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THE DESIGN AND CONSTRUCTION OF THIN FILM RADIATION THERMOPILES

D. F. Frazine

ARO, Inc.

April 1966

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THE DESIGN AND CONSTRUCTION OF THIN FILM RADIATION THERMOPILES

D. F. Frazine
ARO, Inc.

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FOREWORD

The work reported herein was sponsored by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65402234. Partial funding was supplied by the National Aeronautics and Space Administration (NASA) under Project SUPER and Task 951407.

The results presented were obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract AF 40(600)-1200. The work was conducted during the period from November 1, 1964, to July 31, 1965, under ARO Project Number SW3410, and the manuscript was submitted for publication on January 28, 1966.

This technical report has been reviewed and is approved.

Terry L. Hershey
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ABSTRACT

Thin film radiation thermopiles promise substantial improvement in detector performance and construction cost over conventional solid-wire thermopiles when used in space simulation chambers for measuring simulated solar total irradiance. Three types of substrates were used during the investigation of thin film construction techniques: (1) aluminum foil suspended over a channel cut in the heat sink, (2) thin Mylar® suspended over a channel cut in the heat sink, and (3) the heat sink containing a channel which is filled with an insulating resin. These substrates provide thermal resistance between active and reference junctions. Sixteen junction thermopiles of bismuth and antimony were vacuum evaporated onto the substrates, and the completed detectors were tested for sensitivity, response time, and resistance to damage caused by temperature cycling over the range from 80 to 440°K. Expected sensitivities were obtained (from 1×10^{-4} to 55×10^{-4} $\text{v-w}^{-1}\text{-cm}^{-2}$ per active junction for the channel configuration used). Response times (99 percent) ranged from 50 msec for the aluminum foil type to 7 sec for the Mylar type. All units were undamaged by temperature cycling. Operating principles, construction techniques, performances, and relative merits of these thin film thermopiles are described.

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TABLE

I. Measured Characteristics of 16-Junction, Bismuth-Antimony, Thin Film Thermopiles 21

NOMENCLATURE

A	Intensity of radiation on the thermopile (irradiance), $w\text{-}cm^{-2}$
a	Half of suspended substrate length, cm
b	Surface absorptance
d	Heat sink channel depth, cm
h	Suspended substrate thickness, cm
k	Thermal conductivity, $w\text{-}cm^{-1}\text{-}°K^{-1}$
n	Number of active thermopile junctions
p	Thermoelectric power, $v\text{-}°K^{-1}$
S	Thermopile detector sensitivity, $v\text{-}w^{-1}\text{-}cm^{2}$
T	Heat sink temperature, °K
v	Thermopile emf, v
x	Distance from center of suspended substrate, cm
y	Width of substrate element, cm
σ	Stefan-Boltzmann constant: 5.67×10^{-12} $w\text{-}cm^{-2}\text{-}°K^{-4}$

SECTION I
INTRODUCTION

The radiation thermopile is an instrument used to measure thermal radiation. In one form, it contains a receiver which absorbs the radiation and a thermopile which indicates the receiver's temperature rise. Over a limited range, the thermopile electromotive force (emf) is proportional to the radiant power incident on the receiver.

At AEDC, radiation thermopiles are used inside space environmental chambers to measure simulated solar radiation (Ref. 1). These detectors contain circular blackened receivers to which are attached thermopiles made from small diameter copper and constantan wires. As many as 50 detectors may be used in one chamber.

Substantial improvement in detector performance and construction cost can result if the thermopile is made from thin metal films deposited in vacuum. In this form the receiver and thermopile can easily be made small in size with a corresponding reduction in detector response time. Fabrication time is reduced because several thermopiles can be deposited simultaneously.

Thin film thermopiles date from 1933 when L. Harris and E. A. Johnson (Ref. 2) deposited antimony (Sb) and bismuth (Bi) films on thin cellulose and presented an analysis of their performance (Ref. 3). Their purpose was to measure adiabatic heat produced in sound fields and low levels of thermal radiation. Roess and Dacus (Ref. 4) in 1945 built several thin film radiation thermocouples for use in infrared spectrographs. More recently, thin film radiation thermopiles have been commercially produced for spaceborne infrared systems (Ref. 5); however, they are not directly applicable to in-chamber measurements without special mountings and are not economically feasible in the quantity required.

In the course of this investigation, identical thermopiles were deposited onto three substrate configurations. By using different substrates, a wide range of detector response times and sensitivities was obtained. The operating principles, construction techniques, performances, and relative merits of the detectors are described in this report.

SECTION II
THIN FILM THERMOPILE SUBSTRATES

The substrate configurations used are shown schematically in Fig. 1. Radiation absorbed over the area above the heat sink channel is partly reradiated and partly conducted through the deposited metal films and substrate to the heat sink. A steady-state temperature in the substrate is thereby established. The resulting temperature rise at the channel center is sensed by the active thermopile junctions and is an indication of the amount of radiation absorbed. Detector sensitivity, S, is proportional to the substrate temperature rise.

$$S = \frac{v}{A} = \frac{n p \theta_o}{A}, \quad v - w^{-1} - cm^2 \tag{1}$$

where v = Thermopile emf

A = Intensity of radiation on the thermopile (irradiance)

n = Number of active junctions in the thermopile

p = Thermoelectric power of the junction materials

θ_o = Temperature rise of active junction above heat sink temperature

Radiation absorbed by the reference junctions does not produce a significant thermopile emf because they are in relatively good thermal contact with the heat sink.

Sensitivity, often specified as a design objective, will be treated separately for each of three substrate configurations.

2.1 SUSPENDED ALUMINUM FOIL (TYPE 1)

Although aluminum (Al) is a good heat conductor, a thin foil presents sufficient thermal resistance for use as the thermopile substrate. Additionally, the foil can be anodized to provide the necessary electrical insulation on its surface. As shown in Figs. 1 and 2, aluminum foil is attached to the heat sink and suspended over the heat sink channel. After anodizing the aluminum foil, thermopile conductors are deposited on the foil with active junctions positioned over the channel center and reference junctions positioned on the heat sink. Antimony and bismuth are used as thermopile conductors because of their high thermoelectric power and ease of evaporation. The entire surface containing the deposited films is blackened to obtain a high absorptance.

In operation, heat loss by radiation from the suspended foil is negligible compared to that which is conducted lengthwise through the foil. As represented in Fig. 3, a heat balance on the volume element, hydx, gives

$$bAxy = -khy \frac{d\theta}{dx}$$

where

b = surface absorptance

k = conductivity of substrate material

From the above equation, the temperature drop across the element is

$$d\theta = \frac{-bAx}{kh} dx$$

The temperature difference between the element and the heat sink is obtained by integrating $d\theta$ from x to a.

$$\theta = \frac{bAa^2}{2kh} \left(1 - \frac{x^2}{a^2}\right) \tag{2}$$

The curve shown in Fig. 3 is a plot of this equation.

Detector sensitivity is proportional to the temperature rise at the active thermopile junction where $x = 0$. Setting $x = 0$ in Eq. (2) and substituting into Eq. (1), the detector sensitivity is obtained:

$$S = \frac{npba^2}{2kh} \tag{3}$$

Sensitivity of the thermopile computed from Eq. (3) is given in Table I. Values used were:

n = 16 junctions

$p = 100 \times 10^{-6}$ v-°K^{-1}

b = 1

a = 0.0787 cm

k(Al) = 2.06 w-cm^{-1}-°K^{-1}

$h = 1.27 \times 10^{-3}$ cm

Thermal conductance of the deposited antimony and bismuth films is small compared to the aluminum foil conductance and has been ignored.

2.2 SUSPENDED MYLAR (TYPE 2)

This substrate is identical to the suspended aluminum foil except that thin Mylar® is used in place of aluminum foil. Because of the reduced conductance of the Mylar and a greater temperature rise in the suspended films, radiation loss is significant and Eq. (3) does not describe the situation accurately.

A solution for the temperature rise of a suspended film considering both conductance and radiation losses is given in Ref. 3. Here it is assumed that radiation loss from the back side of the supporting film is equal to that from the blackened front side and that incident radiation is uninterrupted. At the active junctions,

$$\theta_0 = \frac{bA}{2E}\left[1 - \frac{2}{e^{\alpha a} + e^{-\alpha a}}\right] \tag{4}$$

where $\alpha = \left(\frac{E}{kh}\right)^{1/2}$

and $E = 4\sigma T^3$.

By substituting Eq. (4) into Eq. (1), the following equation for detector sensitivity is obtained.

$$S = \frac{npb}{2E}\left[1 - \frac{2}{e^{\alpha a} + e^{-\alpha a}}\right] \tag{5}$$

Because heat losses through the deposited metal films and the Mylar substrate are both significant, an equivalent conductance-thickness product (kh)' is used to account for the combination of substrate and deposited films. Deposited metal films actually cover two-thirds of the area suspended over the channel. However, in calculating (kh)', the films are assumed to be uniformly distributed over the area with two-thirds of their actual thickness. Equal conductances of the antimony and bismuth films are produced by depositing film thicknesses inversely proportional to the metal conductivities.

Values used in Eq. (5) to calculate the suspended Mylar detector sensitivity are:

$n = 16$ junctions

$p = 100 \times 10^{-6}$ v-°K^{-1}

$b = 1$

$E = 6.1 \times 10^{-4}$ w-cm^{-2}-°K^{-1}, $T = 300$°K

$(kh)' = 6.25 \times 10^{-6}$ w-°K^{-1}

h (Bi) $= 10400 \times 10^{-8}$ cm

k (Bi) $= 0.067$ w-cm^{-1}-°K^{-1}

h (Mylar) $= 1.27 \times 10^{-3}$ cm

k (Mylar) $= 1.25 \times 10^{-3}$ w-cm^{-1}-°K^{-1}

$a = 0.0787$ cm

The calculated detector sensitivity is given in Table I. As indicated in Eq. (5), the sensitivity depends on heat sink temperature. It also depends on the thermoelectric power, p, and thermal conductivities, k, which are themselves functions of temperature. Changes in sensitivity with temperature are determined during detector calibration.

Equation (5) also applies, in principle, to the suspended aluminum foil type. However, when the actual values are substituted in Eq. (5), αa is so close to zero that all accuracy is lost in computation.

2.3 FILLED CHANNEL (TYPE 3)

The filled channel type of construction is shown schematically in Fig. 1. Instead of suspending the substrate over the heat sink channel, the channel is filled with an insulating resin to provide a substrate for the thermopile active junctions. Radiation absorbed at the surface of the filled channel is partly reradiated and partly conducted to the heat sink through both the metal films and the insulating resin. If the channel width is large compared to its depth, most of the heat loss is through the insulating resin. In this case,

$$\theta = \frac{hAd}{k}$$

where d = channel depth

Detector sensitivity is obtained by substituting θ into Eq. (1).

$$S = \frac{npbd}{k} \qquad (6)$$

Values used in calculating detector sensitivity from Eq. (6) are listed below; the calculated sensitivity is given in Table I.

$n = 16$ junctions

$p = 100 \times 10^{-6}$ v-°K^{-1}

$b = 1$

$d = 0.0254$ cm

$k = 2.09 \times 10^{-3}$ w-cm^{-1}-°K^{-1} (Ref. 6)

SECTION III
THIN FILM THERMOPILE CONSTRUCTION

An advantage of depositing the conductors, as compared to the construction of a wire-type thermopile, is the simplicity and rapidity with which the conductors are formed. The only limit to the number of thermopile substrates which can be mounted and processed simultaneously in the vacuum evaporator is the available space. A description of the process follows.

3.1 MASK-SUBSTRATE CHANGER

In order to deposit successively the soldering pads, antimony conductors, and bismuth conductors without exposing the freshly deposited surfaces to a contaminating atmosphere, some means of aligning the substrate with each mask is necessary. For this purpose, a mask-substrate registration mechanism, shown in Figs. 4, 5, and 6, was designed and built. As many as eight substrate holders, shown in Fig. 7, can be registered over four different masks. Each mask is mounted on a holding frame, shown in Fig. 8, and aligned over an evaporation source. The substrate must also be aligned over the masks so that active junctions will be positioned accurately over the heat sink channels. A vibrating quartz crystal thickness monitor, visible in the upper left corner of Fig. 6, is used to measure film thickness during deposition. It is mounted on a rotating boom so it can be positioned over each evaporation source.

3.2 PREPARATION OF MASKS

Three deposition masks are necessary to deposit the copper soldering pads and interconnectors, antimony conductors, and bismuth conductors. Mask designs were laid out ten times actual size and photographically reduced. These designs were chemically etched in 2-mil-thick brass foil. The antimony conductor mask is shown in Fig. 9. After a mask was mounted on its holding frame, it was aligned over an evaporation source by moving the frame to register a pair of small holes 2 in. apart in the mask with a similar pair of holes in an alignment fixture. The alignment fixture was held firmly in the position a substrate holder would occupy. In the center of each mask there is a hole which allows the evaporated material to pass through and deposit on the crystal thickness monitor directly above.

3.3 PREPARATION OF SUBSTRATE

Heat sink blocks for all three substrate types were machined with identical channel dimensions from aluminum. To prepare the Type 1 substrates, 0.5-mil-thick aluminum foil was bonded to the heat sink with an impregnant resin (Ref. 6) and then anodized to form an electrical insulator on the surface. To prepare the Type 2 substrates, 0.5-mil-thick Mylar was bonded to the heat sink with the same resin. Type 3 substrates, which require the heat sink to have electrically insulating surfaces, were prepared by anodizing the heat sink block first. Filler resin was then poured into the channels and cured at an elevated temperature.

Completed substrates were clamped in a holder and aligned with one mask by adjusting the position of the holder. The substrate holder was then clamped in position.

3.4 METAL FILM DEPOSITION

The mounted substrates were cleaned in vacuum by ion bombardment. Electrodes for this purpose are shown on the left in Fig. 5. Soldering pads and interconnectors were deposited first. In order to improve adhesion of the copper (Cu) soldering pads, copper was deposited over a film of chromium (Cr), which adheres well to the aluminum oxide surfaces.

Antimony and bismuth film thicknesses were determined from the arbitrary requirements that the thermal conductances of the two films were to be equal, and the total thermopile resistance was to be 100 ohms. Copper films had to be thick enough to allow a good solder connection. Deposited film thicknesses were: Cr - 500Å; Cu - 3000Å; Sb - 4170Å; Bi - 10,400Å.

To determine any effects which may depend on substrate temperature during deposition, the Types 1 and 2 substrates were heated to temperatures as high as 433°K. Type 3 substrates were not heated above 383°K during deposition to preserve the Mylar.

3.5 LEAD ATTACHMENT AND BLACKENING

Copper wire leads were soldered to the copper film pads. Before soldering, the entire heat sink block was heated to approximately 433°K. In this manner, the region just under the wire lead could be rapidly heated with a soldering iron to a temperature in excess of the solder melting point. After lead attachment the entire surface containing the thin film thermopile was blackened by spraying with optical black lacquer. A Type 2 thermopile is shown in Fig. 10 before lead attachment and blackening.

SECTION IV
MEASURED CHARACTERISTICS OF NINE THERMOPILES

Characteristics of primary interest are sensitivity, response time, and operating temperature ranges. The values given in Table I for each type are averages from three thermopiles.

4.1 SENSITIVITY

Sensitivity was determined by exposing the thermopiles, through the glass bell jar, to a calibrated 200-w quartz-iodide lamp outside the vacuum chamber. Changes in sensitivity at higher levels of irradiance were determined by exposure to the quartz-iodide lamp in the presence of "background" radiation produced by a 1000-w tungsten lamp. Irradiances from the 200-w quartz-iodide lamp and the 1000-w lamp were approximately 20 mw-cm^{-2} and 100 mw-cm^{-2}, respectively.

4.2 RESPONSE TIME

Response time was measured by suddenly exposing the thermopile to a radiation source and observing its output on an oscilloscope or strip chart recorder.

4.3 OPERATING TEMPERATURE RANGE

During testing, the Types 1 and 3 thermopiles were not heated above 443°K to avoid inadvertently melting the solder by which the leads were attached. They were maintained at 413°K for 18 hr in vacuum without damage. Type 2 detectors are limited to 393°K by the Mylar.

To determine if the detectors would be damaged by operation at low temperatures, all three types were lowered slowly into a partially filled dewar of liquid nitrogen. During two cycles between room temperature and 78°K, heat sink temperature and thermopile resistance were measured. No damage was observed. At liquid-nitrogen temperature, thermopile resistance increased by a maximum of 25 percent over room temperature resistance.

SECTION V
CONCLUDING REMARKS

The thermopiles described above were fabricated and tested for development of construction techniques and are not optimum designs. In redesigning one substrate type for a specific application, the relative advantages of each type should be considered. For equal numbers of junctions, the relative advantages of the three types are: suspended aluminum foil - fast response; suspended Mylar - good sensitivity; filled channel - resistance to shock and vibration.

It is generally true that increasing the sensitivity per active thermopile junction will result in a longer response time and greater nonlinearity over a given range of irradiance. Considering the design of suspended aluminum foil and suspended Mylar substrates, sensitivity may be increased by increasing the suspended length, using thinner foil, and increasing the number of active thermopile junctions deposited on the foil. Sensitivity of the filled channel type may be increased by enlarging the channel and adding more junctions. However, if the overall detector size is fixed, thereby limiting the number of junctions which can be deposited in the available area, the required sensitivity or response time must determine the choice of substrate.

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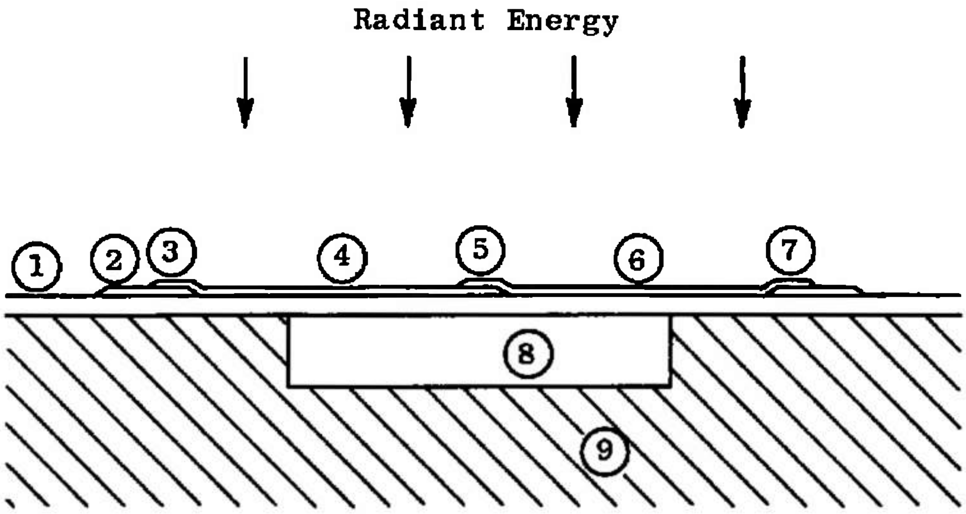
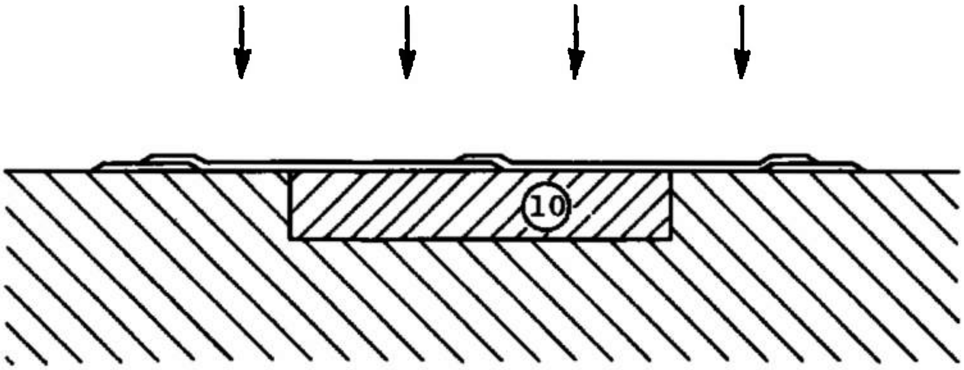


a. Suspended Substrate



b. Filled Channel

1 Mylar® or Aluminum Foil Substrate
2 Deposited Copper Film
3 Reference Junction
4 Deposited Bismuth Film
5 Active Junction
6 Deposited Antimony Film
7 Reference Junction
8 Channel
9 Aluminum Heat Sink
10 Filler Resin

Fig. 1 Thermopile Substrate Configurations

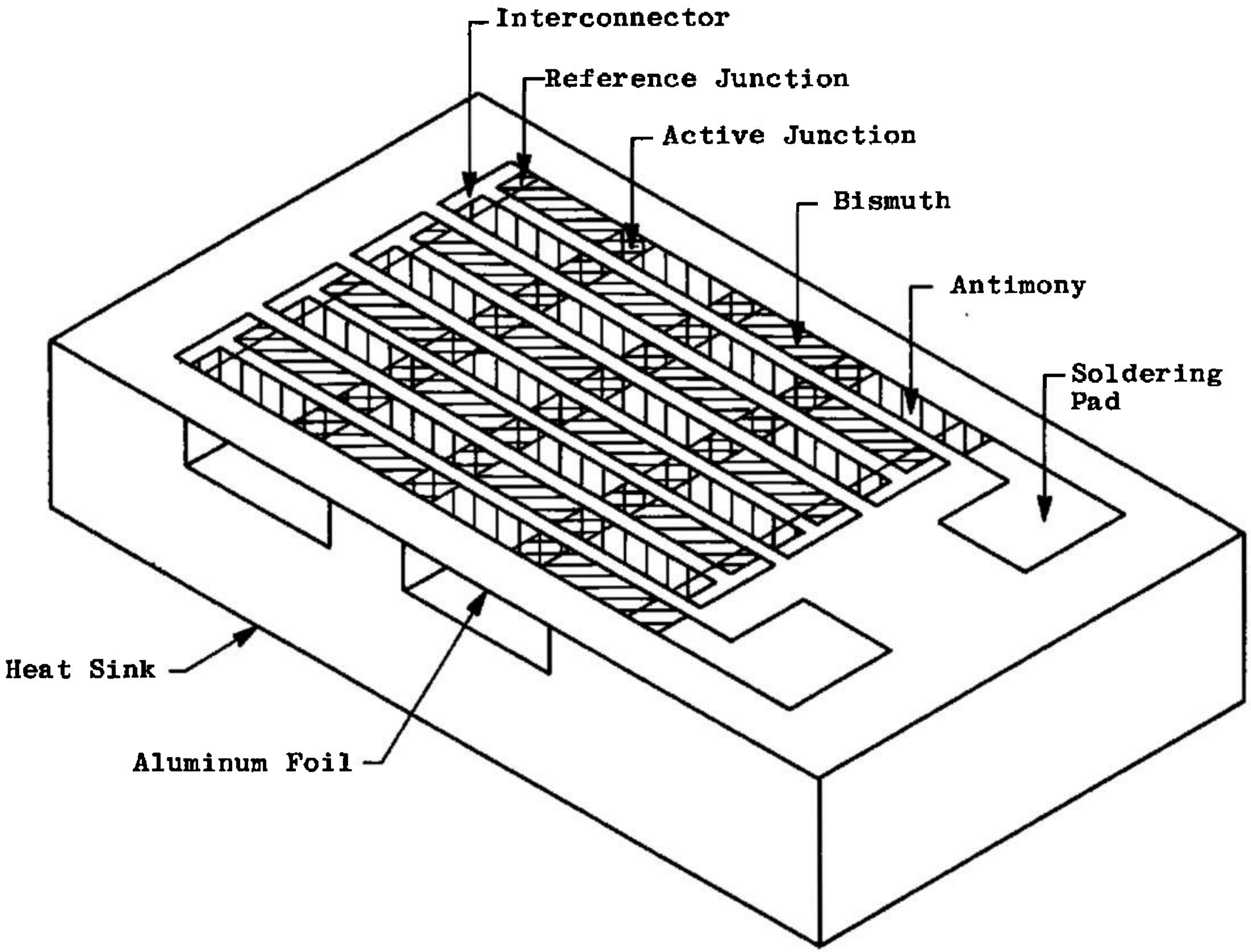


Fig. 2 Sixteen-Junction Thermopile

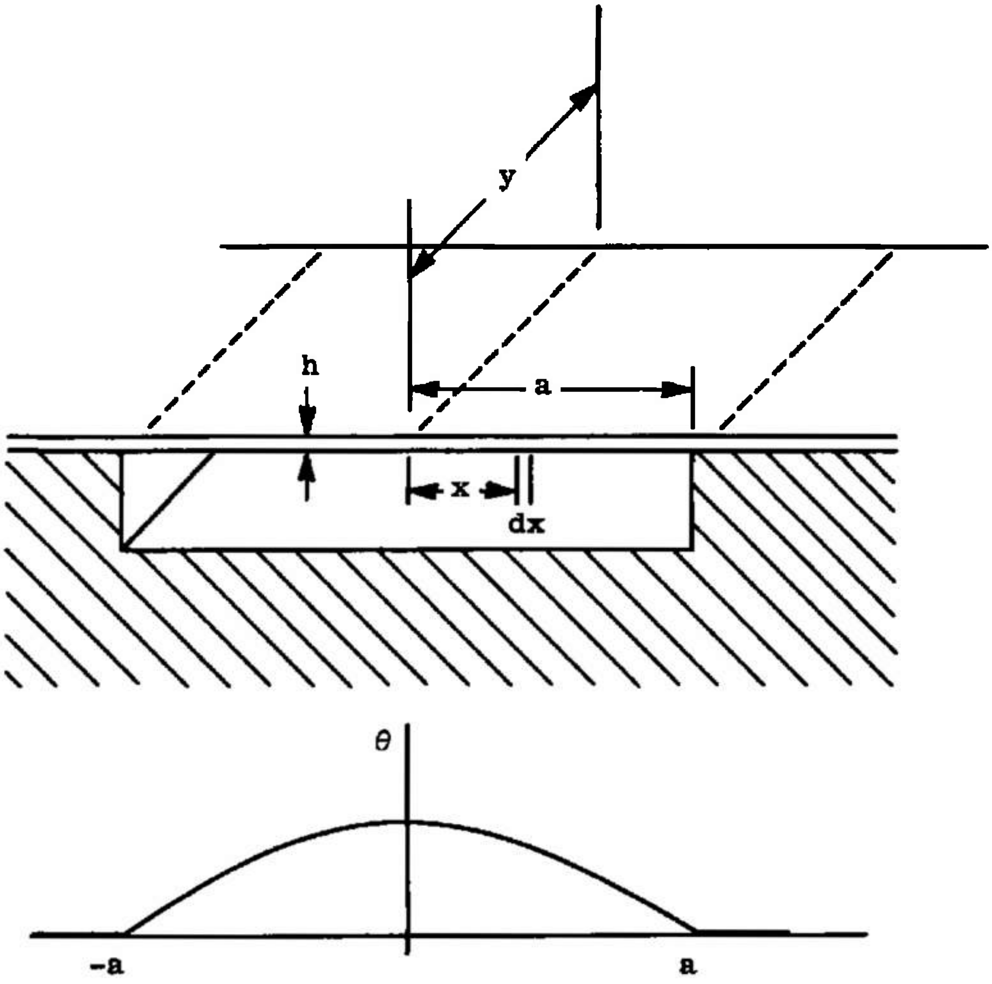


Fig. 3 Temperature in Suspended Aluminum Foil Substrate

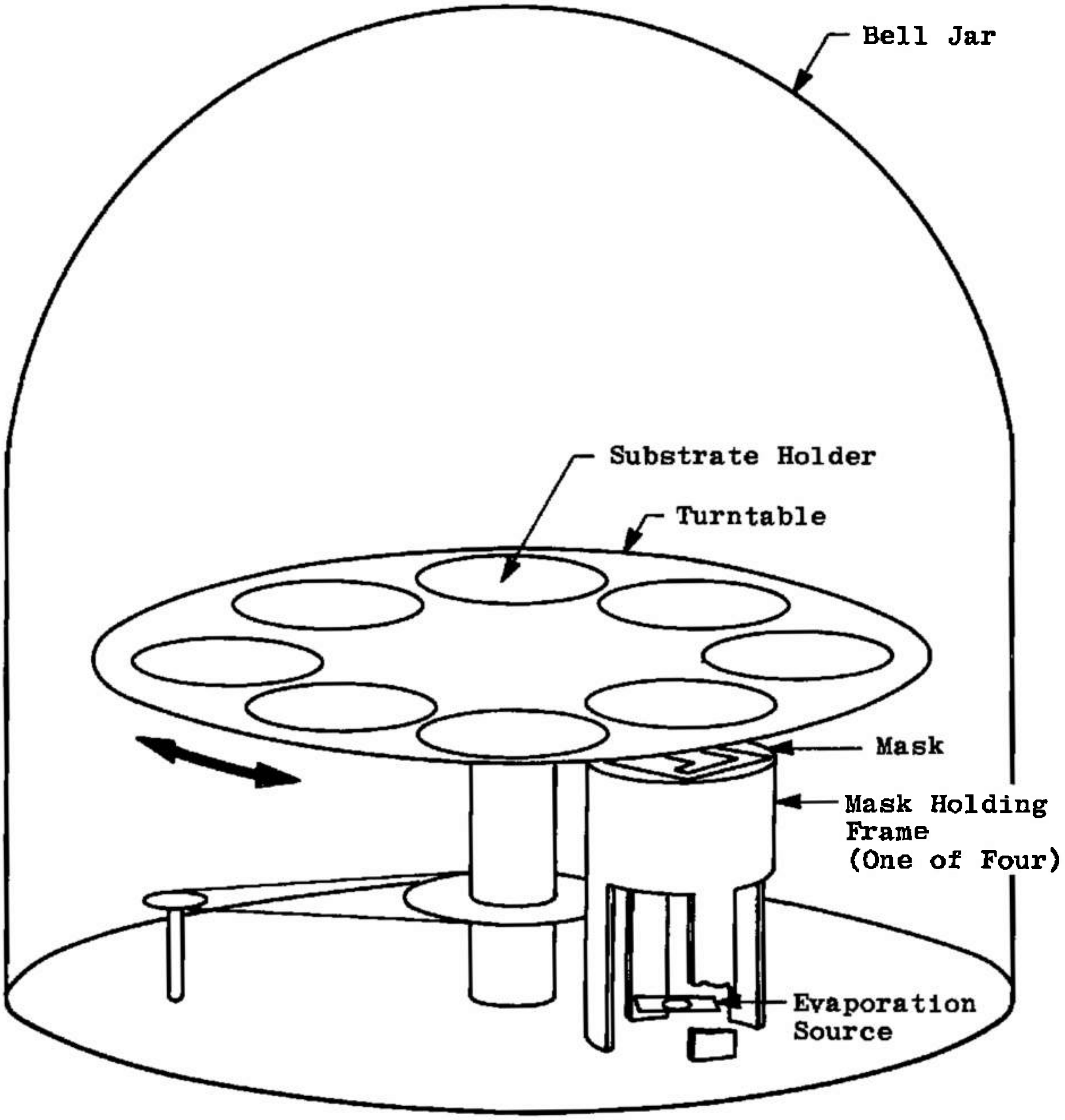


Fig. 4 Schematic of Mask-Substrate Registration Mechanism

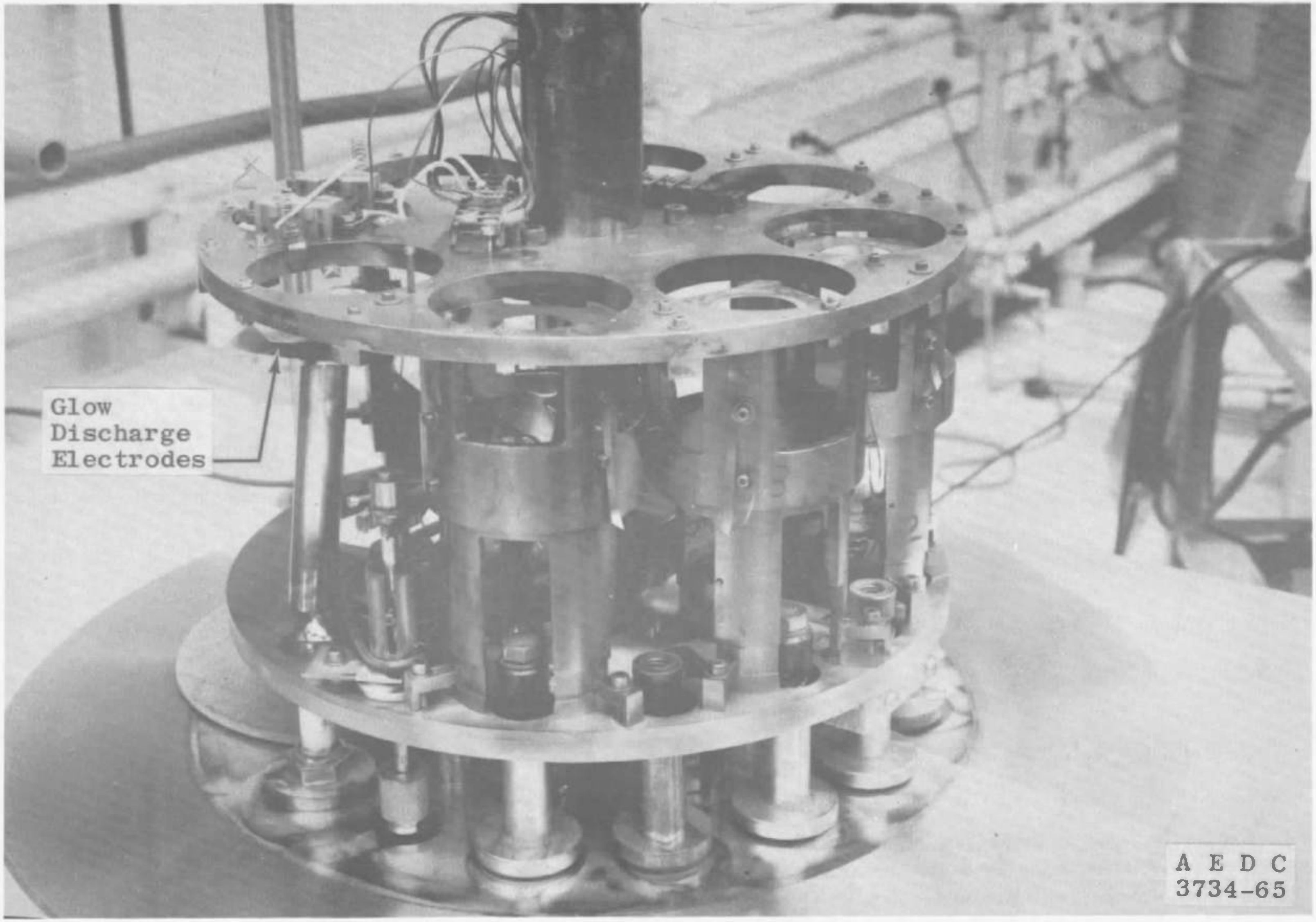


Fig. 5 Mask-Substrate Changer, View 1

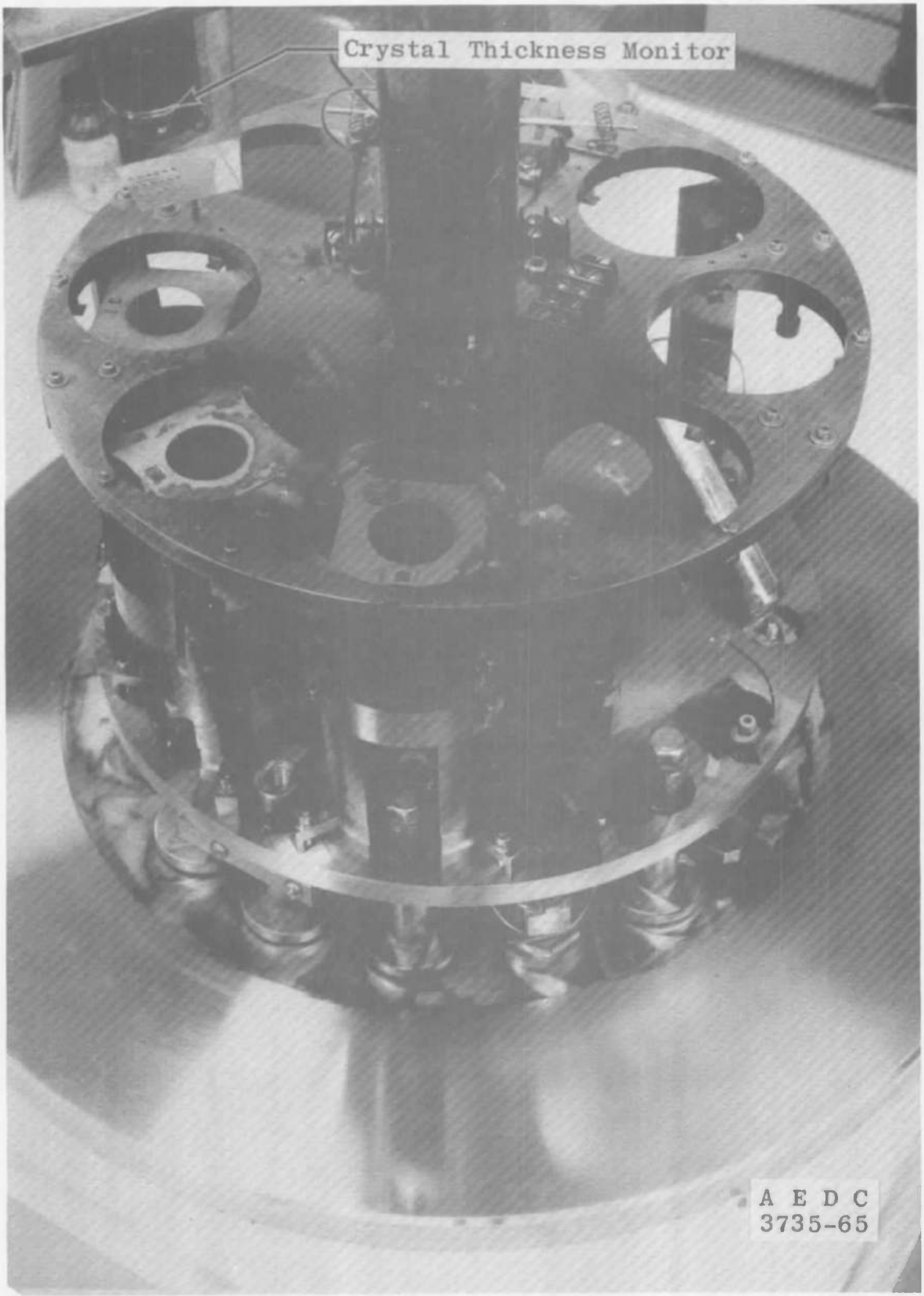


Fig. 6 Mask-Substrate Changer, View 2

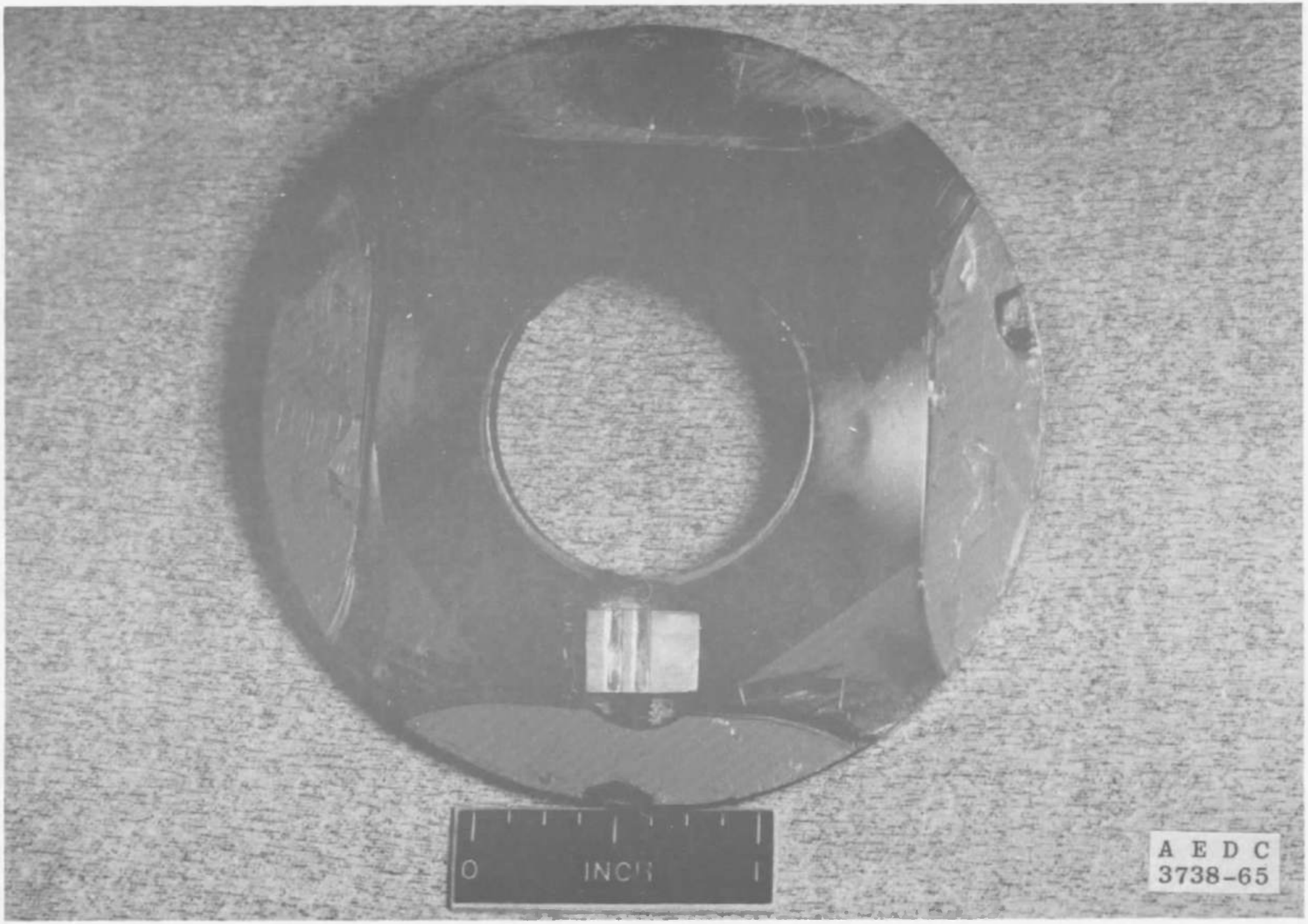


Fig. 7 Substrate Holder

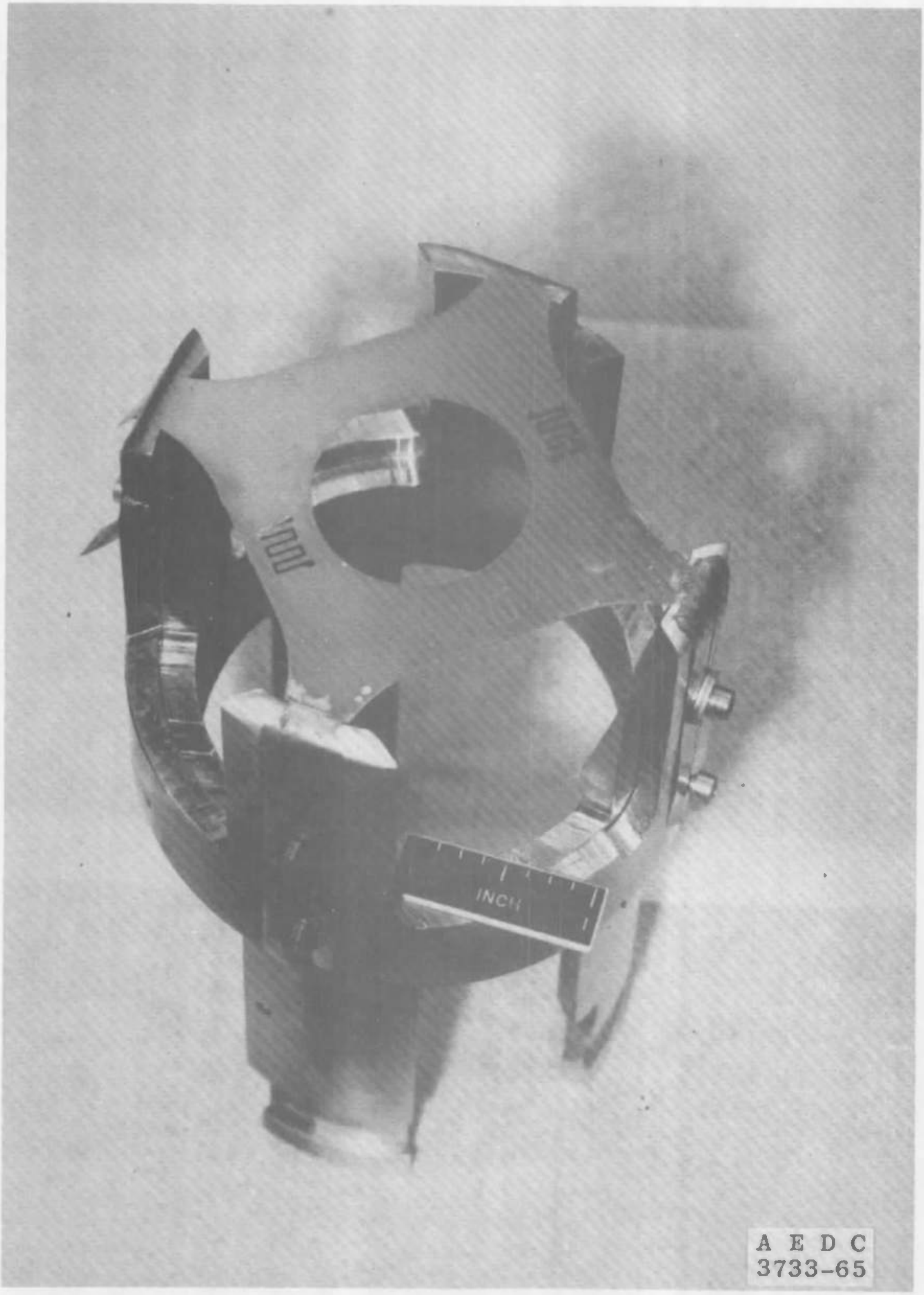


Fig. 8 Mask Holder

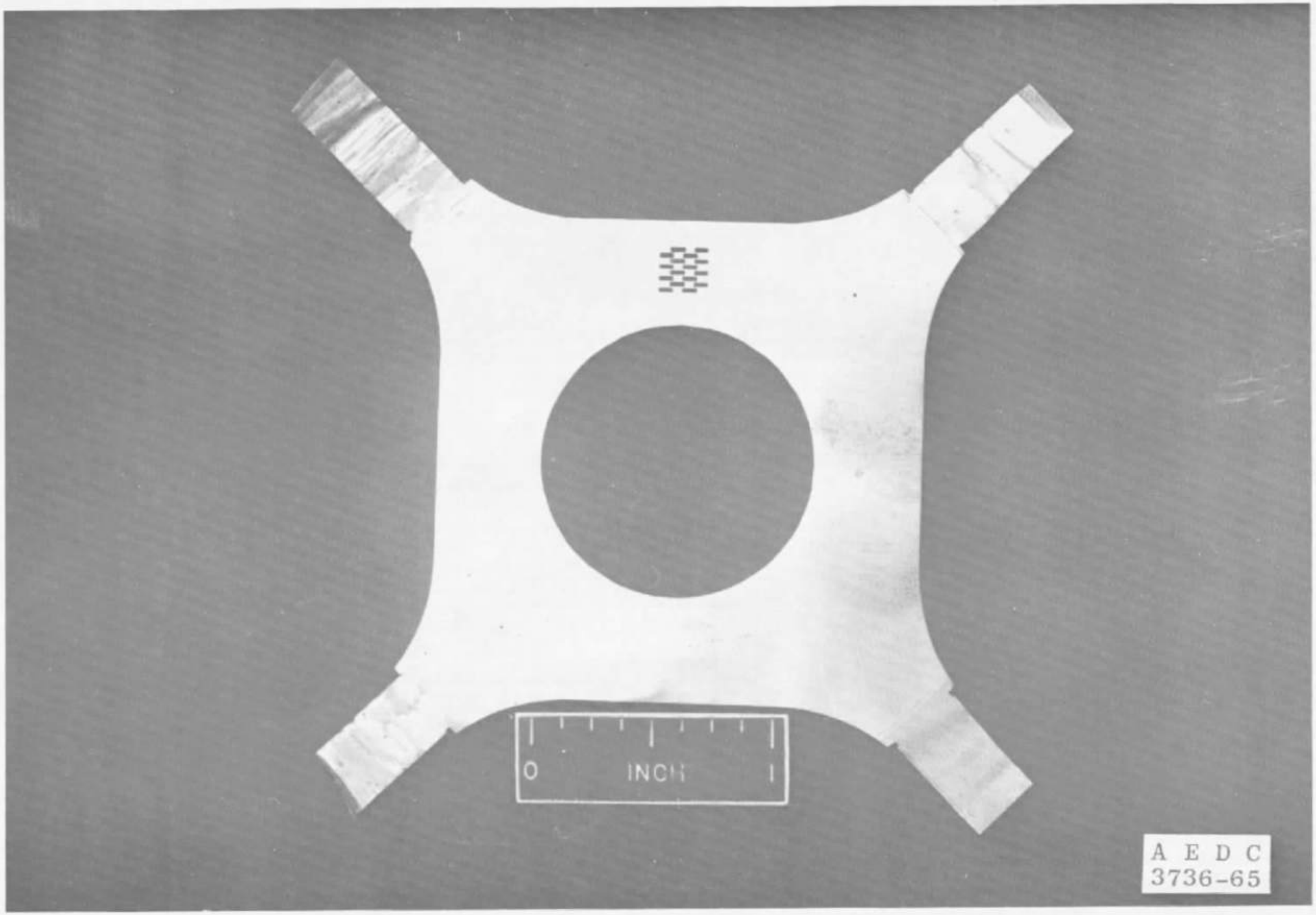


Fig. 9 Deposition Mask

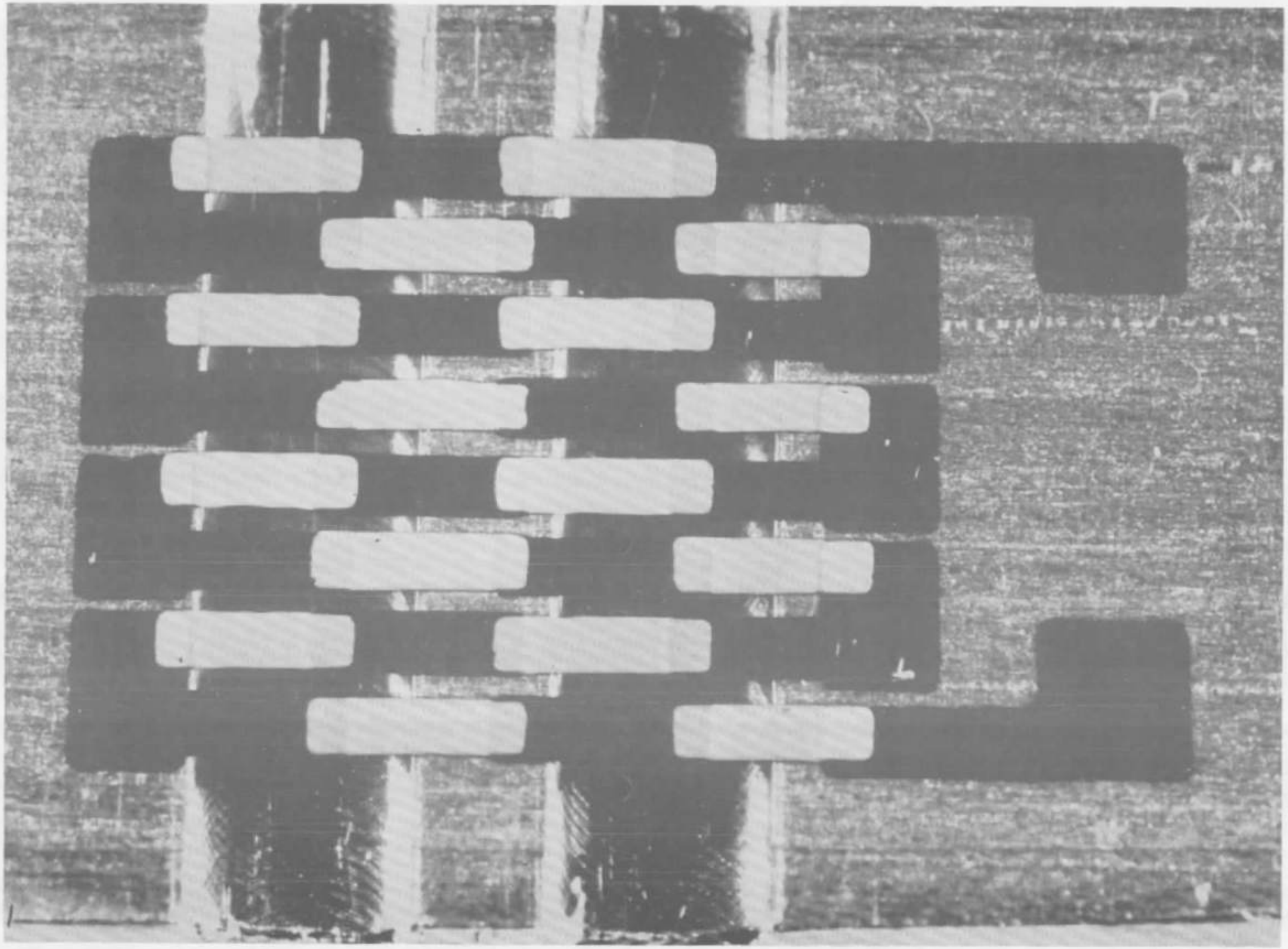


Fig. 10 Type 2 Thermopile (Suspended Mylar)

TABLE I

MEASURED CHARACTERISTICS OF 16-JUNCTION, BISMUTH-ANTIMONY, THIN FILM THERMOPILES

Characteristics	Substrate Type		
	1 Suspended Aluminum Foil	2 Suspended Mylar	3 Filled Channel
Radiation Sensitivity - Air, mv-mw^{-1}-cm^{2}	0.00162	0.0878	0.0168
Radiation Sensitivity - Vacuum mv-mw^{-1}-cm^{2}	0.00154	0.248	0.0174
Radiation Sensitivity - Calculated Vacuum, mv-mw^{-1}-cm^{2}	0.00189	0.315	0.0192
Percent Decrease in Sensitivity over 100 mw-cm^{-2} Range	Not Measured	3.0	1.0
Response Time to 99 Percent Final Value - Air	50 msec	5 sec	1 sec
Response Time to 99 Percent Final Value - Vacuum	50 msec	7 sec	1 sec
Thermopile Resistance, ohms	109	104	137
Operating Temperature Range, °K	78 to 443	78 to 393	78 to 443

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13. ABSTRACT

Thin film radiation thermopiles promise substantial improvement in detector performance and construction cost over conventional solid-wire thermopiles when used in space simulation chambers for measuring simulated solar total irradiance. Three types of substrates were used during the investigation of thin film construction techniques: (1) aluminum foil suspended over a channel cut in the heat sink, (2) thin Mylar® suspended over a channel cut in the heat sink, and (3) the heat sink containing a channel which is filled with an insulating resin. These substrates provide thermal resistance between active and reference junctions. Sixteen junction thermopiles of bismuth and antimony were vacuum evaporated onto the substrates, and the completed detectors were tested for sensitivity, response time, and resistance to damage caused by temperature cycling over the range from 80 to 440°K. Expected sensitivities were obtained (from 1×10^{-4} to 55×10^{-4} $v\text{-}w^{-1}\text{-}cm^{-2}$ per active junction for the channel configuration used). Response times (99 percent) ranged from 50 msec for the aluminum foil type to 7 sec for the Mylar type. All units were undamaged by temperature cycling. Operating principles, construction techniques, performances, and relative merits of these thin film thermopiles are described. (U)

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1 thermopiles						
2 thin films						
~~irradiance measurements~~						
3 space ~~simulation~~ chambers						
~~instrumentat~~ion						

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