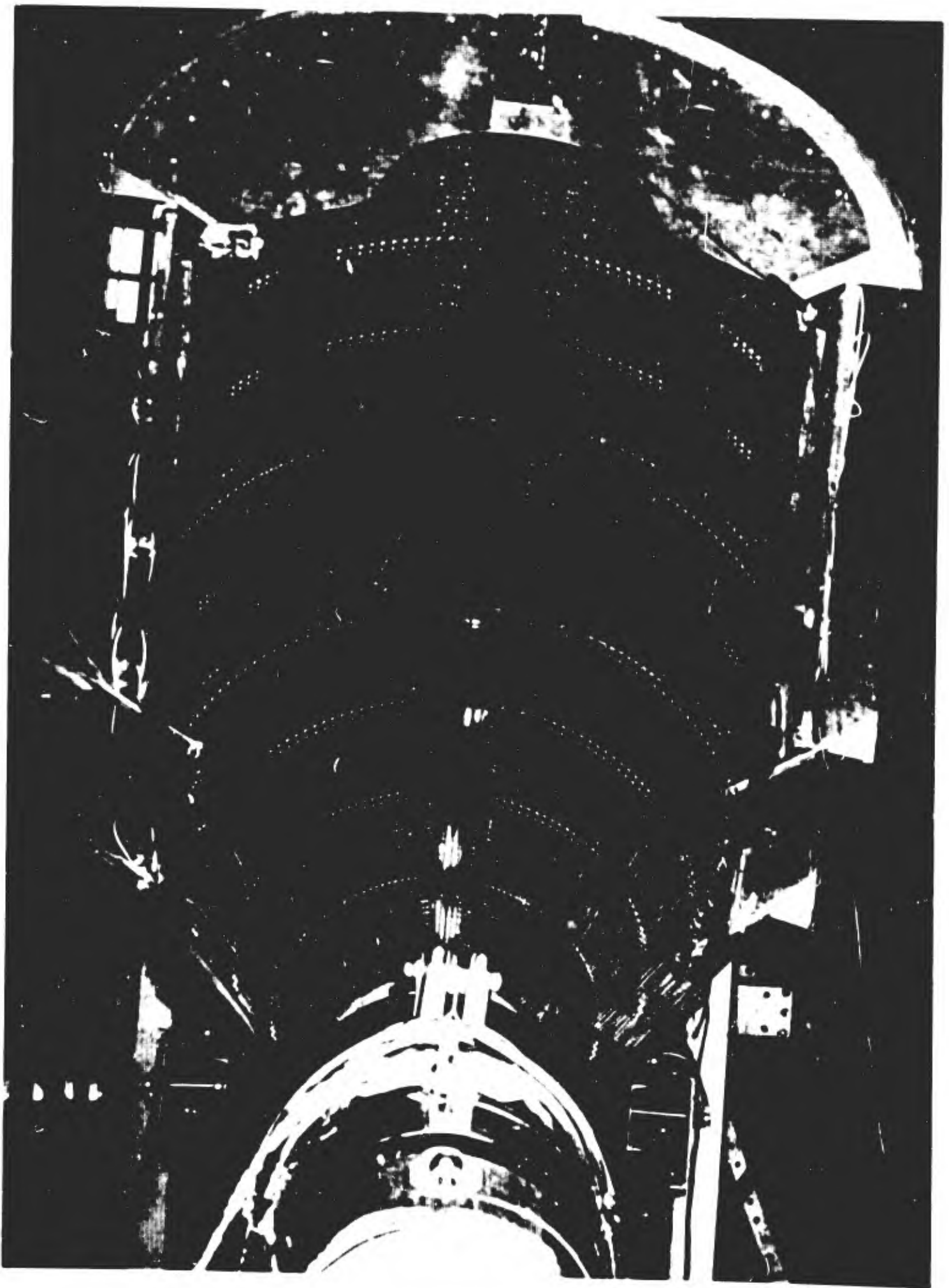


Figure 13. Infrared Lamps in Reflector, View as Upward from Aircraft.

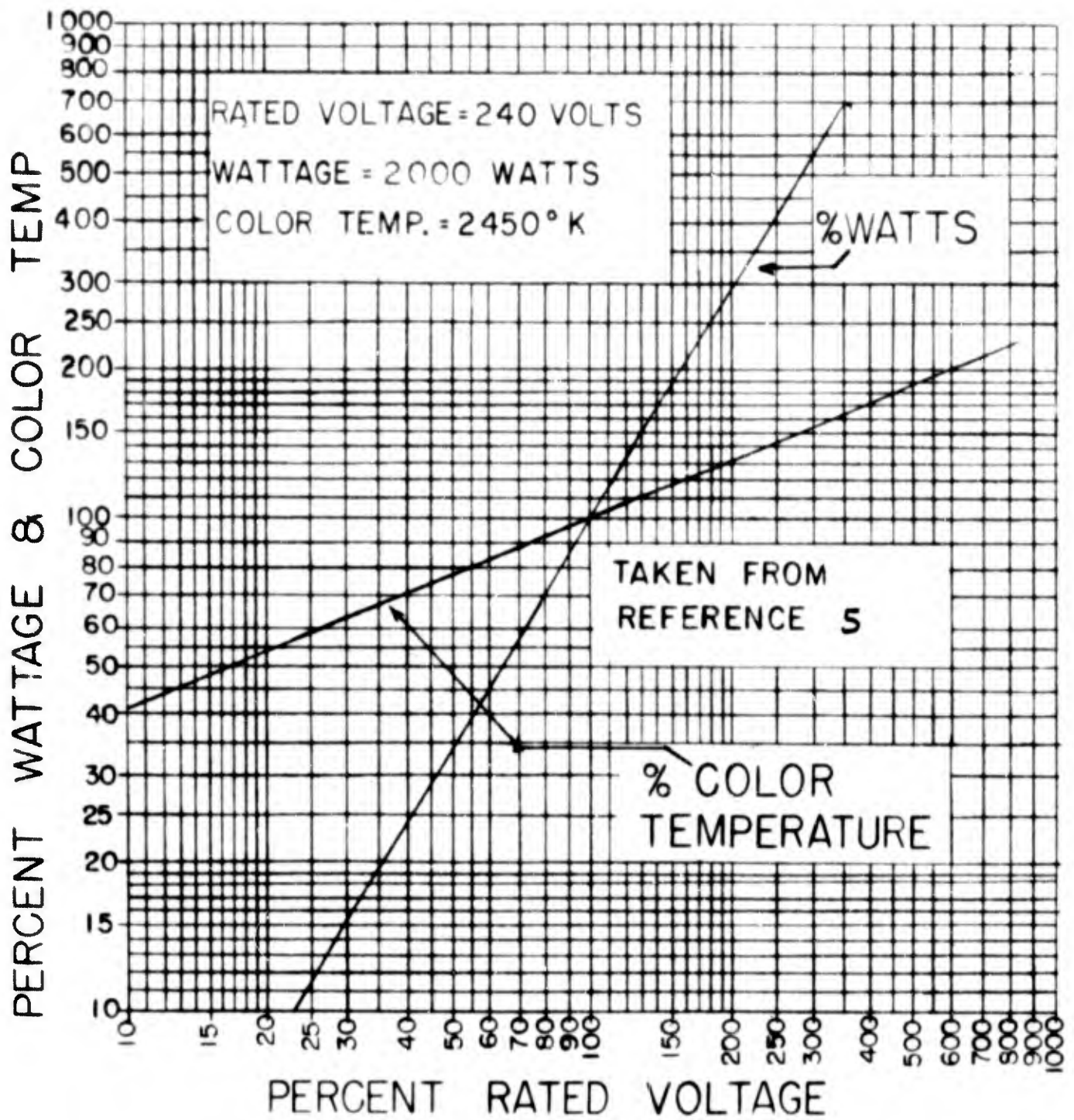


Figure 14. Voltage Characteristics for G. E. T-3 Tubular Quartz Infrared Lamps.

## Instruments

Calorimeters. All calorimeters were supplied by the Naval Radiological Defense Laboratory and were of the type used extensively for measuring thermal effects during nuclear tests. The calorimeter sensor is a blackened copper button, exposed to the thermal energy, with a 90-degree field of view, through a quartz filter. The temperature of the button increases when energy is absorbed and this change in temperature is measured by a thermocouple. When a correction is made for re-radiation heat losses, this temperature is an integrated measure of the thermal energy incident on the button. Calorimeters of four sensitivities were used in the experiment.

Radiometers. Radiometers were also supplied by the Naval Radiological Defense Laboratory. A thin foil with a blackened spot in the center is the sensing element of the radiometer. The temperature of the black spot is measured by a thermocouple. In this instrument the mass is small, conduction and re-radiation losses are high. Therefore the temperature of the blackened spot is a measure of the rate of energy input. Radiometers of 3 sensitivities were used.

Skin Simulant. A device designed by the Navy Materials Laboratory to have the same thermal characteristics as human skin was used in the experiments considered unsafe for human subjects. The skin simulant could be exposed bare, with clothing samples drawn tightly over it, or with clothing samples over the simulant but not in contact with it. During the experiment exposures were made with under and outer clothing samples drawn tightly over the simulant. Figure 3 shows the installation.

Photography. Motion and still photography supplemented data gathered by other means. Photographic exposures were such that, in spite of extremes of light intensity, the cockpit could be observed during all phases of the experiment.

Pilot. A rapid response radiometer was not available for measuring bare skin temperatures. Thermocouples were pulled taut against the skin and accurately measured temperatures under the clothing. Errors in the measurement of forehead skin temperature were reported by Kaufman et al (ref 1).

Recording Equipment and Calibration Procedures. The electrical outputs of calorimeters, radiometers, skin simulant, and pilot's thermocouples were recorded on a 36-channel recording oscillograph with immediate readout capability. Calibration of radiometers, calorimeters, and the skin simulant was performed by applying a known millivolt source of low impedance. Varying the applied emf then gave a plot of galvanometer deflection against emf.

The published calibrations of the Naval Radiological Defense Laboratory for each sensor were then used to convert the galvanometer deflection to proper units of measurement. Thermocouples were calibrated by immersing them in stirred water of known temperature and plotting galvanometer deflection against temperature.

The pilot's electrocardiogram was displayed on an oscilloscope and his heart rate was recorded continuously.

## DESCRIPTION OF EXPERIMENTAL ASSEMBLY AND DATA ACQUISITION

### Experimental Assembly

Prior to the experiment proper, four sets of radiometers and calorimeters were placed above the canopy to map the distribution of energy. The canopy was covered with an asbestos and aluminum shield to prevent damage. Discrepancies in uniform energy distribution were corrected. Internal feedback as required in two channels in order to make the energy distribution uniform to  $\pm 5\%$ , a figure considered adequate for experimental purposes.

Thermal pulse shapes are shown in figs. 12, 15, 16, and 17. These are plots of lamp power compared with the idealized thermal pulse. It can be assumed that this was the energy pulse shape,  $\pm 5\%$ , at any point on the canopy.

The aluminum reflector housing the lamps was pivoted about a single point near the nose of the aircraft. A hydraulic system provided power to raise and lower the assembly.

All sensors were installed in simple mounts and the electrical leads protected by shielding from the radiant energy.

Calorimeter. The total energy applied during the experiment as measured from the deflection of the galvanometer was corrected for losses due to re-radiation from the cooling instrument and corrected to consider a  $180^\circ$  field of view.

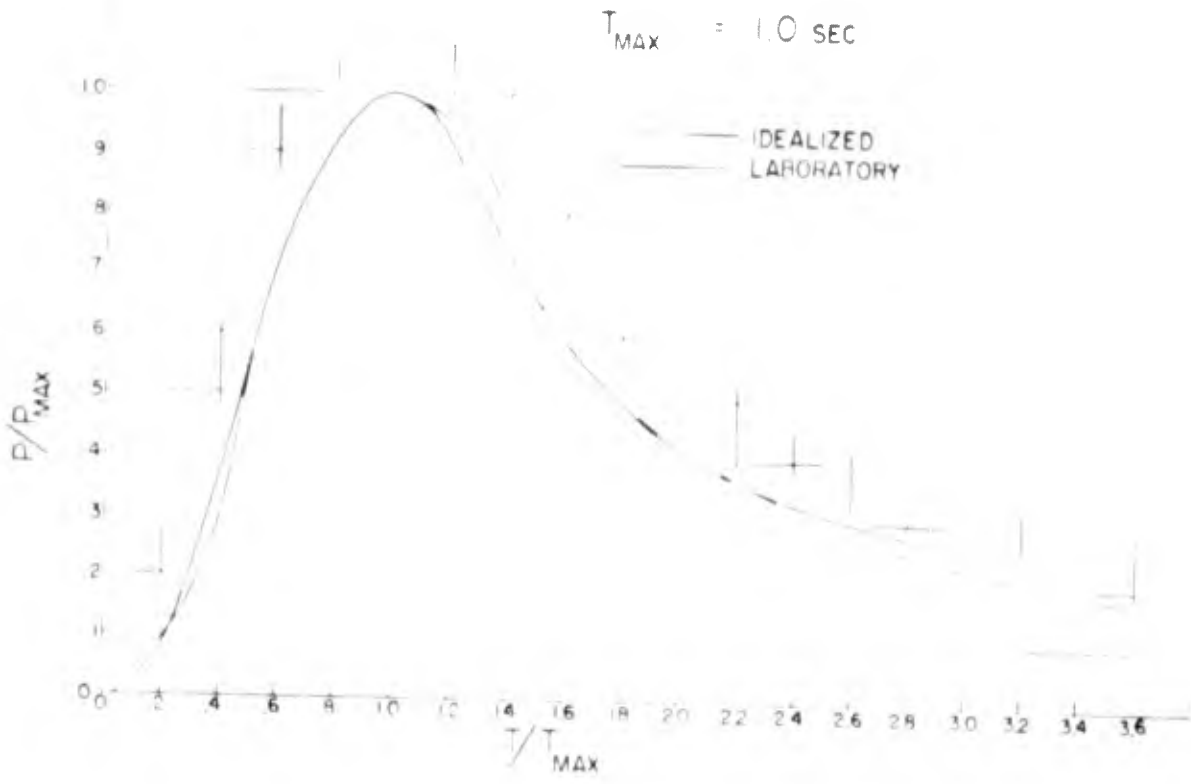


Figure 15. Thermal Pulse Shape Correlation,  
 $t_{max} = 1.0 \text{ sec.}$

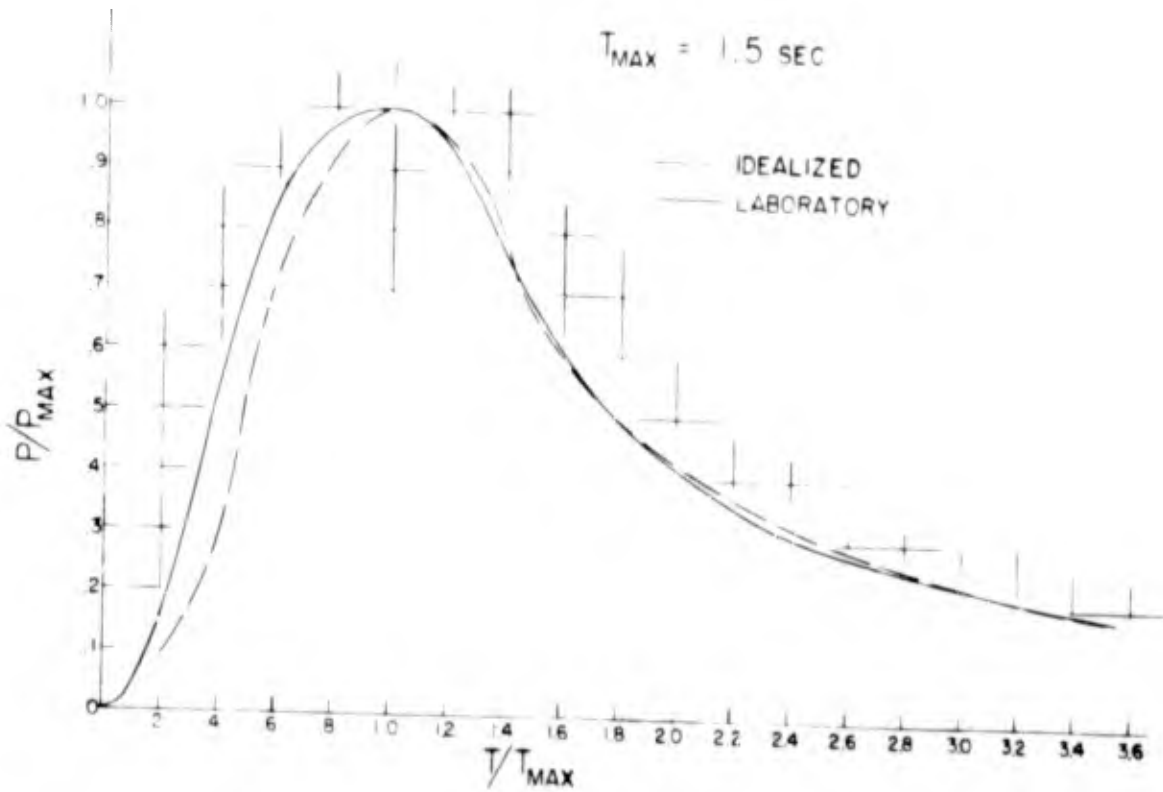


Figure 16. Thermal Pulse Shape Correlation,  
 $t_{max} = 1.5 \text{ sec.}$

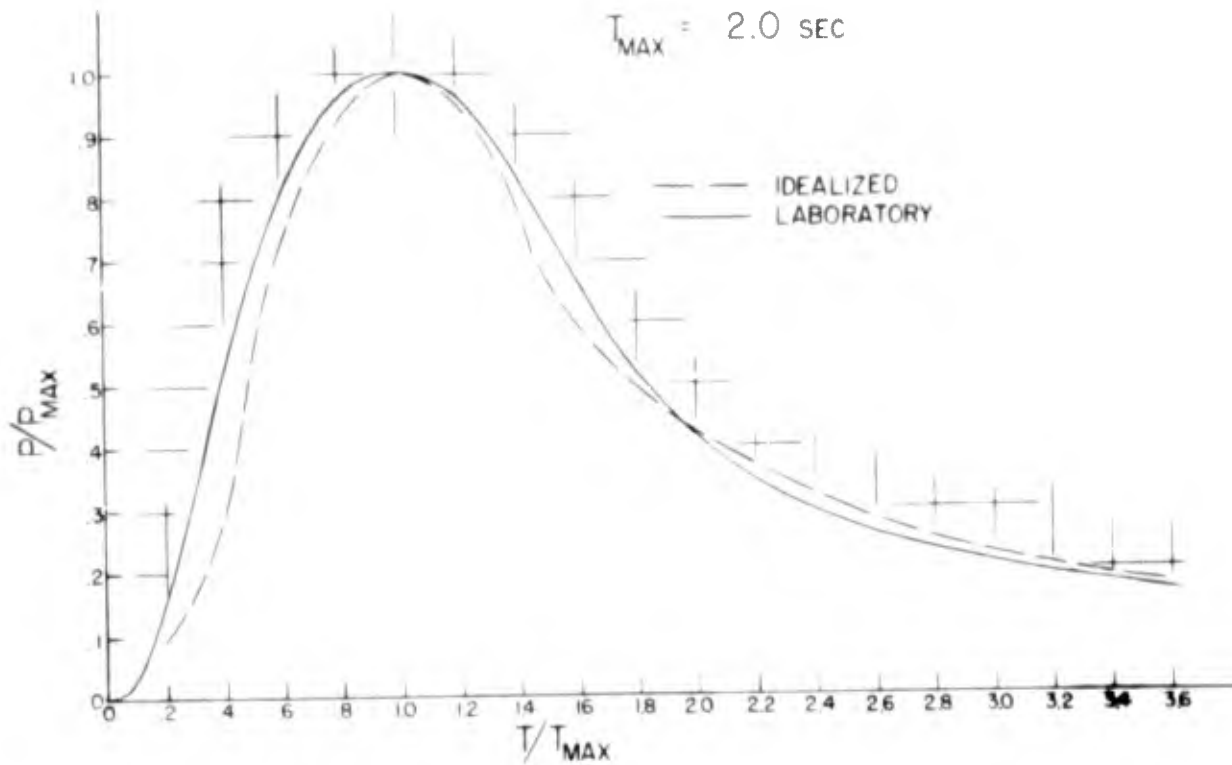
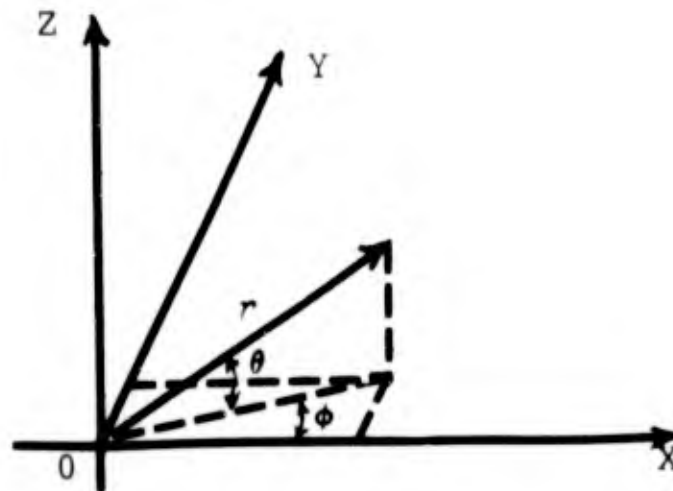


Figure 17. Thermal Pulse Shape Correlation,  
 $t_{\text{max}} = 2.0 \text{ sec.}$

The field-of-view correction was made by assuming that the energy incident on the instrument was isotropic and that the instrument was therefore only looking at a 90-degree conical section of the 180-degree isotropic field. All quantities measured must therefore be adjusted by the ratio:

$$\frac{\text{Energy over } 180^\circ \text{ field-of-view}}{\text{Energy over } 90^\circ \text{ field-of-view}}$$



(Coordinate System)

To obtain the flux passing through an infinitesimal flat plate located at the origin and in the X-Y plane, the incident energy must be weighted by  $\sin \theta$ . The energy over a 180-degree field-of-view becomes

$$r \int_0^{2\pi} \int_0^{2\pi} \theta \sin \theta \, d\theta \, d\phi \quad \text{with ratio to } 90^\circ \text{ view of:} \quad \frac{r \int_0^{2\pi} \int_0^{\pi} \theta \sin \theta \, d\theta \, d\phi}{r \int_0^{2\pi} \int_{\frac{\pi}{4}}^{\frac{\pi}{4}} \theta \sin \theta \, d\theta \, d\phi} = \sqrt{2}$$

Therefore, each calorimeter reading was multiplied by the factor 1.414.

The cooling correction was taken from a technique described by Mills (ref 6) and recommended by the Naval Radiological Defense Laboratory. This technique determines a cooling coefficient by plotting the decaying calorimeter curve (deflection of the trace versus time, after energy input to the instrument has ceased) on a semilogarithmic plot.

Spectral Analysis and Canopy Response. The responses of most cockpit components (dark colored) are relatively insensitive to the spectral distribution of energy applied, since they absorb most of the visible, and essentially all of the infrared spectra. The plexiglass of the canopy does not fall into this insensitive category, however, so a spectral analysis was performed. By using the data shown in fig. 14, a color temperature-versus-time curve can be obtained for any exposure level. This curve is a function only of the peak power because the pulse shape is fixed. For an exposure with a given peak power the total energy delivered was divided into discrete segments, each with a characteristic color temperature. The wavelength spectrum was divided into segments that corresponded to absorption color temperature. By averaging the absorption in each of the wavelength segments and properly weighting it by the proportion of energy in each segment, the total proportion of the energy that the plexiglass absorbed was obtained. Following this procedure for the exposures with several peak powers yielded the curve shown as fig. 18.

Since the spectrum of the radiation striking the aircraft in a real delivery will have been modified by the atmosphere, it was necessary to compare the absorption curve for plexiglass with that of the atmosphere. If only a small portion of the thermal energy produced by a nuclear detonation is in spectral regions transmitted by the atmosphere, then the percentage of energy absorbed by the plexiglass in the laboratory will be much greater. This is shown by the absorption curves (figs. 11 and 19) and the information in tables III and IV.

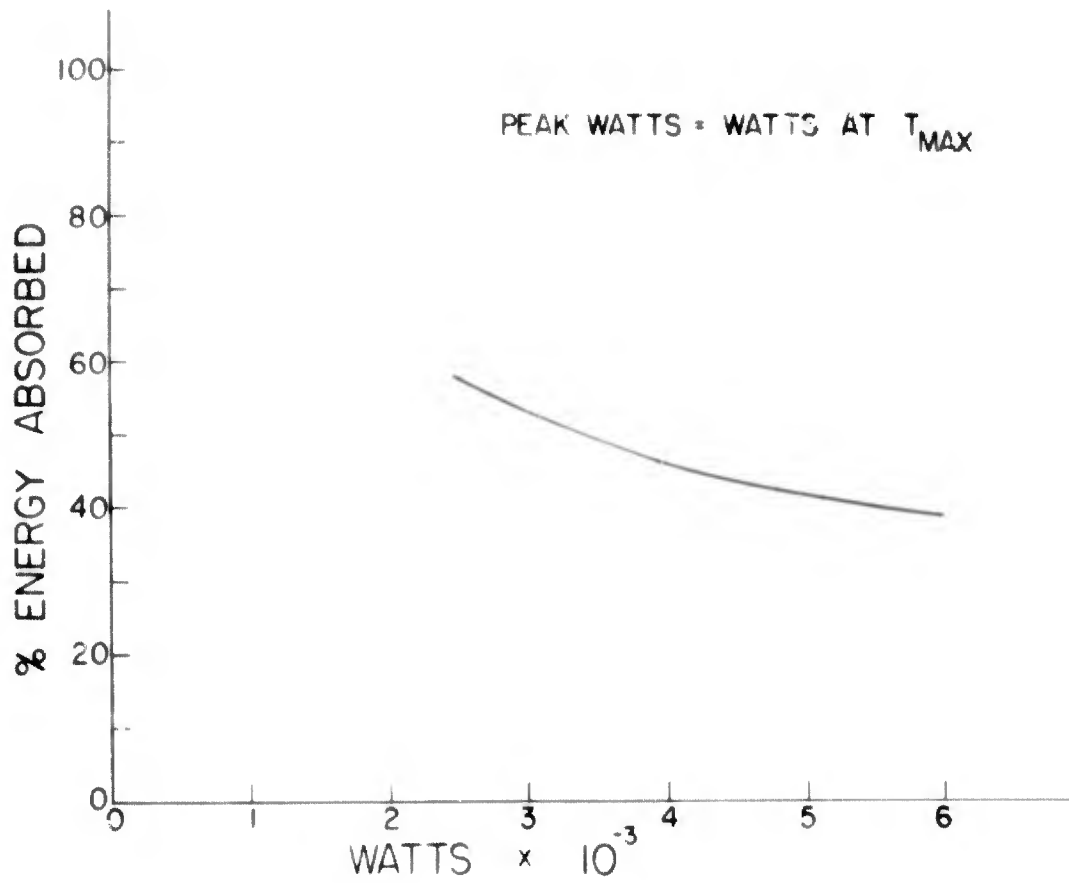


Figure 18. Plexiglass Absorption vs Peak Lamp Wattage

WATER VAPOR  
 .1 CM. PRECIPITABLE  
 WATER VAPOR  
 →



CARBON DIOXIDE  
 10 KM. PATH LENGTH  
 →



WAVELENGTH - MICRONS

Figure 19. Atmospheric Transmission of Infrared Radiation (Sea Level) (Ref 4)

TABLE III

WAVELENGTH INTERVALS CHARACTERIZED BY THEIR  
COMMONLY ACCEPTED IDENTIFYING NAMES\*

Band (Index No.)	Wavelength Limits (In Microns)	(Microns)	Band Identification	Absorbing Gas or Vapor
1	0.32-0.70	.38		None
2	0.70-0.80	.10		H <sub>2</sub> O+O <sub>2</sub>
3	0.80-0.87	.07		None
4	0.87-1.08	.21	.94 H <sub>2</sub> O	H <sub>2</sub> O
5	1.08-1.20	.12	1.1 H <sub>2</sub> O	H <sub>2</sub> O
6	1.20-1.25	.05		None
7	1.25-1.54	.29	1.38H <sub>2</sub> O+1.4CO <sub>2</sub>	H <sub>2</sub> O+CO <sub>2</sub>
8	1.54-1.70	.16	1.6 CO <sub>2</sub>	CO <sub>2</sub>
9	1.70-2.08	.38	1.87H <sub>2</sub> O+2.0CO <sub>2</sub>	H <sub>2</sub> O+CO <sub>2</sub>
10	2.08-2.27	.19		None
11	2.27-3.00	.73	2.7H <sub>2</sub> O+2.7CO <sub>2</sub>	H <sub>2</sub> O+CO <sub>2</sub>
12	3.00-3.57	.57	3.2 H <sub>2</sub> O	H <sub>2</sub> O

TABLE IV

FRACTIONAL BLACK-BODY IRRADIANCE FOR FIVE TEMPERATURES  
CONTAINED WITHIN THE WAVELENGTH INTERVALS OF TABLE III\*

Band (Index No.)	3500°K	4500°K	5500°K	6500°K	7500°K
1	.150	.298	.419	.492	.524
2	.077	.097	.096	.086	.074
3	.056	.062	.057	.048	.040
4	.156	.150	.127	.103	.082
5	.077	.065	.051	.039	.030
6	.030	.023	.018	.013	.010
7	.134	.101	.073	.053	.039
8	.054	.037	.026	.019	.013
9	.090	.058	.039	.027	.019
10	.031	.019	.012	.008	.006
11	.069	.041	.025	.017	.012
12	.027	.015	.009	.006	.004

\* Extracted from ref 5

The spectral problem, the lack of aerodynamic and cockpit pressurization load, and the lack of airstream cooling in the laboratory simulation, prevent application of the canopy response in the experiments, to the field situation. However, the canopy characteristics do not invalidate the response of the cockpit components, since the canopy will act as an optical filter in the field as well.

Radiometer-Calorimeter Data Correlation. Since the calorimeter recorded the integrated energy received and the radiometer recorded the rate of energy delivery, the integration of the radiometer output should yield the calorimeter trace. A series of radiometer traces was integrated. Table V shows the ratio of integrated radiometer values to corrected calorimeter values. Although there is some scatter, there appears to be a systematic discrepancy between the integrated radiometer readings and the corrected calorimeter readings. The integrated radiometer information indicates that a significantly greater amount of energy was delivered than the calorimeter data indicates (fig. 20). No explanation has been found for the discrepancy.

TABLE V

INTEGRATED RADIOMETER/CORRECTED CALORIMETER VALUES

<u>Instrument Type</u>	<u><math>E_{rad}/E_{corr}</math></u>
Black	1.08
Black	1.35
Black	1.21
Black	1.30
White	1.32
White	1.36
White	1.35
White	1.35
White	1.41
White	1.33
White	1.33
Red	1.65
Red	1.26

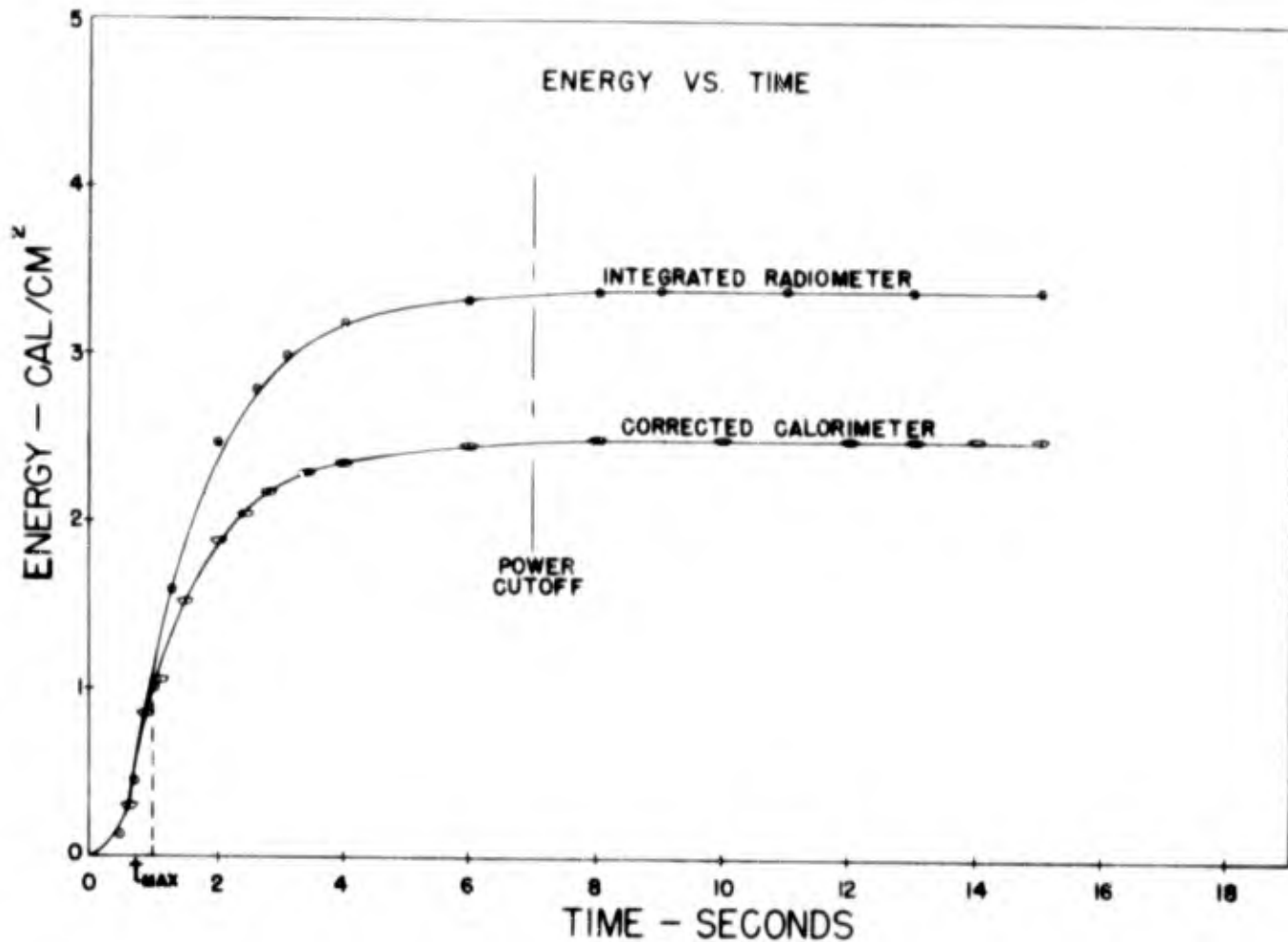


Figure 20. Integrated Radiometer and Corrected Calorimeter Curves.

Cockpit component and human subject responses presented in this report are based on calorimeter data. Scatter of calorimeter data was less than radiometer data; indicating better reliability. Additionally, the calorimeter data presents a conservative estimate which will assure safety of the pilot.

A plot of corrected calorimeter readings versus time and integrated radiometer readings versus time is shown in fig. 20. The calorimeter and the radiometer were located at the same point.

## APPENDIX II

### NUCLEAR DETONATION SIMULATOR SERIES

During January of 1962, a group of 45 tactical fighter pilots were brought to the Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, for a special orientation on the cockpit hazard of thermal radiation of a nuclear detonation. These were a cross section of tactical fighter-bomber pilots concerned with the delivery of nuclear weapons in high performance aircraft, and low altitude delivery and escape maneuvers. They were assigned to squadrons flying F-100D, F-101A and C, F-105B, F-105D, and F-84F aircraft. The F-84F pilots were from activated National Guard units. Tactical Air Command, Pacific Air Forces, and U.S. Air Forces in Europe were represented.

The orientation was to acquaint pilots with the nature of thermal radiation and the conditions under which this hazard may be encountered. Blast effects are easily understood because gust loads are a part of everyday flying but radiant energy of the degree associated with nuclear detonation has no counterpart. Because radiant energy is not commonly understood, the orientation started with a discussion of radiant heat transfer. This was demonstrated by showing that flammable materials will ignite and aluminum sheet can be melted with intense radiant energy in the absence of convective or conductive heat transfer.

The group was briefed on the capabilities of the experimental setup, the results as presented in the body of this report, and then each pilot participated as a subject. The subject donned standard flying equipment, entered the cockpit, strapped in, and was exposed to radiant energy of  $2.5 \text{ cal/cm}^2$  at head level and  $1.6 \text{ cal/cm}^2$  at hand level, delivered over the time of a 1-megaton yield (table I, exposure No. 3). This exposure simulated the following conditions:

- a. A 1-megaton burst at 3000 feet
- b. Heavy overcast, base 6000 feet, tops 8000 to 11,000 feet
- c. Aircraft between clouds and ground 40,000 to 60,000 feet from the burst depending on whether terrain is snow-covered or bare.

The exposure level was the same that originally seared the flying gloves, but was readily tolerable. In each exposure the searing of the gloves was repeated. We think that this exposure provides a realistic simulation. A critique was held in which questions were answered and the protection provided by a shielding hood emphasized. The fact that this thermal radiation hazard only exists in the presence of reflecting clouds was also emphasized.

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