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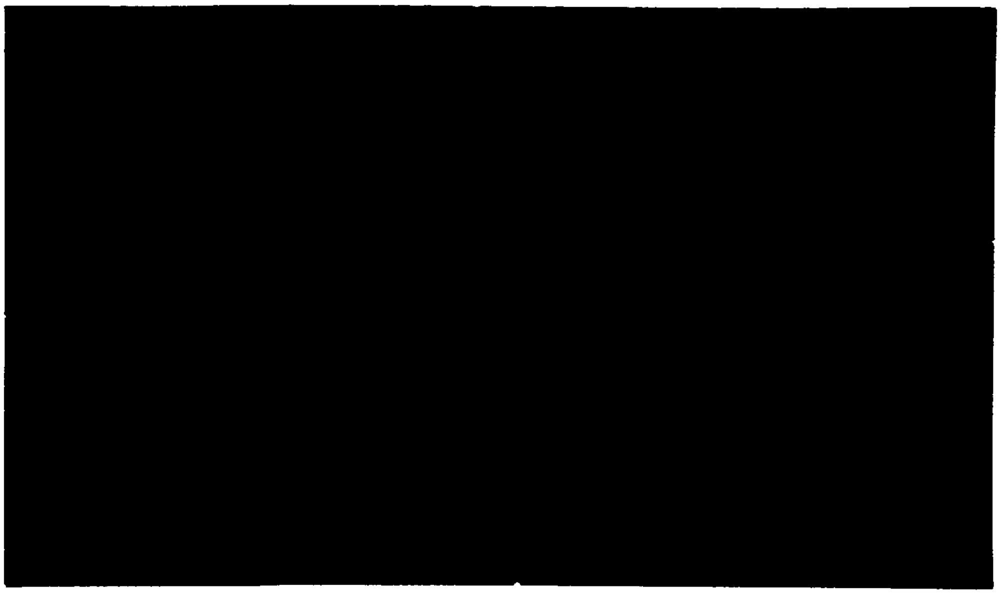

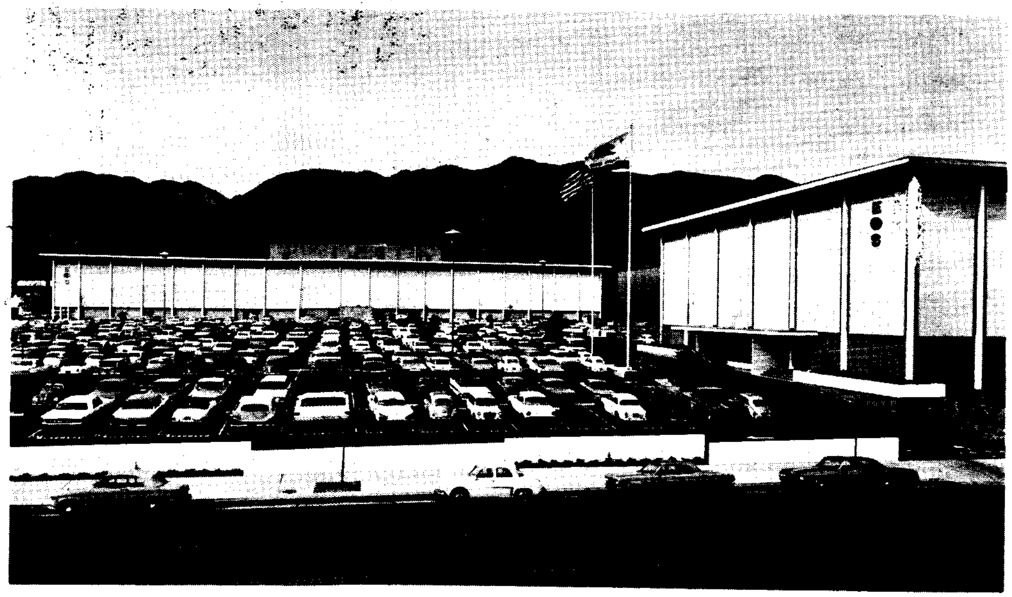

Final Report

TWO CESIUM RESERVOIR CONTROL UNITS

Prepared for
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California
Attention: Mr. J. T. Heie

JPL Contract 951228

EOS Report 7011-Final

10 July 1966

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Prepared by

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Approved by

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ELECTRO-OPTICAL SYSTEMS, INC. - PASADENA, CALIFORNIA
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SECTION I

PROGRAM SUMMARY

## 1.0 INTRODUCTION

This report on JPL Contract Number 951228 covers the period from 28 September 1965 to 27 May 1966. The contract was concerned with the design and fabrication of two cesium reservoir control units for thermionic diodes. Task I covered the design effort, including the measurement of parameters necessary for an effective configuration. Task II included the fabrication and testing of the two control units.

The control units were of two types: active and passive. They are easily attached or removed from the EOS or JPL thermionic converters. The active control consists of a heater and thermal sensor combined into a unit structure and fitted with suitable mounting hardware for attachment to the diode reservoir. To regulate the reservoir temperature, the signal from the sensor controls the output of an electronic power source.

The passive control consists of a vane-type radiation shield mounted on the reservoir. The position of the shield, as governed by a bimetallic element, will control the temperature of the reservoir by varying the amount of thermal energy radiated from the surface.

### 1.0.1 Purpose and Scope

The purpose of this program was to investigate the feasibility of making a passive reservoir control which will adequately control the reservoir temperature of the thermionic converter without the need for any electrical power input. In addition, an electrical control which is compatible with flight hardware was fabricated. The scope of the program involved the generation of the concepts involving the design, making prototypes, and testing them on actual converters under normal operating conditions.

1.0.2 Requirements (Program Ground Rules)

The requirements of this program as applied to the active and the passive control are outlined below for each type.

1.0.2.1 Active Control

The heater sensor portion of the active control will include the following considerations:

1. The control unit shall be adaptable to the reservoir diameters of the converters to be supplied by JPL and shall be easily removable from the converter.
2. The control unit shall use a resistor-type element as a sensor which shall be easily removable and adaptable for use with the heater. The control unit design shall incorporate components capable of reliable operation over a 1-year period of continuous use. The electronic control portion of the active control must be built according to the following considerations:
   a. The control unit shall have the capability of a temperature adjustment of 50 degrees when the reservoir is at 325-degree and shall bring the reservoir to a given temperature within 10 minutes to an accuracy of ±5 degrees.
   b. The power input to the heater shall be a maximum of 5 watts from a power source operating with a 440-Hz square wave. The standby power consumed by the control unit shall be less than 2 milliwatts.
   c. A screw-type adjustment shall be provided to adjust the temperature level between 325 and 375$^{\circ}$C. A ground command feature can be incorporated to turn off the cesium reservoir control as desired. The total weight of the heater element, electronics, and other parts of the control unit shall be less than 6 ounces for each converter exclusive of the leads from the converter

to the electronics and mounting structure for the electronics.

1.0.2.2 Passive Control

The design of a cesium reservoir passive control unit using a bimetallic element and suitable placement of radiation shields should adhere to the following considerations:

1. The control unit shall be adaptable to the converters supplied by JPL and shall be easily removable.
2. The control unit shall be completely automatic, maintaining the temperature of the reservoir at a given level within $\pm 5^{\circ}C$ when the natural temperature of the reservoir (without the control unit) varies from 325 to $375^{\circ}C$.
3. The total weight of the control unit shall be less than 3 ounces per converter and shall operate without external power. Both the active and passive control units shall incorporate, if possible, components capable of reliable operation over a 1-year period of continuous use. Each control unit shall be tested by being attached to a converter supplied by JPL and operating the control unit/converter combination in a laboratory test facility. Each unit shall have demonstrated operation for not less than 24 hours prior to acceptance and delivery.

1.0.3 Method of Attack

The method of attack used to meet the conditions outlined above was as follows: Concepts were developed for both the active and passive controls which were able to meet the above requirements which at the same time were compatible with existing technology. Measurements were taken of various thermal constants to supply data that were lacking. From the data and the concepts, designs were evolved, built, and tested. The results were then compared with the desired program goals.

### 1.0.4 Concepts Considered

#### 1.0.4.1 Active Control

A rather large number of concepts was considered in the early portion of the program. The active control was the simplest in concept and consisted of a heater and thermo-sensor combined into a single structure and fitted with suitable mounting hardware for attachment to the diode reservoir. To regulate the reservoir temperature, a signal from the sensor controlled the output of an electronic power source. Very little variation from this concept occurred during the course of the program and the final control is essentially that which was visualized originally.

#### 1.0.4.2 Passive Control

The passive control, on the other hand, being a much more difficult and sophisticated device, was studied in much greater depth. Many methods were considered and included torsion controlled device, rotating shutter device, linear bimetallic element, trapezoidal cantilever, and two types of spiral bimetallic elements. These concepts and their advantages and disadvantages are outlined below.

OUTLINE OF METHODS CONSIDERED

1. Torsion Controlled - Fig. 1-1

   Advantages

   Cylindrical symmetry and mechanical ruggedness

   Problems

   1. Actuating mechanisms as shown will not produce the desired angle of twist with such a small amount of material.
   2. Cylindrically symmetrical geometry as shown cannot easily be mounted on tubulation as shown because of spread of exhaust pinch-off, and danger of damaging fragile feather-edge.

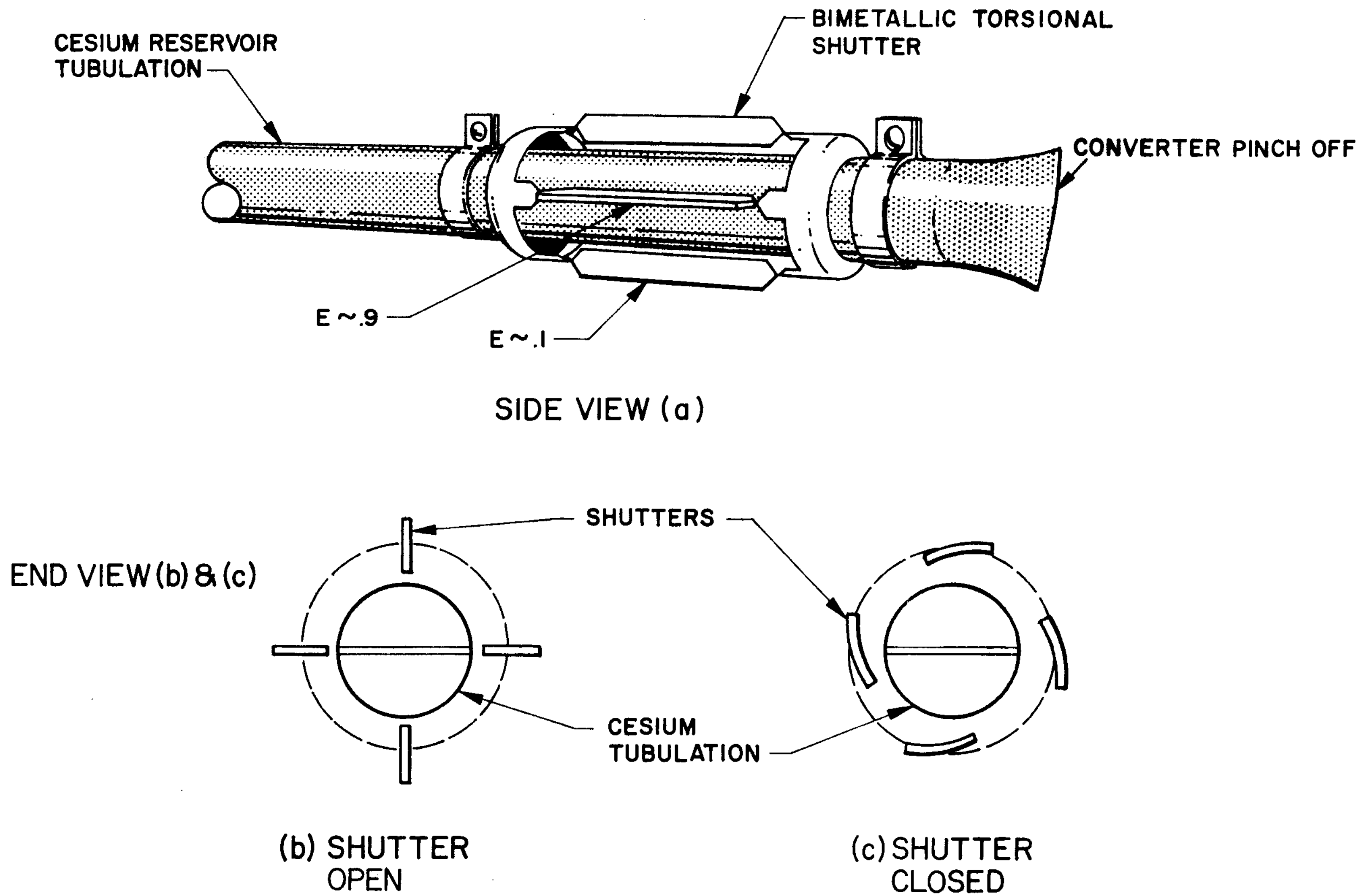


FIG. 1-1 PASSIVE BIMETALLIC ACTUATED TORSION CONTROLLED LOWER RESERVOIR TEMPERATURE CONTROL

3. Since all bimetallic elements respond to <u>temperature changes</u> only, mounting of the actuating elements on the reservoir end will not work. Any change in vane position can be accomplished only by a temperature change. Therefore, for constant reservoir temperature, there is constant vane position. Conversely, for variable vane position (variable emissivity), there is the accompanying variable reservoir temperature.
4. Extension of mechanism along the axis of tubulation theoretically can solve problem 3 for the EOS converter but in practice the available clearance is inadequate. Such extension is impossible for the JPL converter due to the spider used for a vibration snubber.

<u>Disposition</u>

Rejected as an unsuitable approach

2. <u>Rotating Shutter - Fig. 1-2</u>

<u>Advantages</u>

Cylindrical symmetry and mechanical ruggedness

<u>Problems</u>

1. Actuating mechanisms as shown will not produce the desired angle of twist with such a small amount of bimetallic material.
2. Cylindrically symmetrical geometry as shown cannot easily be mounted on tubulation as shown because of spread of exhaust pinch-off, and danger of damaging fragile feather-edge.
3. Since all bimetallic elements respond to <u>temperature changes</u> only, mounting of the actuating elements on the reservoir end will not work. Any change in vane position can be accomplished only by a temperature change. Therefore, for constant reservoir temperature, there is constant vane position. Conversely, for variable

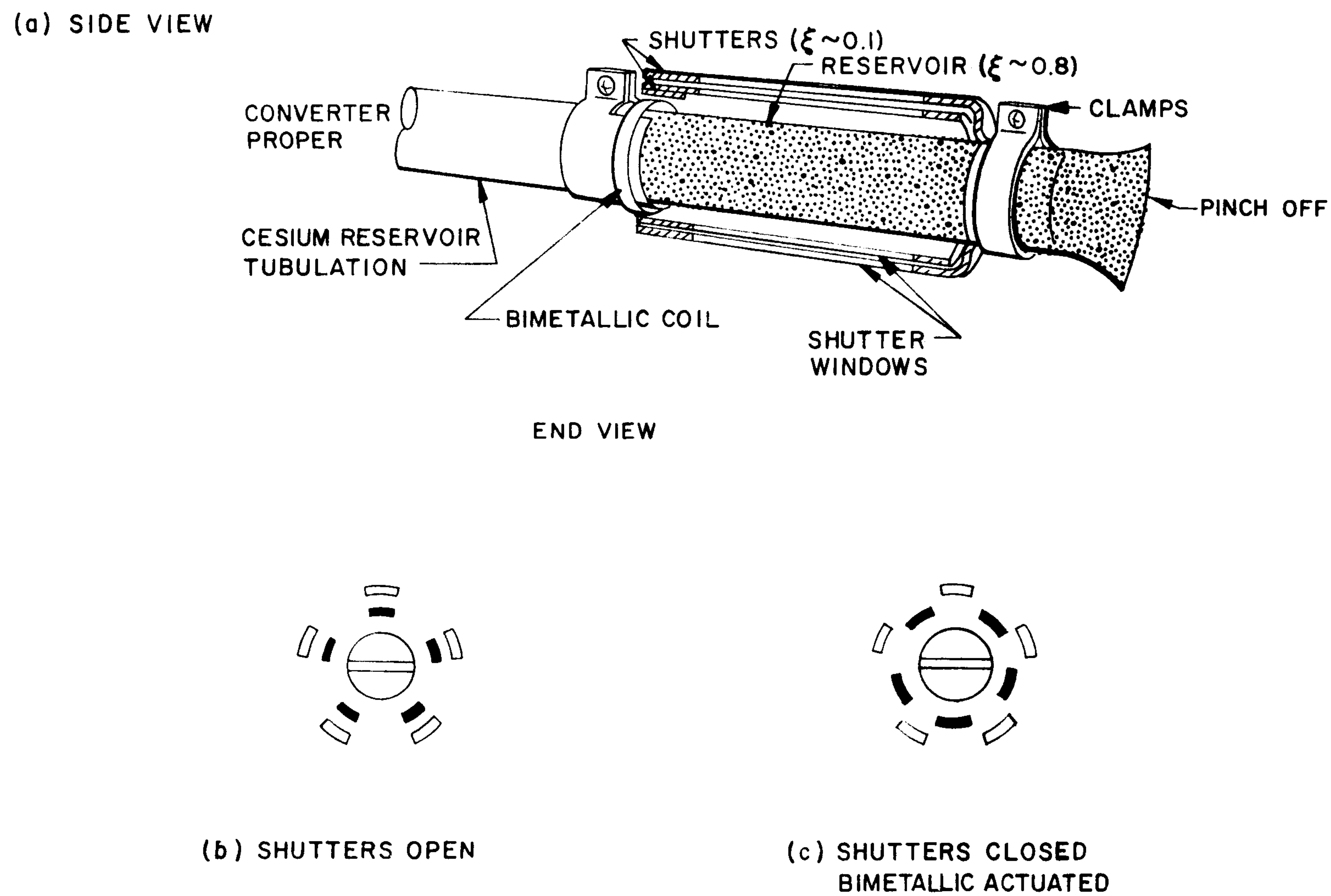


FIG. 1-2 ROTATING SHUTTER BIMETALLIC ACTUATED PASSIVE CESIUM RESERVOIR TEMPERATURE CONTROL

vane position (variable emissivity), there is the accompanying variable reservoir control.

4. Available clearance on EOS converter inadequate for extension of actuating elements to variable temperature zone. No axial extension possible for JPL converter due to spider.

<u>Disposition</u>

Rejected as an unsuitable approach

3. <u>Linear Bimetallic Element - Fig. 1-3a</u>

<u>Advantages</u>

Simplicity

<u>Problems</u>

1. Insufficient linear motion available.

$$D = \frac{K_{DS}\,(\Delta T)\,L^2\,m}{4.5\,t} = 0.009 \text{ in. } (L = 1 \text{ in.})$$

where

$D$ = deflection

$K$ = deflection constant

$L$ = free length

$t$ = thickness

$m$ = specific deflection $0 \le m \le 1$ $m = \frac{D}{D_F}$

$D_F$ = free deflection

<u>Disposition</u>

Rejected as an unsuitable approach

4. <u>Trapezoidal Cantilever - Fig. 1-3b</u>

<u>Advantages</u>

Simplicity, ruggedness

<u>Problems</u>

1. Small variable temperature zone (1 in. long, maximum) limits available motion. Motion could be magnified

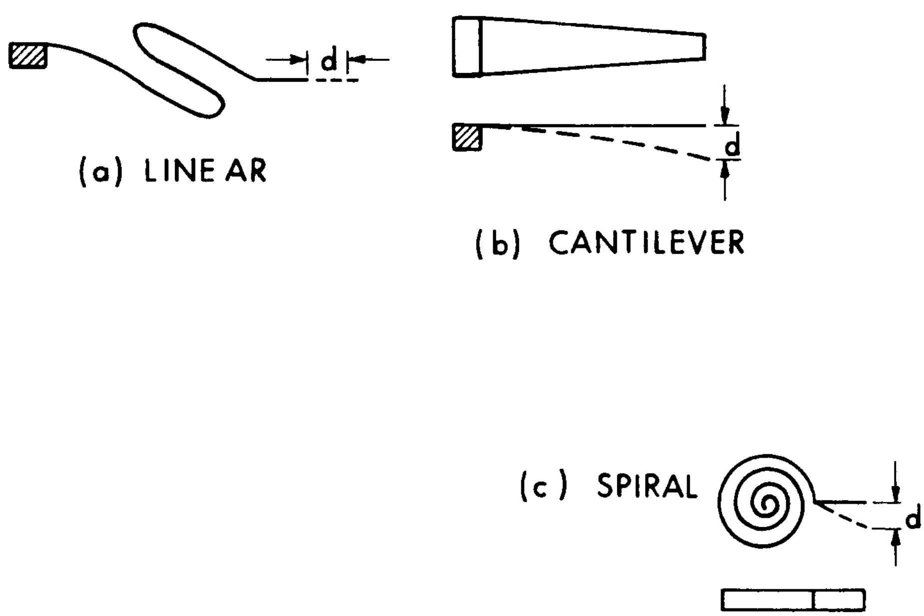


FIG. 1-3 BIMETALLIC ACTUATOR SHAPES



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but available force too low for repeatable positioning of any vanes driven by cantilever.

$$D = \frac{K_{DS} (\Delta T) L^2 m}{t} = 0.030 \ (L = 1)$$

Disposition

Rejected as an unsuitable approach

5. Spiral - Fig. 1-3c

Advantages

1. Large angular deflection available with small temperature change and small heat zone.
2. Can be made into rugged actuator.

Problems

1. Angular deflection must be amplified mechanically to obtain total desired motion.
2. Thin material gives largest deflection but lowest torque.
3. Thick material is strong but it is difficult to get enough material in the hot zone for adequate motion.

$$D(ang) = \frac{K_C L (\Delta T)}{t} \doteq 30^{\circ} \text{ for } L = 3 \text{ in.}$$

4. By use of lever, motion can be amplified - requires axle and bearings.

Disposition

Spiral approach incorporated into rotating vane design submitted for approval.

1. Device as shown will mount on EOS converter (Fig. 1-4).
2. Device with modified vane shape, mounting block, and radiation cone will mount on JPL converter (Fig. 1-5).

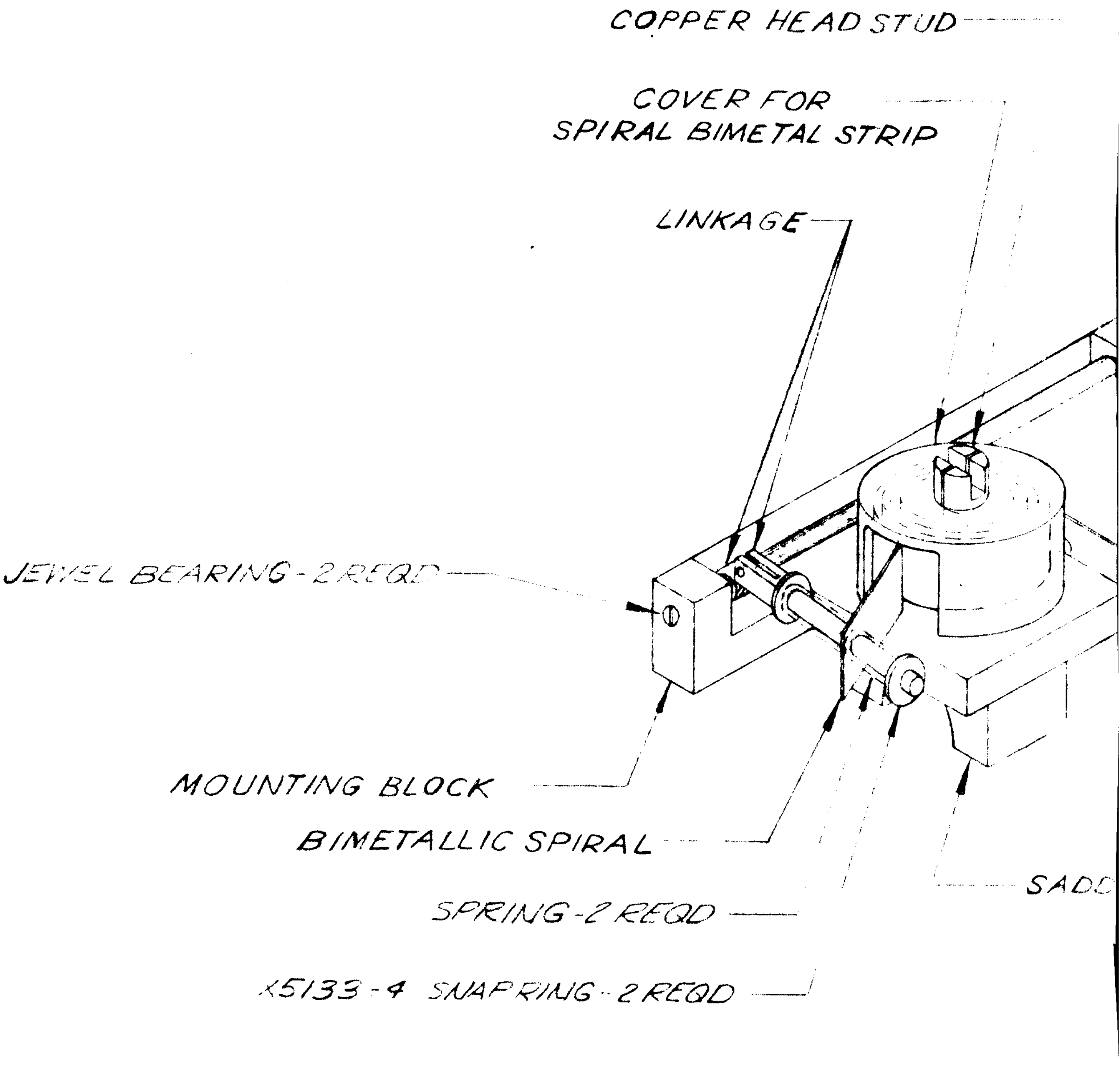


FIG. 1-4 PASSIVE CONTROL CONCEPTUAL ISOMETRIC ASSEMBLY (ROTATING VANE - EOS)



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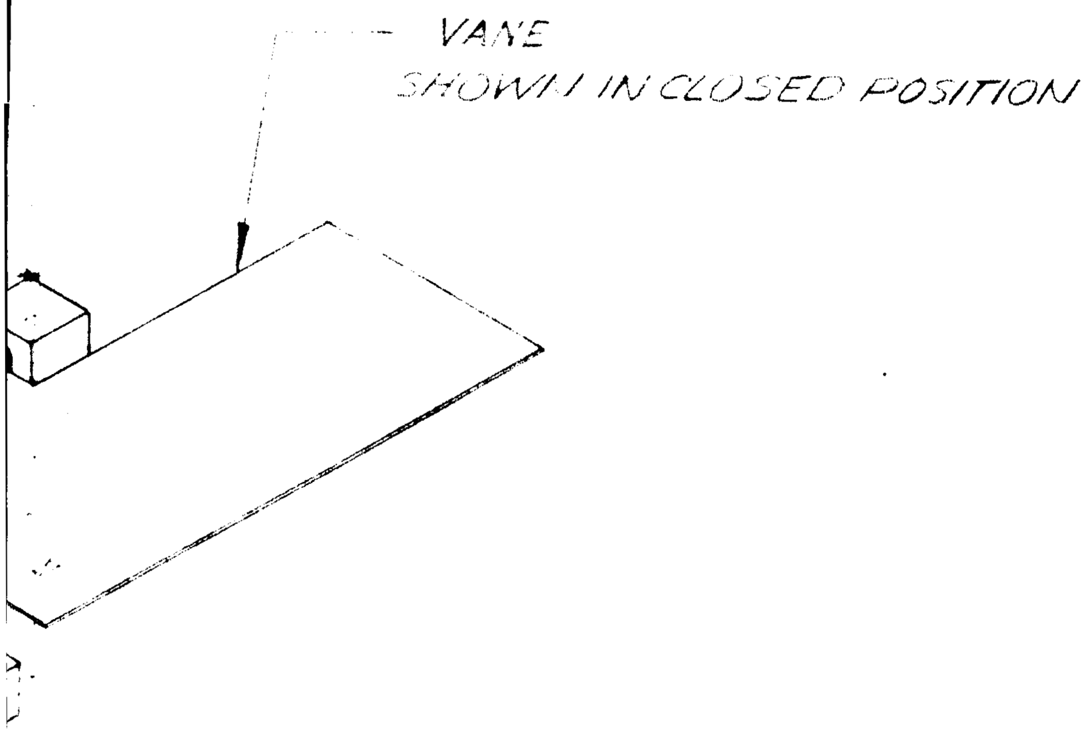


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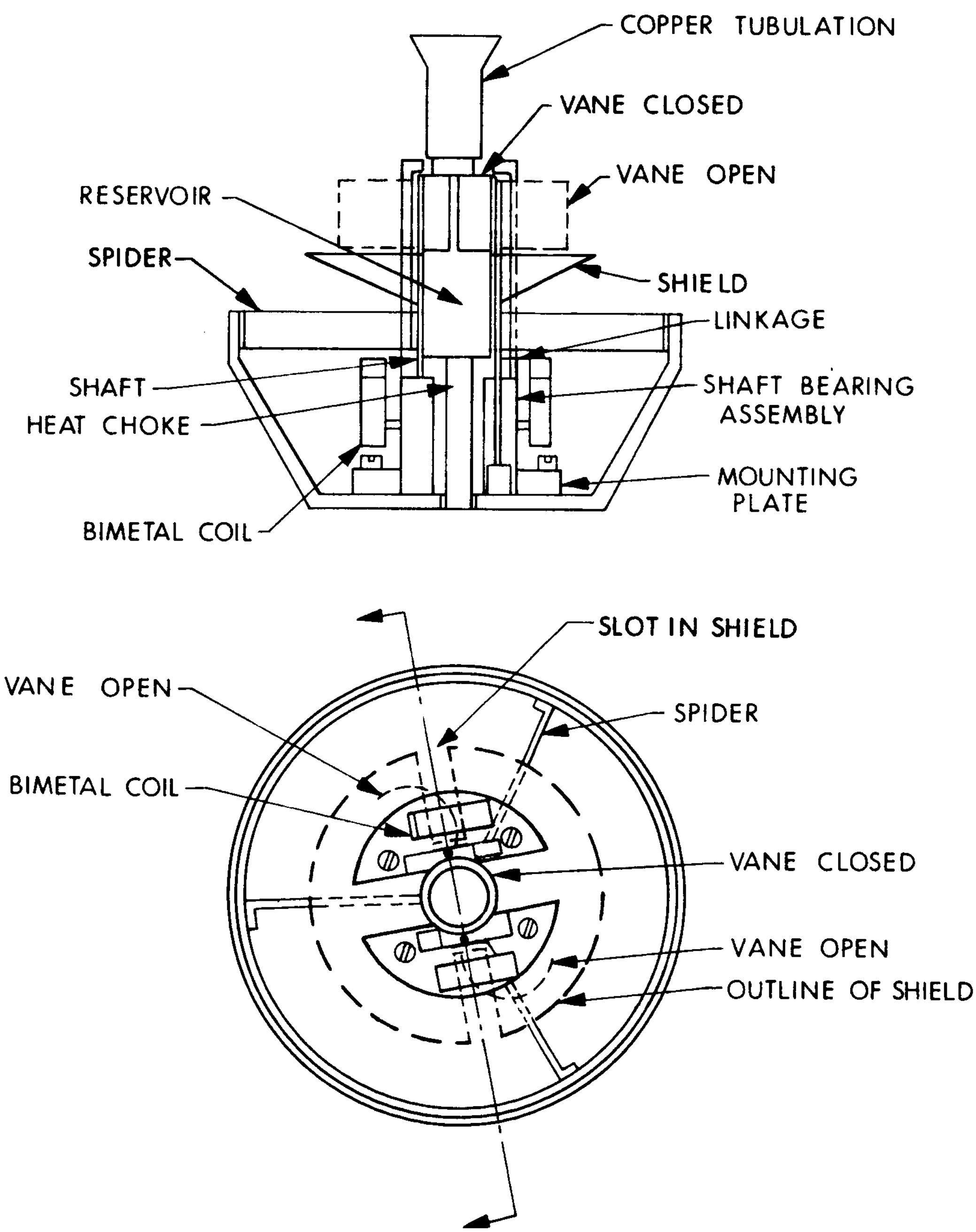


FIG. 1-5 ROTATING VANE CONTROL

6. Swinging Vane — Fig. 1-6 EOS; Fig. 107 JPL

Advantages

1. Simplicity, no precise bearings required.
2. Large angular deflection in small temperature zone.
3. Mechanical amplification achieved without elaborate lever system.
4. Extension of spiral can be used for lever actuating the vane, thus providing slight additional motion due to cantilever effect.

Problems

1. Long lever arm and vane may vibrate quite a bit during mechanical agitation. However, should cause no permanent ill effect or change in device characteristics.
2. Requires two fastening points — one at base or root of heat choke and one at reservoir proper (JPL).
3. Requires slots in heat shield as shown in sketch (JPL). (Heat shield itself can be used as anchor point for vanes, thus eliminating one clamp.)
4. May need vibration snubber for EOS version.

Disposition

Recommended as alternate approach adaptable to both converters.

Of all the designs shown above, the one in Fig. 1-4 was selected as the best all-around approach. It was adaptable to JPL converter as shown in Fig. 1-5.

1.0.5 Materials

The materials used in both the active and passive controls are capable of long-life operation, some of which will operate at temperatures in excess of 500$^{o}$C in a space environment. Therefore, only materials of similar physical properties to those used in present-day converter fabrication can be considered. For the electronic control,

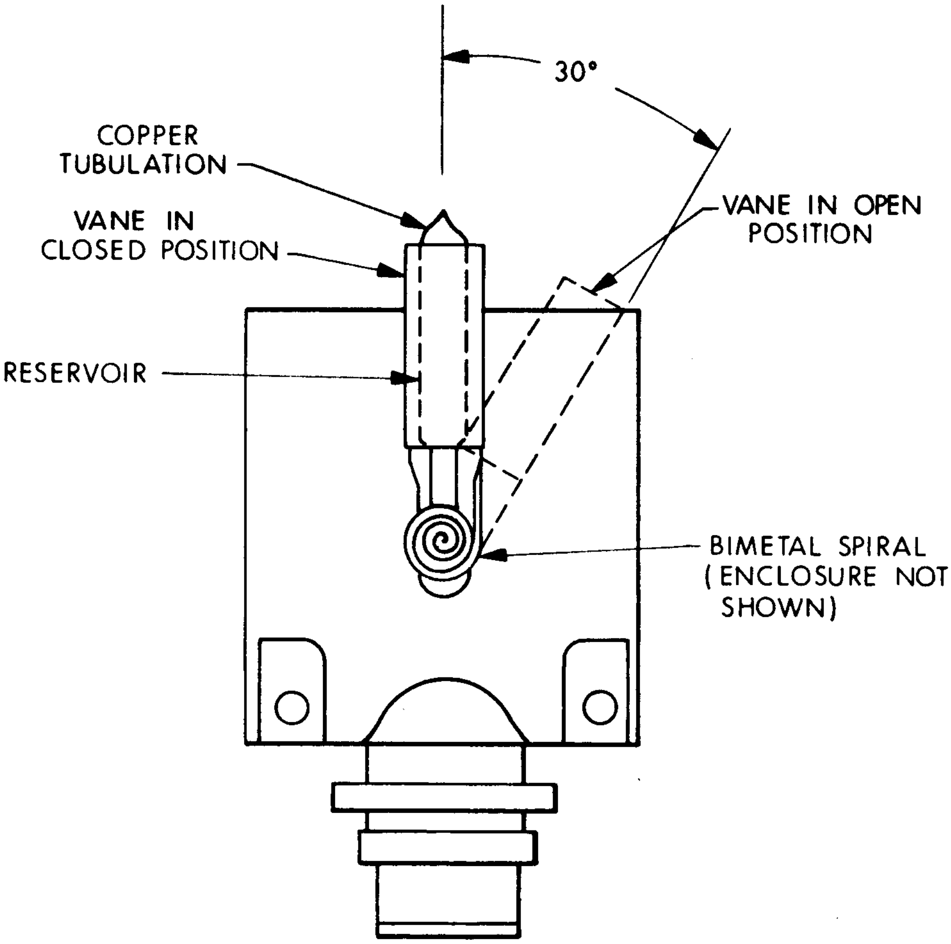


FIG. 1-6 SWINGING VANE FOR ECS CONVERTER

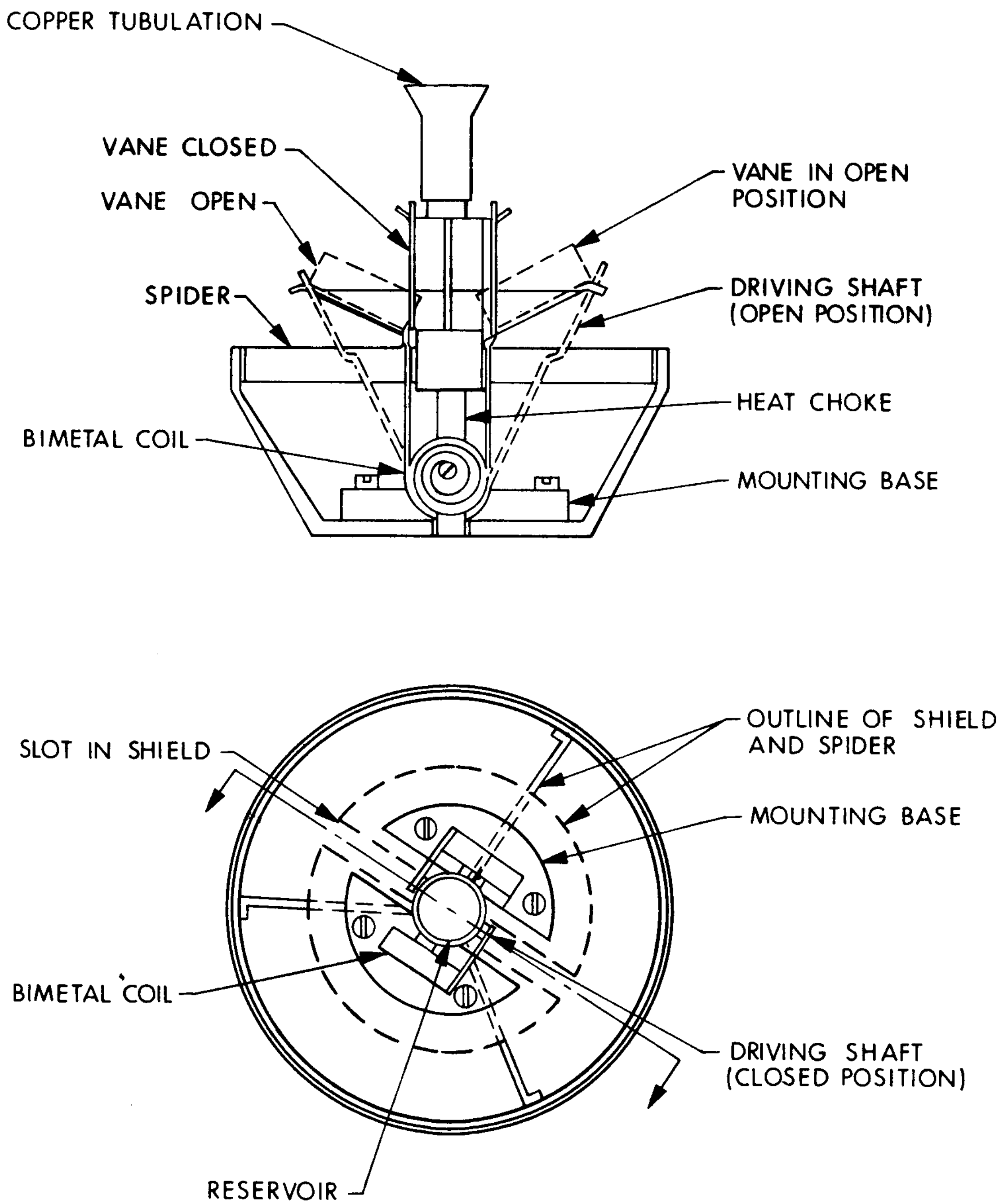


FIG. 1-7 SWINGING VANE CONTROL (JPL)

highly reliable electronic components properly arranged in a mechanically rugged control module must be used if the desired ruggedness and reliability is to be achieved. All of the materials used in the construction and testing of these controls fit these criteria.

1.1 Passive Control Unit

A passive control unit was constructed. This unit utilized a spiral, bimetallic driving element mechanically coupled to a vane which, in turn, controlled the effective emissivity of the cesium reservoir. The effective emissivity was determined by the position of the vane or radiation shield relative tothe reservoir. Tests on a mock-up control using very lightweight vanes showed that the principle could be made to work. The actual control, as devised in this program, worked on the EOS diode in a less than satisfactory manner due to sticking of the bearings and due to the fact that the bimetallic element required a fairly high degree of temperature overshoot before motion occurred. It was not possible to run similar tests on the JPL diode because of mechanical interference of the radiation shield which was on the JPL diode. If converters are made with the idea that they will be used in conjunction with the passive reservoir control, suitable configurational changes on existing converters must be made to make the attachment of passive control units to converters practical. However, before such a practical control is realized a considerable amount of effort will be required to develop the intricate mechanical amplification scheme that is necessary to achieve reliable control of the motion of a vane or other emissivity controlling element.

1.2 Active Control Unit

The active control unit as conceived, designed, constructed, and tested on this program has shown itself to be a very reliable device which more than meets the specifications outlined above. In particular, when operating on the EOS converter which has a lower thermal mass than the

JPL converter, the thermal response time was only 6-7 minutes for a temperature change from 325 to 375°C.

The time required to accomplish the same change of the JPL converter was 10-12 minutes. However, with a slight increase in power output this can be readily remedied.

The unit is capable of controlling the temperature within a 50-degree temperature band to within ±1/2 degree for any load changes which can be impressed upon the converters. Just as with the passive control unit, active control units must be considered as a permanent part of the thermionic diode configuration, and provisions should be made during the manufacture of the diodes for mounting the active control sensing unit.

## SECTION II

## CONTROL UNIT DESIGN

### 2.0 INTRODUCTION

Both the active and passive controls were initially conceived along the simplest lines possible and were to be made so that they could be easily attached or removed from EOS or JPL thermionic converters. The active control from the beginning consisted of a heater and thermal sensor which were combined into a unit structure and fitted with suitable mounting hardware for attachment to the diode reservoir. A signal from the sensor controlled the output of an electronic power source to regulate the reservoir temperature.

The passive control was equally simple in concept, in that a vane structure was used to control the effective emissivity of the reservoir of the thermionic diode. Problems arose in finding a suitable actuating component which would not only operate at the high temperatures required but would have adequate thermal sensitivity at the high temperature to give adequate control. One of the major problems encountered with both the EOS and JPL converters was the lack of space for mounting the bimetallic elements at the proper hot zone. Because of the radically different shapes of the radiators on the EOS and JPL converter, it was very difficult to arrive at a structure which was compatible with both converters. As will be shown below, it was also difficult to find enough space in the hot zone to accommodate the required length of bimetallic material to provide adequate mechanical motion even with amplification by means of levers.

Probably the single, most important consideration, however, which covers the design of the passive reservoir control is that the bimetallic control element must be mounted closer to the reservoir heat source than the temperature-controlled region. The significance of that statement will be realized by considering the various methods outlined above. One additional comment on this type of mechanical control in general is that it should not be designed as a mechanical null type device. This is because any bimetallic material when at the null position has zero torque. Therefore, a fairly large $\Delta T$ must be realized before enough torque is generated by the bimetallic element to effect the desired mechanical movement.

## 2.1 Passive Control

### 2.1.1 Thermal Calculations

All thermal calculations for reservoir heat transfer are based on heat rejection by radiation only. The effective emissivity of the major area of the reservoir is the major parameter in this heat transfer. The effective emissivity, in turn, is based on surface emissivity and geometrical factors. The amount of heat that can be rejected by the reservoir of a converter is given by the radiation equation

$$W_r = \sigma A_2 \varepsilon (T_r^4 - T_o^4) \tag{1}$$

and the amount of heat conducted into the reservoir through the heat choke is given by

$$W_c = \frac{k A_1}{\Delta x} (T_c - T_r) \tag{2}$$

In thermal equilibrium, the radiated power must equal the conducted power which yields:

$$W_r = W_c ; \frac{kA_1}{L} (T_c - T_r) = \sigma A_2 \varepsilon (T_r^4 - T_o^4) \tag{3}$$

where

| | | |
|---|---|---|
| $W_r$ | = | the heat radiated from the converter |
| $W_c$ | = | the heat conducted into the reservoir |
| $k$ | = | the thermal conductivity of the heat choke |
| $A_1$ | = | cross-sectional area of the heat choke |
| $A_2$ | = | surface area of the reservoir |
| $\Delta x$ | = | length of the heat choke |
| $T_c$ | = | collector root temperature |
| $T_r$ | = | reservoir temperature |
| $T_o$ | = | ambient temperature |
| $\sigma$ | = | Boltzmann constant |
| $\epsilon$ | = | effective emissivity of the reservoir |

For space operation of a converter, $T_o$ is equal to $0^oK$ which is also a good approximation for the laboratory. Therefore, Eq. 3 can be written as

$$\frac{kA_1}{\Delta x}(T_c - T_r) = \sigma A_2 \epsilon T_r^4 \tag{4}$$

Now for a given geometry and set of materials, $\frac{kA_1}{\Delta x}$ and $\sigma A_2$ are constant.

If the reservoir temperature, $T_r$, is to be constant over a given range of collector root temperature, $T_c$, Eq. 2 can be written as

$$\frac{kA_1}{\Delta x}(T_c - \Phi) = \sigma A_2 \epsilon \Phi^4 \tag{5}$$

where $\Phi$ = a particular reservoir temperature.

The only way $T_r$ can be constant is for $\epsilon$, the effective emissivity, to vary properly as $T_c$ varies. To find the range of $\epsilon$ required for $T_{c\ min} \leq T_c \leq T_{c\ max}$, Eq. 5 can be rearranged

$$T_c = \epsilon\left[\frac{\sigma A_2 \Delta x}{kA_1}\right]\Phi^4 + \Phi \tag{6}$$

Equation 6 is a linear equation between $T_c$ and $\epsilon$, the effective emissivity. The desired range of temperature regulation on the reservoir will occur only when the slope m of the curve of Eq. 6.

$$m = \epsilon \left[\frac{\sigma A_2 \Delta x}{kA_1}\right] \leq \frac{\epsilon_{max} - \epsilon_{min}}{T_{max} - T_{min}} \tag{7}$$

Even with the required slope the constant term $\Phi$ must be of the proper magnitude to center the operating temperature range. This concept is shown schematically in Fig. 2-1 which shows in 2-1a the extremes of emissivity and collector temperature which will permit regulation of the reservoir temperature over the desired collector root temperature range.

Assuming conditions 6 and 7 can be satisfied for the range of reservoir temperature desired ($\Phi_{min} = 325^{o}C$, $\Phi_{max} = 375^{o}C$) for any given $\Phi$, the collector root temperature and $\epsilon$ are related by a simple linear relationship. Control of the effective emissivity of the reservoir can be achieved by controlling areas of the reservoir surface with vanes of very low emissivity which are activated by bi-metallic elements. The effective emissivity includes the emissivities of the two surfaces which view each other (in this case, the vane and the reservoir surface), their areas and an angle or view factor $F_{12}$. In the simplest case for heat exchange between a body and a complete concave enclosure the effective emissivity is given by:

$$\epsilon = \frac{\epsilon_1}{1 + \epsilon_1 \left(\frac{1}{\epsilon_2} - 1\right) \frac{A_1}{A_2}} \quad F_{12} \tag{8}$$

where the subscript 1 refers to the inner and 2 to the outer surfaces. The geometry of the passive control is much more complicated than this and calculation of $F_{12}$ such as given in Appendix I is required for even

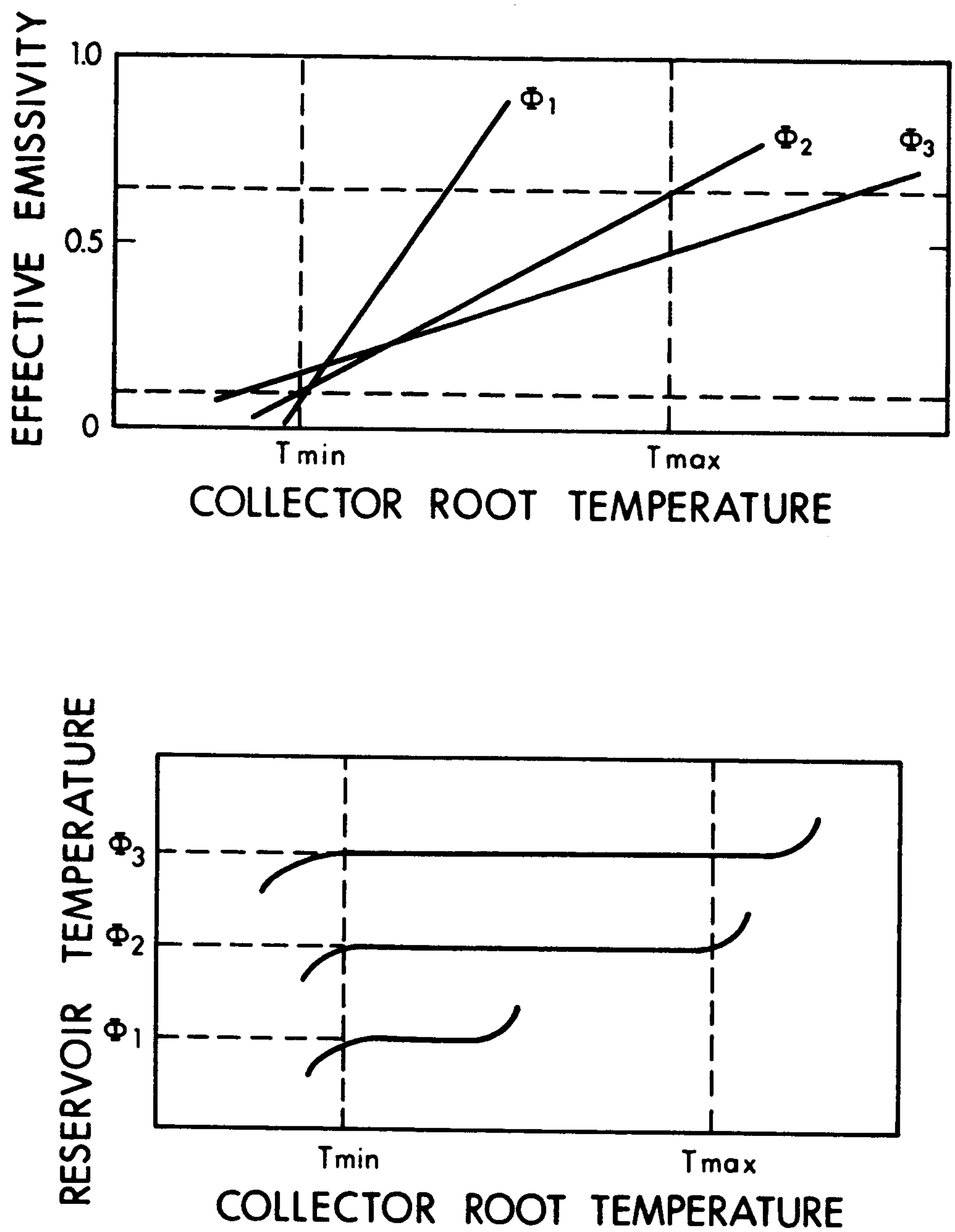


FIG. 2-1 CONCEPT OF DETERMINING CENTER OPERATING TEMPERATURE RANGE



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the simplest angular geometry. Rather than attempt analytical solution to the reservoir control problem over the complete range of temperatures it is possible to make a close estimate by calculating the radiated heat transfer from the reservoir for maximum emissivity and minimum emissivity that can be achieved by any realizable control mechanism. This calculation will establish the end points of any functional relationship between the effective emissivity and the controlling temperatures. To get a complete calculation of this type we need the results of the following calculations:

1. The amount of heat to be radiated from the reservoir
2. The effect of the other surfaces of the reservoir, i.e., the copper tubulations on the reservoir tips
3. The effect of emissivity change on reservoir heat transfer

2.1.1.1 Quantity of Heat to be Radiated from Converter

Figure 2-2 shows the configuration of the JPL diode reservoir tubulation. Equation 2 for the thermal conductivity is used to estimate the amount of heat being radiated from the reservoir tip under the range of operating conditions expected. Figure 2-3 shows the estimated temperature distribution along the heat choke and reservoir of a JPL thermionic converter. The end points of the center line are $497^{\circ}$ and $343^{\circ}$ respectively, as taken from the data sheet on the diode. This is the center of the desired controlling range on the JPL converter. By drawing lines from the extreme temperature limits on both the reservoir and collector root temperature, the extremes in heat transfer can be estimated, as shown by the other curves on Fig. 2-3. A similar chart has been prepared from the EOS data and that is shown in Fig. 2-4 taken with thermocouples placed as shown in Fig. 2-5. The limits of the power radiated by the reservoir over the desired control range are shown in Fig. 2-6 for both the JPL and EOS converter.

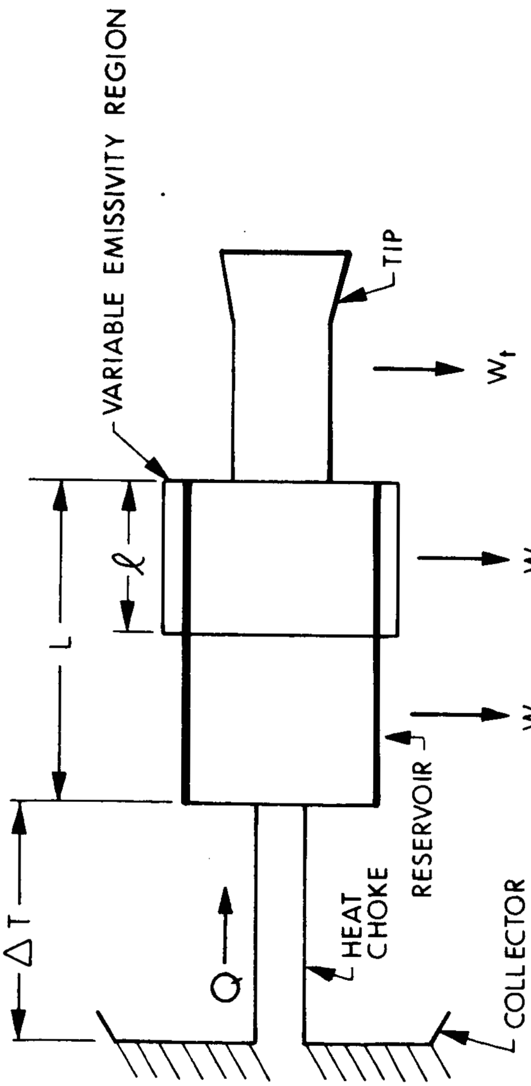



FIG. 2-2 TEECO DIODE RESERVOIR TUBULATION

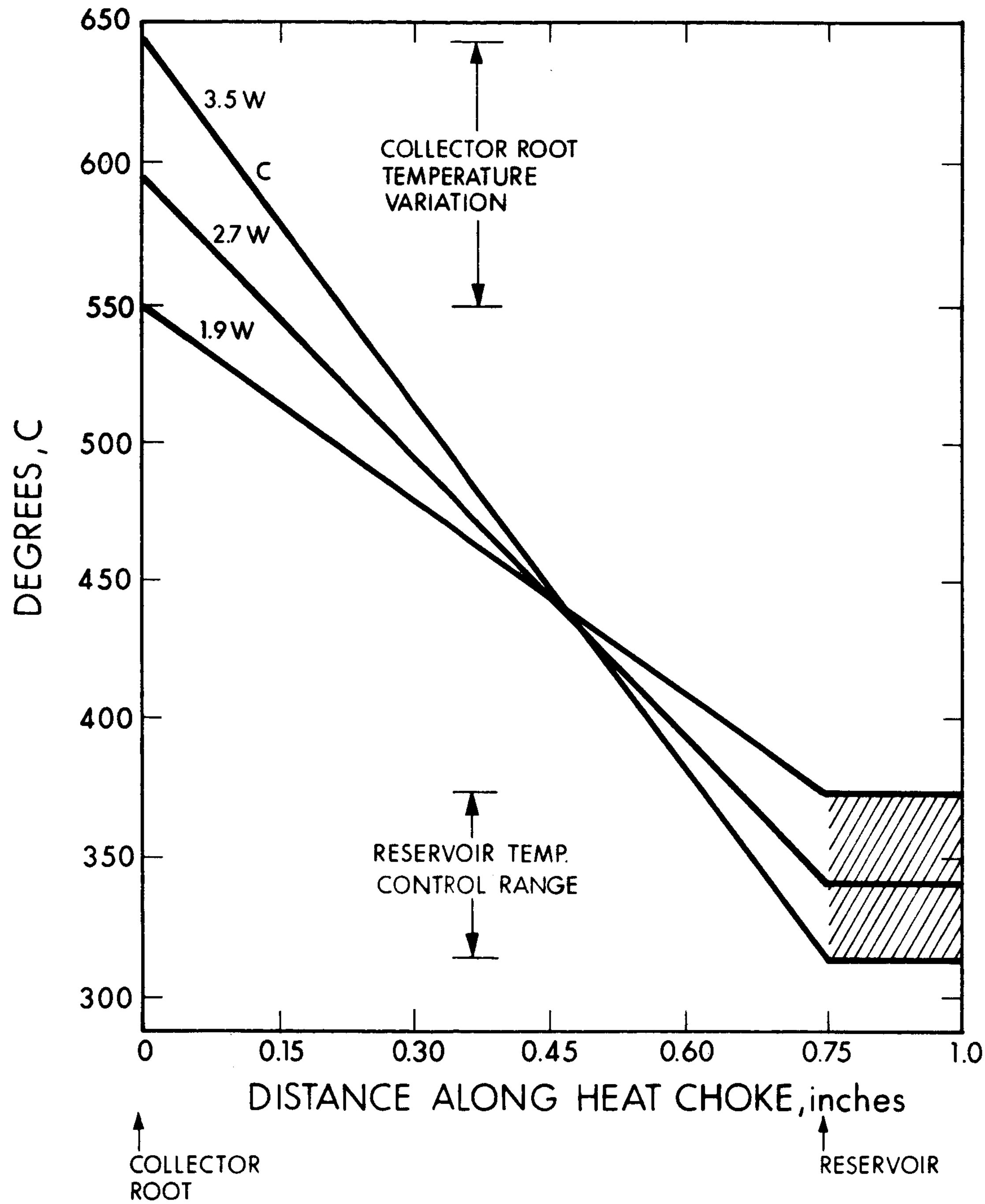



FIG. 2-3 ESTIMATED TEMPERATURE DISTRIBUTION ALONG HEAT CHOKE AND RESERVOIR OF [illegible] THERMIONIC CONVERTER

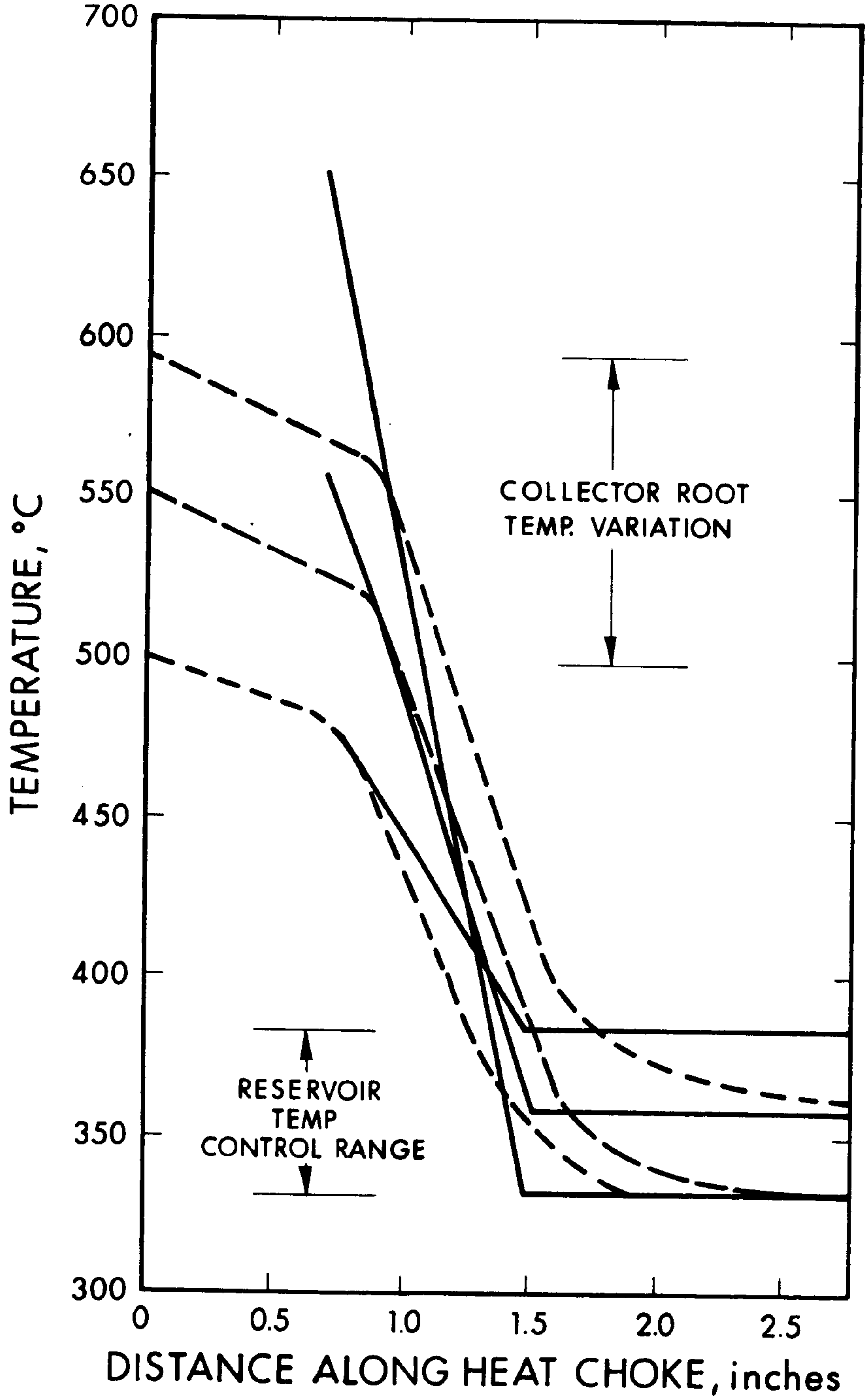



FIG. 2-4 TEMPERATURE DISTRIBUTION ALONG HEAT CHOKE AND RESERVOIR OF EOS PRODUCTION THERMIONIC CONVERTER

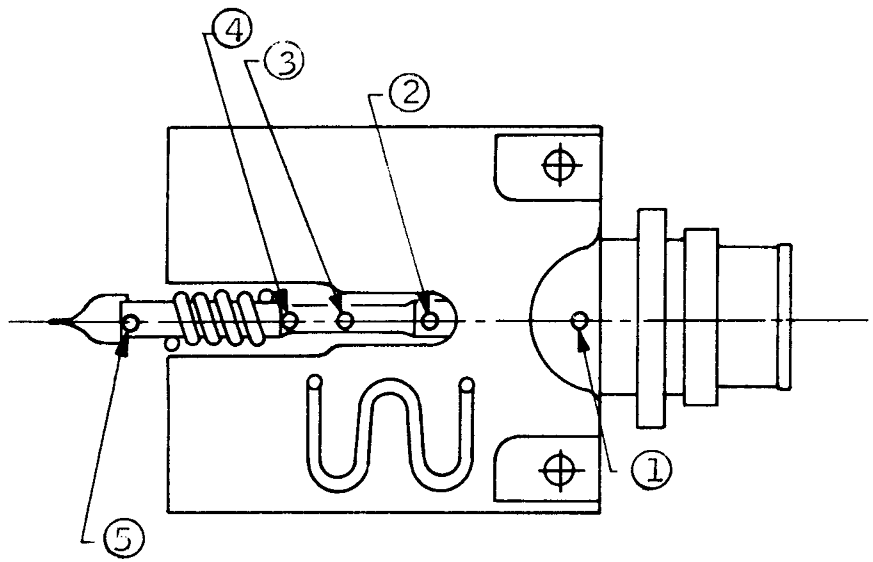



FIG. 2-5 LOCATION OF THERMOCOUPLES FOR MEASURING TEMPERATURE DISTRIBUTION ON EOS CONVERTER

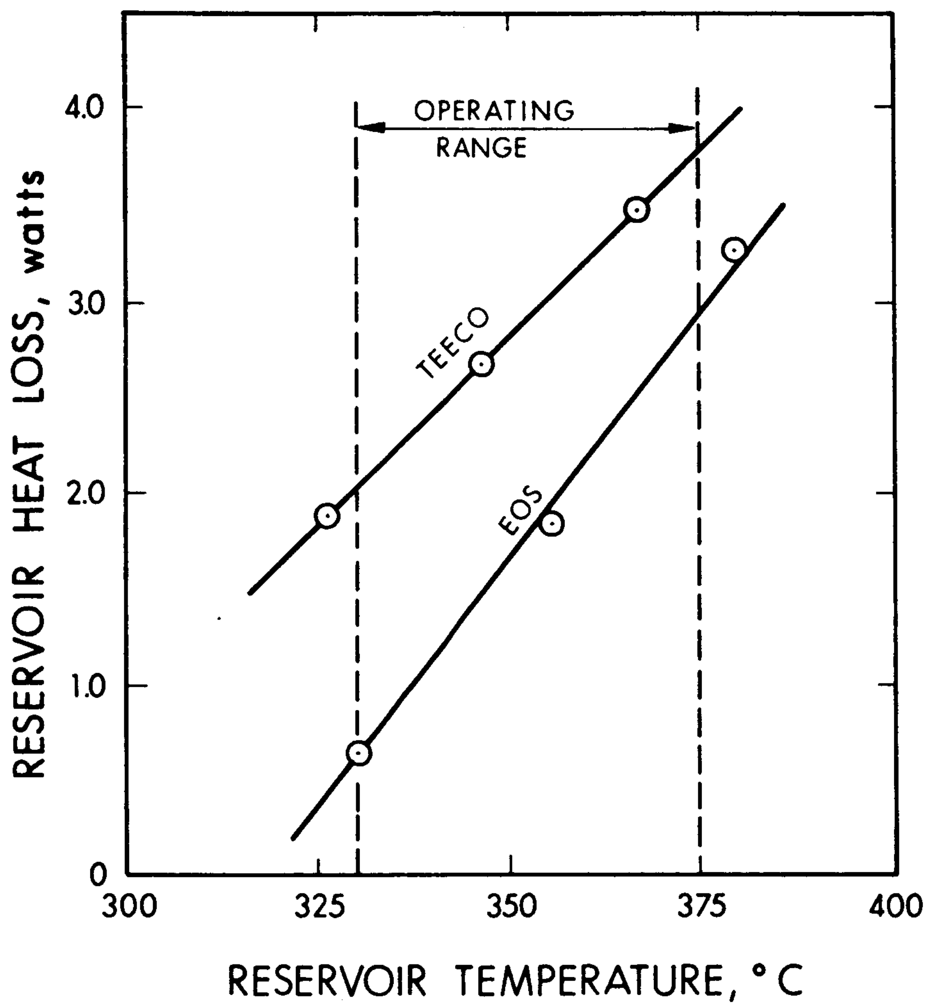



FIG. 2-6 HEAT RADIATED FROM RESERVOIR AS A FUNCTION OF RESERVOIR TEMPERATURE

#### 2.1.1.2 Effect of Copper Tubulation on Converter Reservoir Radiation

A calculation showing the magnitude of the effect of the radiation from the reservoir tip on the total radiated power from the reservoir body for the JPL converter has been made using Eq. 4. This equation can be written as:

$$W_c = \sigma T_r^4 \left[ A_r \epsilon_r + A_t \epsilon_t \right] \quad (9)$$

where $A_r \epsilon_r$ is equal to the effective area of the reservoir and $A_t \epsilon_t$ is equal to the effective area of the reservoir tip. The total amount of energy to be radiated is equal to the amount of heat conducted into the reservoir and tip assembly which is equal to the sum of $W_r$ and $W_t$ where $W_r$ and $W_t$ are the amount of heat radiated by the reservoir proper and reservoir tip, respectively. The relative amount of energy dissipated by the tip can be obtained from the ratio of $\frac{W_t}{W_c}$ and is equal to 0.11. In other words, the tip has about a 10 percent effect on the total emissivity. A similar calculation for the EOS converter yielded the same result.

#### 2.1.1.3 Effect of Emissivity Changes on Reservoir Heat Transfer

The emissivity of the reservoir can be controlled by mechanically moving a radiation shield of low thermal emissivity to cover a portion, or all of, the reservoir surface. Thus, that portion of the reservoir surface covered by the shield will radiate more or less energy, depending upon the degree of coverage. If the reservoir surface emissivity is 0.65, and the shield emissivity is 0.1, then that part of the reservoir surface covered by the shield will have limits of effective emissivity of 0.65 to 0.1 depending on the position of the vane with respect to the surface. If the shield is a close fitting cylinder around the entire length of cylindrical reservoir, and is so arranged that it can be moved or swung away from the reservoir surface, then maximum control of heat loss from the reservoir is obtained. By using a shield which covers only a portion of the reservoir surface, the unshielded portion will radiate normally but the radiation from the covered portion will vary. Thus, an intermediate degree of control is obtained.

Changes in the emissivity of the reservoir cause corresponding changes in the heat rejected by the reservoir. Since this heat is conducted to the reservoir through the heat choke, changes in emissivity are reflected in a change in $\Delta t$ across the heat choke. Conversely, if the reservoir temperature is to be constant, changes in thermal input caused by increased or decreased collector root temperature must be compensated by changing the emissivity of the reservoir to the proper value. Therefore, an estimate of the amount of reservoir emissivity change for a change in collector root temperature is necessary for the design of an actual control.

Refer to Fig. 2-2, and assume a shield of length $\ell$ surrounds the reservoir. The proportion of the reservoir surface thus shielded is $\frac{\ell}{L}$ where L is the total length of the reservoir. Additional assumptions required are:

1. All heat leaving the reservoir comes through the heat choke.
2. The radiator and tip are isothermal; this is reasonable for a copper structure.
3. Emissivities are independent of temperature.
4. For the variable emissivity region, $\epsilon$ varies linearly over the range $0.1 \le \epsilon_v \le 0.65$.
5. Radiation is calculated for constant $T_r$, radiating into empty space with no geometrical complications.

$$W_c = \left(\frac{K A_1}{\Delta X}\right) \Delta T = W_v + W_c + W_t \tag{10}$$

$$W_v = \sigma A_v \epsilon_v T_r^4$$

$$W_c = \sigma A_c \epsilon_c T_r^4$$

$$W_t = \sigma A_t \epsilon_t T_r^4 = \text{constant value} \approx 0.1\ W_c$$

where $K$ = thermal conductivity of heat choke

$A_1$ = cross-sectional area of heat choke

$\Delta X$ = length of heat choke

$\Delta T$ = temperature drop across heat choke

$W_c$ = total heat flux through heat choke

$W_v$ = radiated heat from variable emissivity portion of reservoir

$A_v$ = area of variable emissivity portion of reservoir

$\epsilon_v$ = emissivity variable for emissivity portion of reservoir

$T_r$ = reservoir temperature variable emissivity portion of reservoir

Similarly, subscript c refers to the constant emissivity portion of reservoir and subscript t refers to the tip

$$A_v = \frac{\ell}{L} A$$

where $A$ = total area of reservoir

$\ell$ = length of variable emissivity portion

$L$ = total length of reservoir

Similarly
$$A_c = \frac{L-\ell}{L} A$$

Equation 10 then becomes

$$\Delta T = \left(\frac{\Delta X}{KA_1}\right)\left[\left(\frac{\ell}{L}\epsilon_v + \frac{L-\ell}{L}\epsilon_r\right)A\sigma T^4 + W_t\right] \quad (11)$$

$$\Delta T = \left(\frac{\Delta X}{KA_1}\right)\left[A\sigma T_r^4\,\epsilon_r\left(\frac{\ell}{L}\frac{\epsilon_v}{\epsilon_r} + \frac{L-\ell}{L}\right) + W_t\right] \quad (12)$$

the quantity

$$\epsilon_r\left(\frac{\ell}{L}\frac{\epsilon_v}{\epsilon_r} + \frac{L-\ell}{L}\right)$$

can be considered an effective emissivity for the composite reservoir surface of total area A. For conditions of $T_r = 343^{\circ}C$, $W_c = 2.7W$, $W_t = 0.3W$, and $\epsilon_r = 0.65$, Eq. 3 becomes

$$\Delta T = 95\left[2.7\left(\frac{\ell}{L}\frac{\epsilon_v}{0.65} + \frac{L-\ell}{L}\right) + 0.3\right] \quad (13)$$

The results of calculations using Eq. 13 are presented in Fig. 2-7 where the parameter $\alpha = \ell/L$ is used for convenience. $\Delta T$ has been translated into collector root temperature by adding it to the reservoir temperature of $343^{\circ}C$. The range of $0.1 \le \epsilon_v \le 0.65$ is used as a practical range for the emissivity of the variable portion of reservoir. The curves show that for a given length of reservoir surface whose emissivity can be varied linearly over the above range, the heat transfer is reduced linearly, the amount depending on $\alpha$. For example, to maintain the reservoir constant at $343^{\circ}C$, and the collector root temperature is expected to vary between 500 and $600^{\circ}C$, an area of one-half of the reservoir will control the reservoir temperature if its emissivity can in fact be varied between 0.1 and 0.65.

The method chosen for varying the emissivity is that of swinging two close fitting half cylinders made of very low emissivity material like polished molybdenum, toward or away from the reservoir as shown in Fig. 1-5. Since a spread of collector root temperature of $100^{\circ}$ may be expected, it can be seen from Fig. 2-6

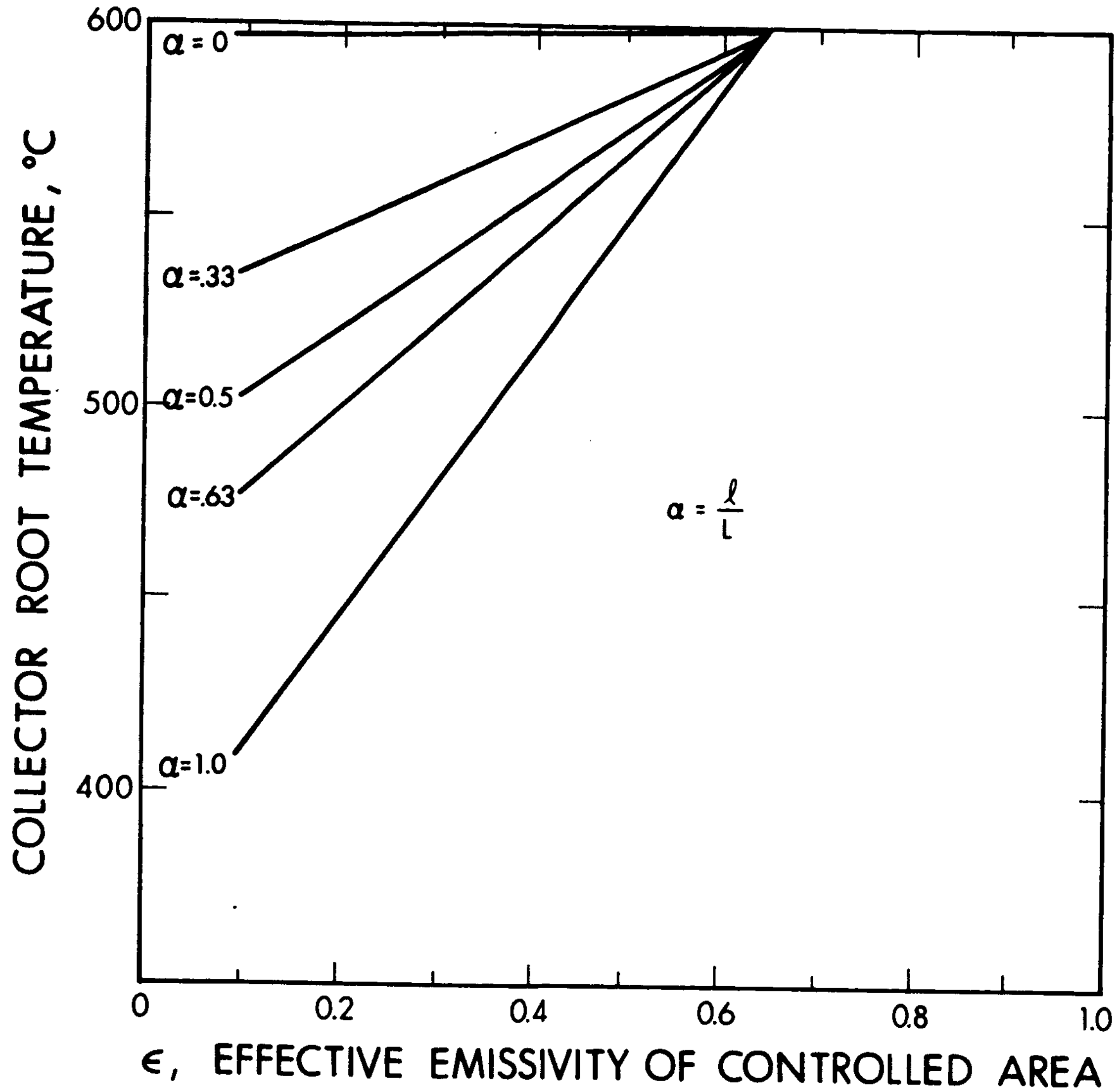



FIG. 2-7 VARIATION OF COLLECTOR ROOT TEMPERATURE AS A FUNCTION OF EFFECTIVE EMISSIVITY OF CONTROLLED AREA OF RESERVOIR $\alpha$, THE RATIO OF CONTROLLED AREA TO TOTAL RESERVOIR AREA IS THE PARAMETER

that a vane or shield equal to half the reservoir length is adequate. Although the root temperature and emissivity are related linearly, the emissivity and vane position are not, due to the complicated geometrical view factor of the shield and reservoir configuration. An estimate of the form of the emissivity variation as a function of vane angle is given in Fig. 2-8. The relationship between the heat choke temperature and vane rotation is shown in Fig. 2-9.

### 2.1.2 Thermal Measurements

Measurements were made on the heat choke of the EOS converter to measure the actual thermal energy control range required by the passive control unit. The results of these measurements are shown earlier in Fig. 2-4. Figure 2-5 shows the outline of the thermionic converter and the location of the thermocouples that were used for the test. From these data the thermal flux through the heat choke, which is equal to the radiator thermal flux output, was calculated fairly accurately.

To estimate the effect on reservoir temperature of a radiation shield a thermionic converter mock-up was fabricated in the form of a vane which could be moved through an angle, thus exposing more or less of the thermal cavity containing the reservoir. The same converter arrangement that was used in the previous measurement (Fig. 2-5) was used for this test. The passive control was simulated by mounting manually operated radiation shields or vanes on an existing EOS radiator reservoir assembly. The reservoir of the assembly had an emissivity of approximately 0.5. The vane angle was changed through $90^{\circ}$ and the reservoir temperatures were recorded while the collector root temperature was held constant by electron bombardment at $590^{\circ}C$. Figure 2-10 shows the reservoir temperature versus the angle of opening. The reservoir temperatures observed were higher than normal for that root temperature due to the low emissivity of the reservoir. In an operating converter the temperature will be lower because a high-emissivity material such as Rokide "C" (emissivity = 0.78), is used to

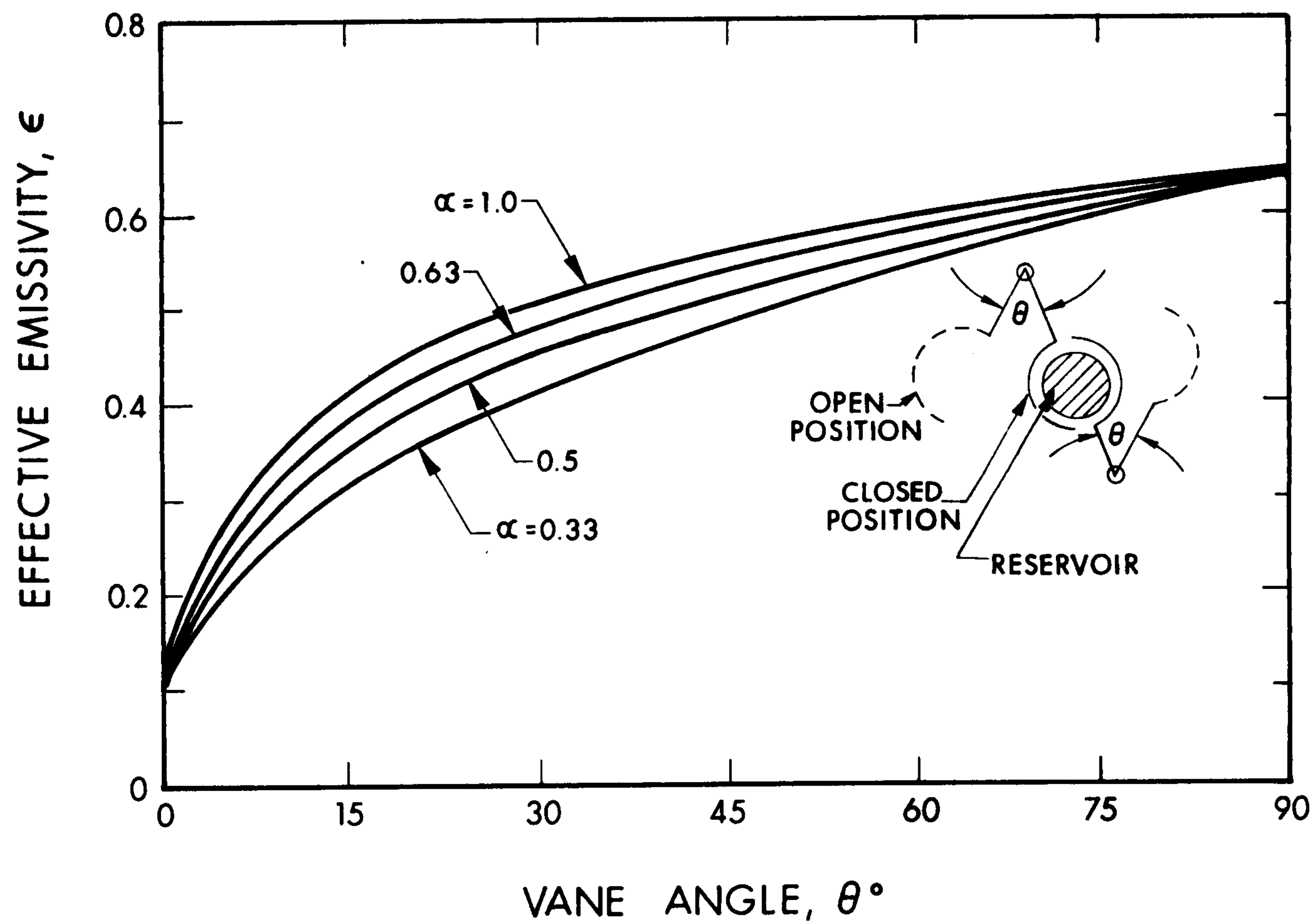



FIG. 2-8 EFFECTIVE EMISSIVITY AS A FUNCTION OF VANE AND ROTATION ANGLE

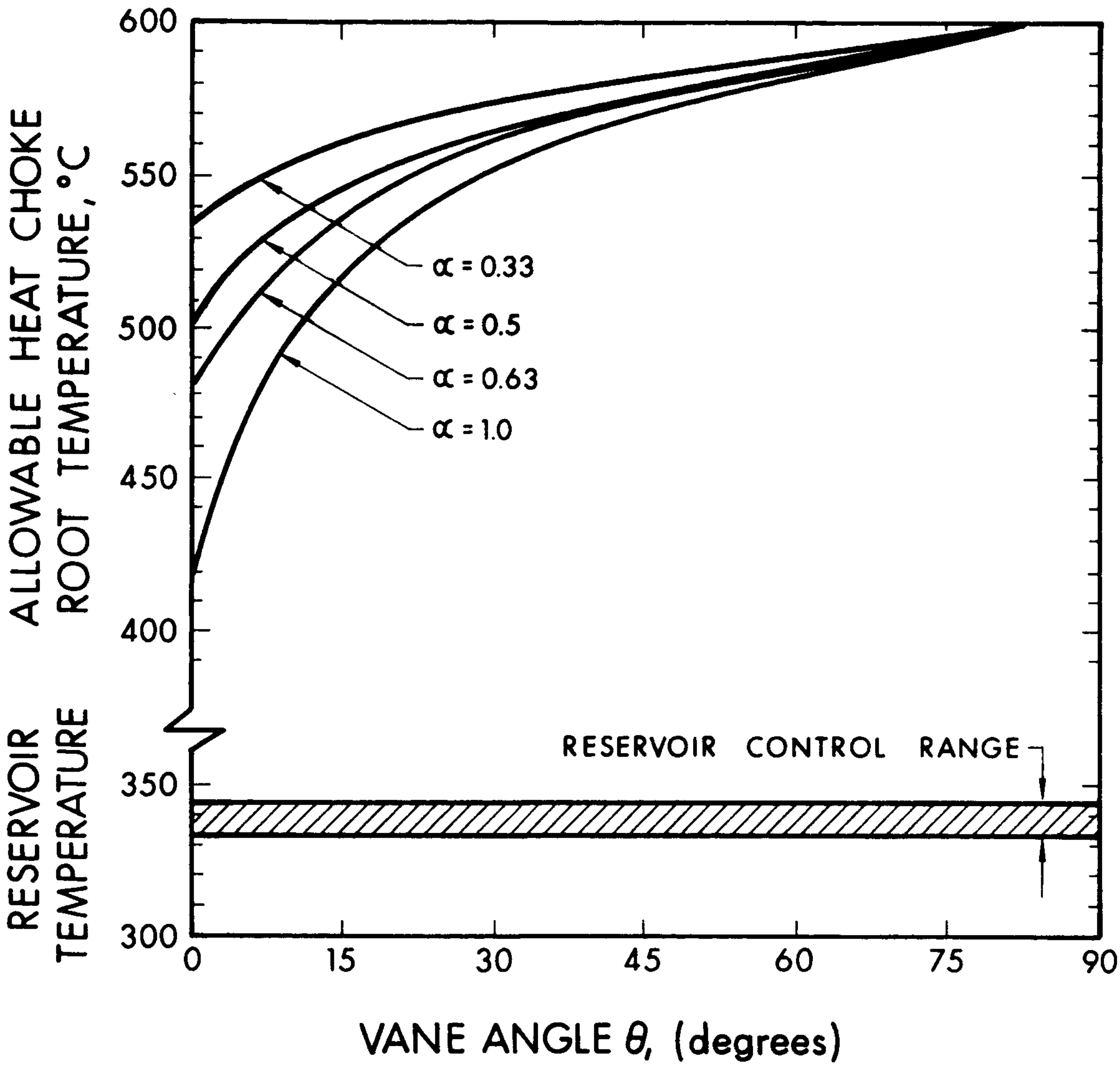



FIG. 2-9 HEAT CHOKE ROOT TEMPERATURE AND RESERVOIR TEMPERATURE VERSUS ANGULAR DEFLECTION OF VANE

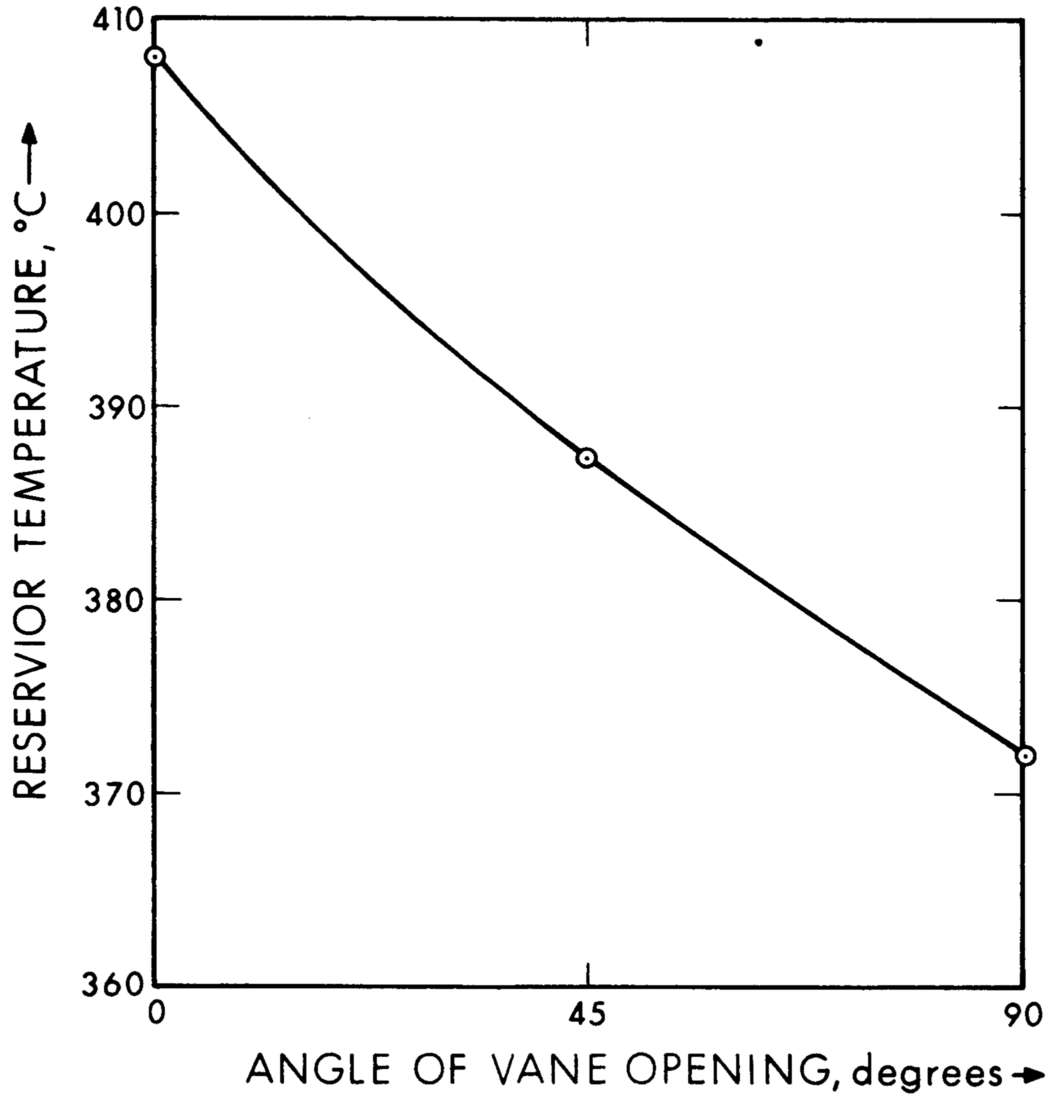



FIG. 2-10 EFFECT OF VANE POSITION ON RESERVOIR TEMPERATURE

coat the reservoir and passive control element. A temperature change of 36°C was obtained by opening the vane from zero degrees to 90 degrees. This $\Delta t$ was lower than the desired temperature change of 50°, but an increased range could be achieved if higher emissivity surfaces were used.

Some initial testing was done on spiral bimetallic actuators. A spiral bimetallic actuator was wound from a sample of material obtained from H. A. Wilson Company. This material, called Hi-heat 47, was tested for total angular deflection by setting it on a hot-plate. A free, or unloaded deflection of about 90° was obtained. Therefore, an element loaded with the vane should, in conjunction with mechanical amplification of the vane linkage, provide the desired movement of the vane. More elaborate tests of the bimetallic materials were made also. A bimetallic spiral of 5 inches by 0.02-inch-thick Saflex material was mounted in a vacuum bell jar on a plate containing a heater and a stainless steel protractor, as shown in Fig. 2-11. The spiral was held by a copper hub. A thermocouple was attached to the hub for determining the spiral temperature. The deflection of the pointer shown in Fig. 2-11 was measured over a temperature range of room temperature to 450°C. The deflection of the pointer in angular degrees is plotted versus the temperature of the coil in Fig. 2-12. This is a much heavier material than originally anticipated, but it was felt that if a higher torque material were needed, some data on the thicker materials should be obtained.

A mock-up of the passive reservoir control itself consisting of a bimetallic spiral linkage and a lightweight vane were set up in a bell jar with a heater and the measurement of the vane deflection as a function of the control temperature was made. The setup is shown in Fig. 2-13. The deflection material was a Chace bimetallic strip No. 2500, 5 mils thick. This control was set up so that at room temperature the control was not under any mechanical strain.

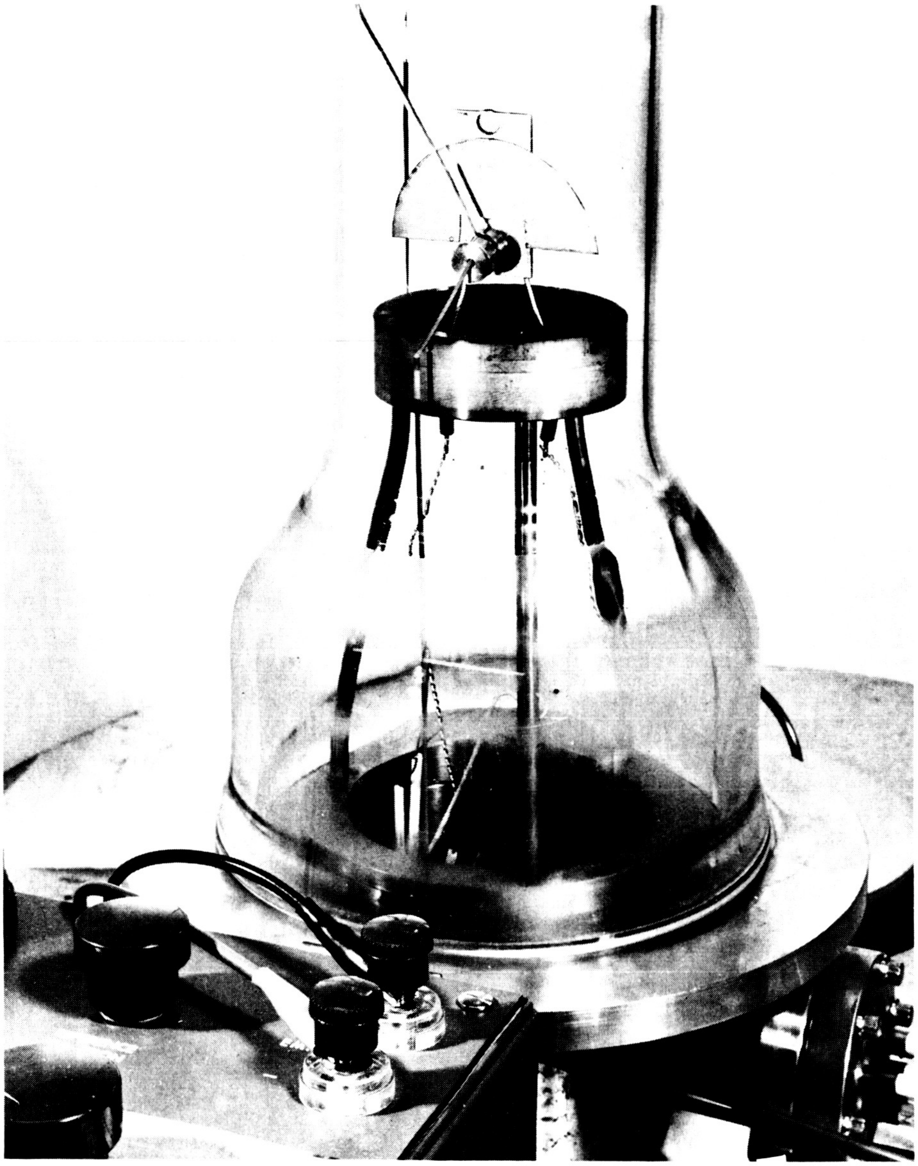


FIG. 2-11 TEST OF SAFLEX MATERIAL

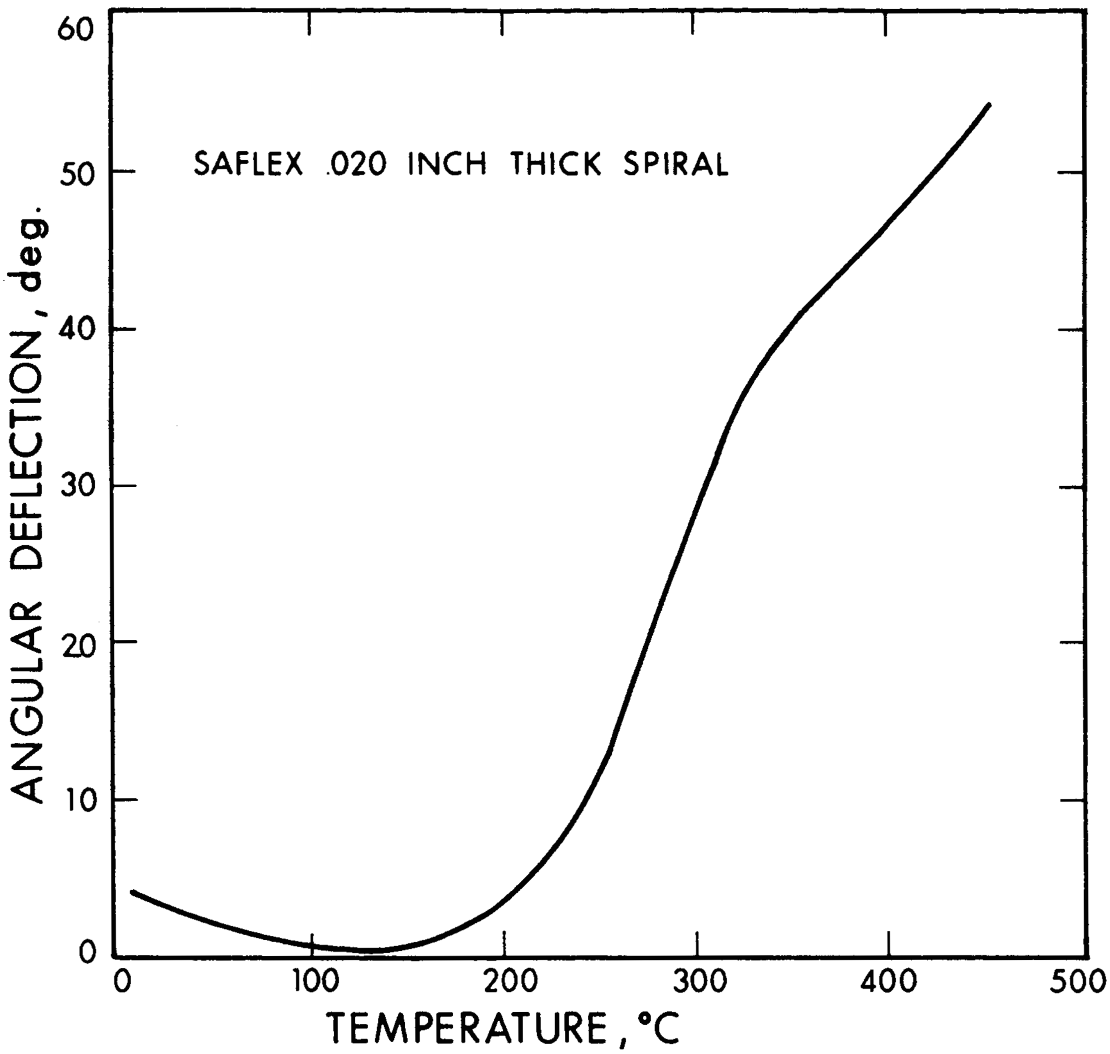



FIG. 2-12 REFLECTION OF SAFLEX BIMETALLIC SPIRAL AS A FUNCTION OF TEMPERATURE

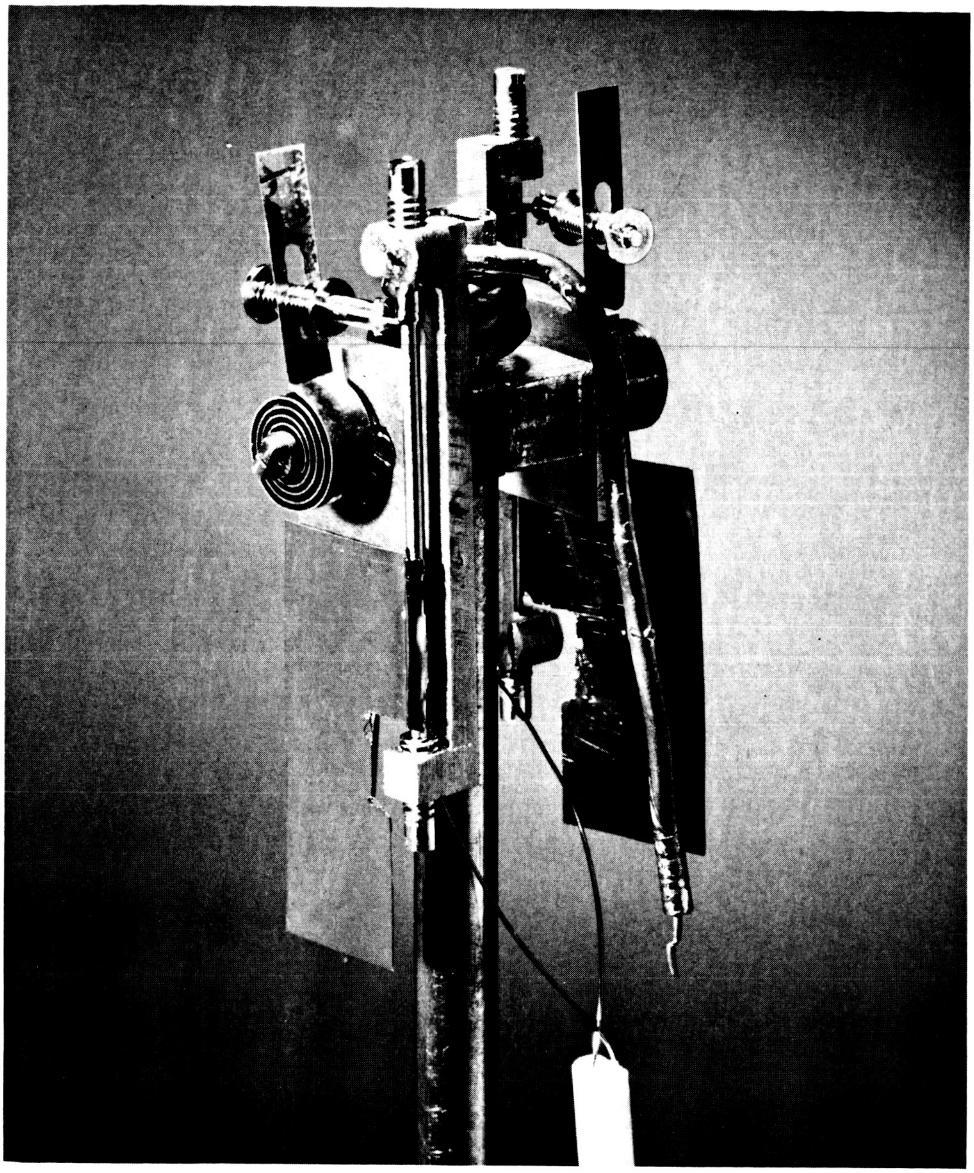


FIG. 2-13  MOCK PASSIVE CONTROL TEST

Therefore, by the time the control temperature had reached 140°C the vane had opened a full 90° and was up against a mechanical stop. The results of the test (Fig. 2-14) showed that this bimetallic strip had the desired deflection sensitivity in the middle range of the angular deflection of the vane. It also indicated that in order to use the control at a higher temperature it must be preloaded or preset so that it does not begin to open up until its temperature is near the desired operating range that would be encountered on a converter. The slope of the curve in the linear portion is about 1.25 angular degrees per degree centigrade. This deflection includes the deflection of the bimetallic spiral itself, plus the amplification obtained by the mechanical linkage.

### 2.1.3 Thermostatic Materials

Of the large number of materials available in bimetallic combinations, only a few are suitable for the application of the passive reservoir control. In fact, even for the ones which are suitable, they are marginal because their upper temperature limit is slightly below the desired operating range of the reservoir control. Three materials chosen for evaluation were the Hi-Heat 47 and Saflex of Wilco Division of Englehard Industries, and Chace No. 2500. Hi-Heat 47 and Chace No. 2500 are very similar in their characteristics and temperature ranges. Saflex has a much lower total deflection over a given temperature range than has either Hi-Heat 47 or Chace No. 2500, but it has a slightly higher deflection sensitivity over the proposed operating temperature range. This is the important criterion, rather than total deflection. Deflection curves of the Wilco materials are shown in Fig. 2-15 and for the Chace materials in Fig. 2-16.

Because thermostatic materials are a composite of two metals of different coefficients of expansion, they have rather unique properties as compared with ordinary metals. Stress-relieving temperatures, the width, the thickness and so on, affect the deflection rate of thermostatic bimetallic elements. The constants available in

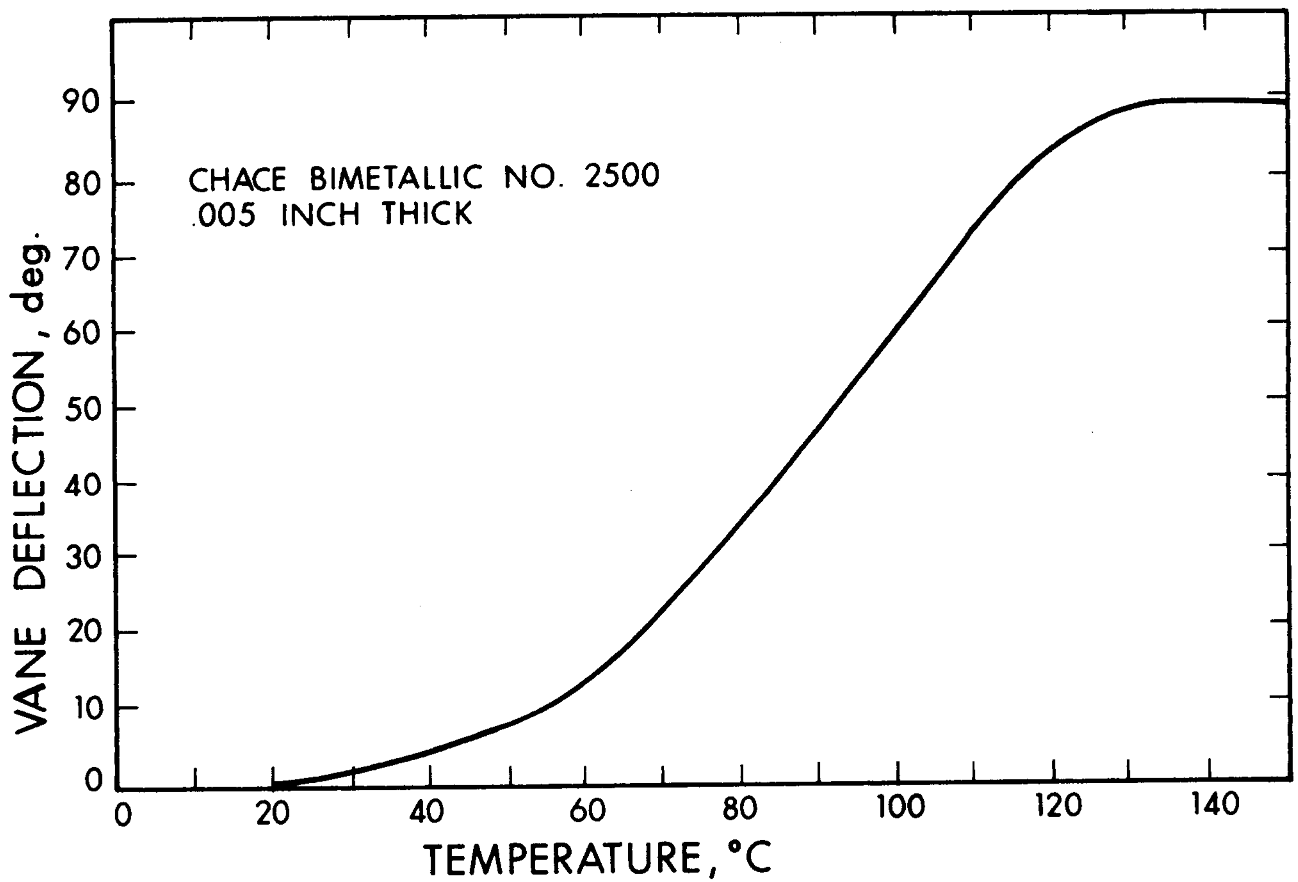



FIG. 2-14 VANE DEFLECTION VERSUS COIL TEMPERATURE WITHOUT TEMPERATURE CORRECTIONS

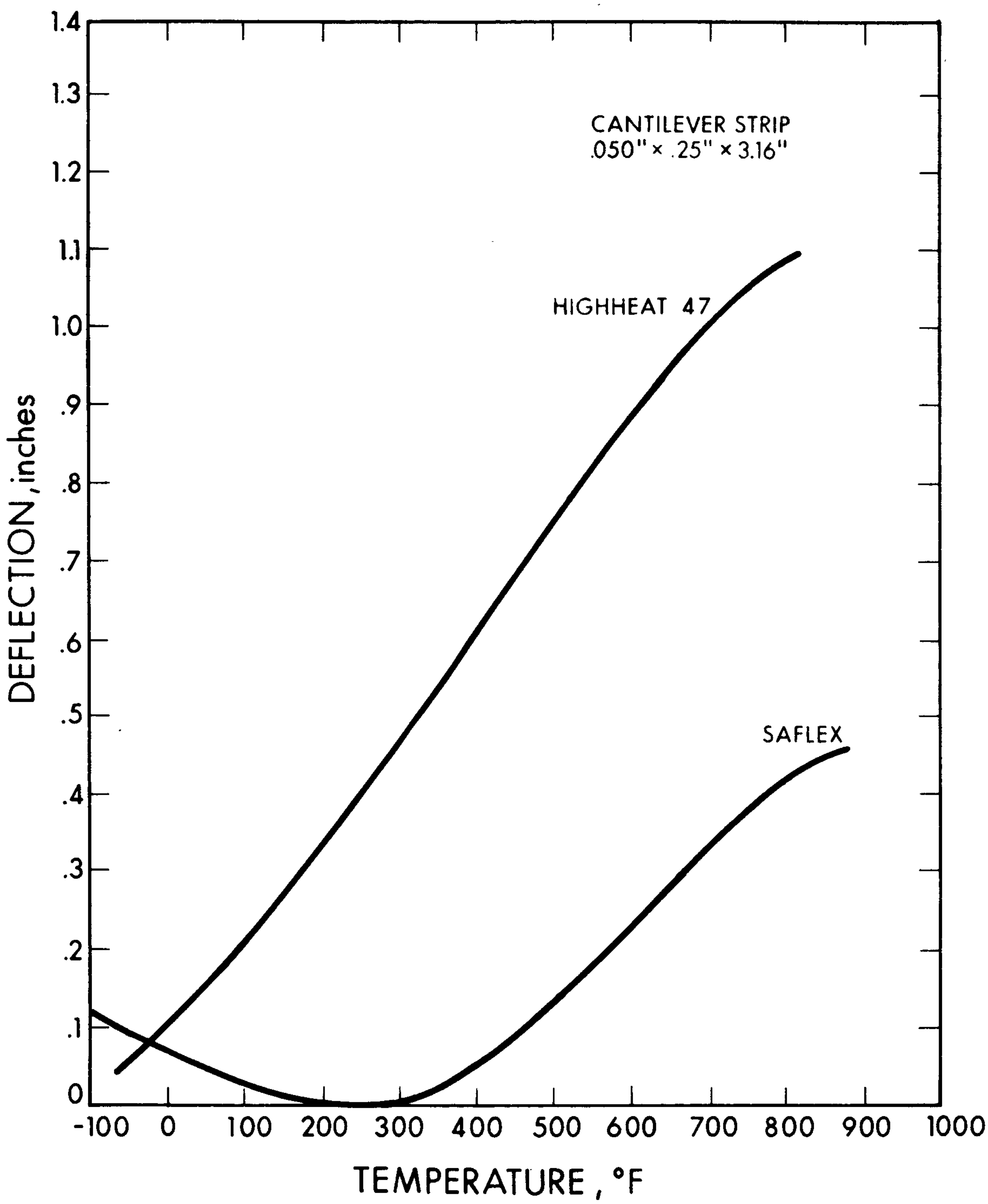



FIG. 2-15 TEMPERATURE VERSUS DEFLECTION CURVES FOR SAFLEX AND HI-HEAT 47

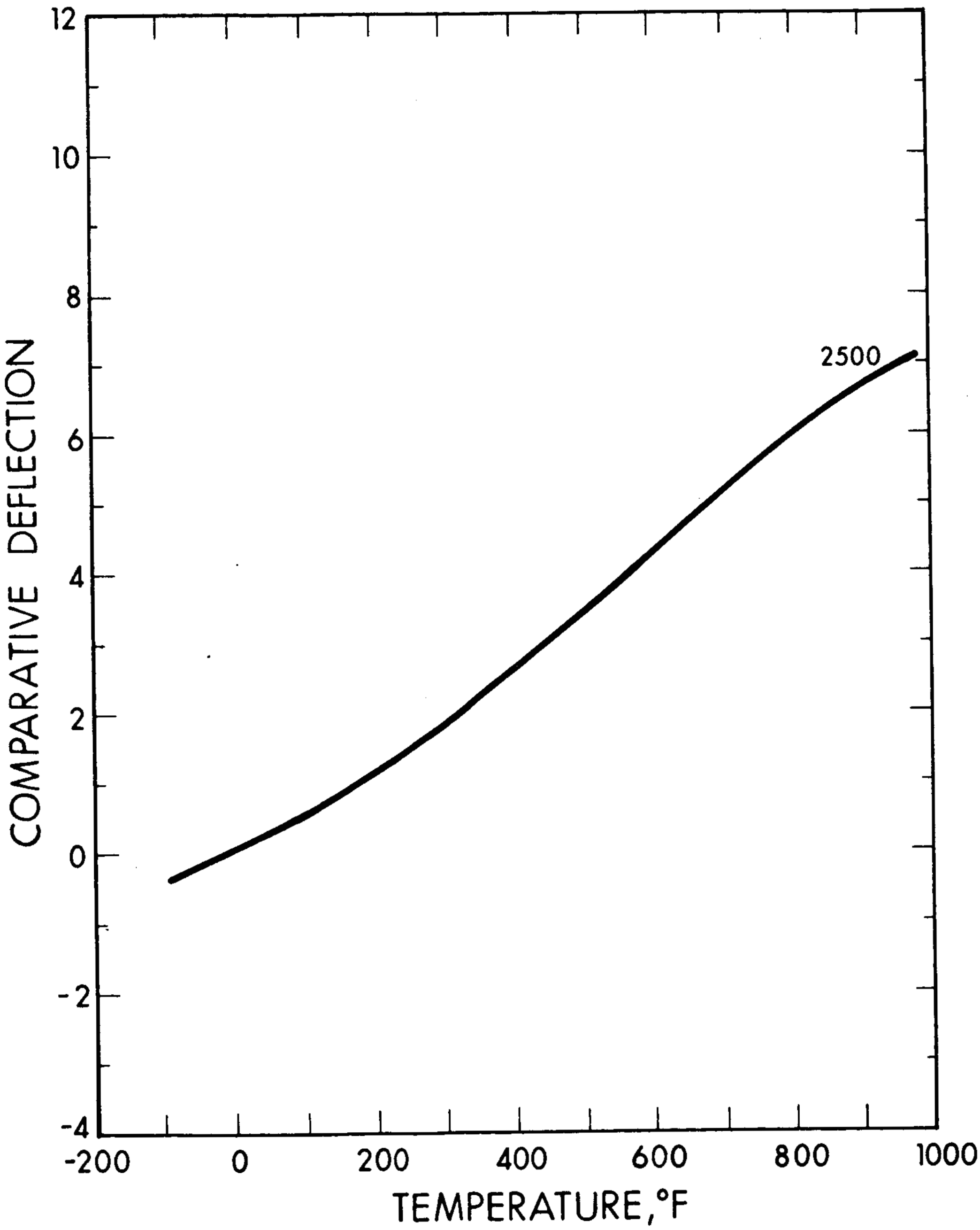



FIG. 2-16 COMPARATIVE DEFLECTION TEMPERATURE CURVE FOR CHACE THERMOSTATIC BIMETAL NO. 2500

various catalogs were used for initial calculations; however, after the preliminary determinations of the type, shape, and size of an element have been made it should be tested under actual operating conditions. Typical physical properties of bimetallic metals are given for the Chace No. 2500 in Table 2-1. By the use of these data and the equations given below the performance of a given bimetallic material and configuration can be determined.

For actual thermal control using a bimetallic element, many approaches were considered. The particular case at hand required maximum linear displacement for desired temperature range. Information such as formulae and materials available was obtained from bimetal manufacturers' manuals. Investigation of their applications techniques indicated that to satisfy the present requirements of maximum mechanical motion (better resolution) in the 325°C to 375°C range, it is necessary to use a spiral coil shape. Since available mounting and operating space is limited, the coil form also appears to be the best configuration. A review of the bimetal literature shows immediately that mechanical motion (deflection) is basically a function of the free length of the element being considered. More free length for a given deflection can be accommodated in a coil form than in any other shape. Typical calculations for the three types shown in Fig. 1-3 are as follows:

Case 1 - Straight-line motion element

$$\text{Defl.} = \frac{K_{DS}\ \Delta T\ L^2\ m}{4.5t} = 0.009 \text{ inch } (L = 1 \text{ inch})$$

Case 2 - Trapezoidal Cantilever

$$\text{Defl.} = \frac{K_{DS}\ \Delta T\ L^2\ m}{t} = 0.080 \text{ inch } (L = 1 \text{ inch})$$

TABLE 2-I

PHYSICAL PROPERTIES

| | | |
|---|---|---|
| Maximum Temperature | | $1000^{O}F$ |
| Useful Deflection Temperature Range | | $-100^{O}F$ to $900^{O}F$ |
| Maximum Sensitivity Temperature Range | | $300^{O}F$ to $850^{O}F$ |
| Coil Deflection Constant ($300^{O}F$ to $850^{O}F$) | $K_{DC}$ | 0.00050 |
| Strip Deflection Constant ($300^{O}F$ to $850^{O}F$) | $K_{DS}$ | 0.0000040 |
| Flexivity ($100^{O}F$ to $300^{O}F$) | F | 0.0000064 |
| Coil Torque Constant | $K_{PC}$ | 620,000 |
| Strip Torque Constant | $K_{PS}$ | 106,000,000 |
| Modulus of Elasticity, lbs per sq inch | | 26,500,000 |
| Electrical Resistivity at $75^{O}F$ | | |
| Ohms per circular mil ft | | 350 |
| Ohms per square mil ft | | 275 |
| Specific Heat | | 0.12 |
| Density, lbs per cu inch | | 0.29 |
| Diamond Pyramid Hardness (Standard Production) | | |
| Low Expanding Side | | 230 to 270 |
| High Expanding Side | | 260 to 300 |

Case 3 - Spiral

$$A = \text{Angular Defl.} = \frac{K_{DC}\ \Delta T\ Lm}{t} = 30^{o}\ (L = 3\text{ inch})$$

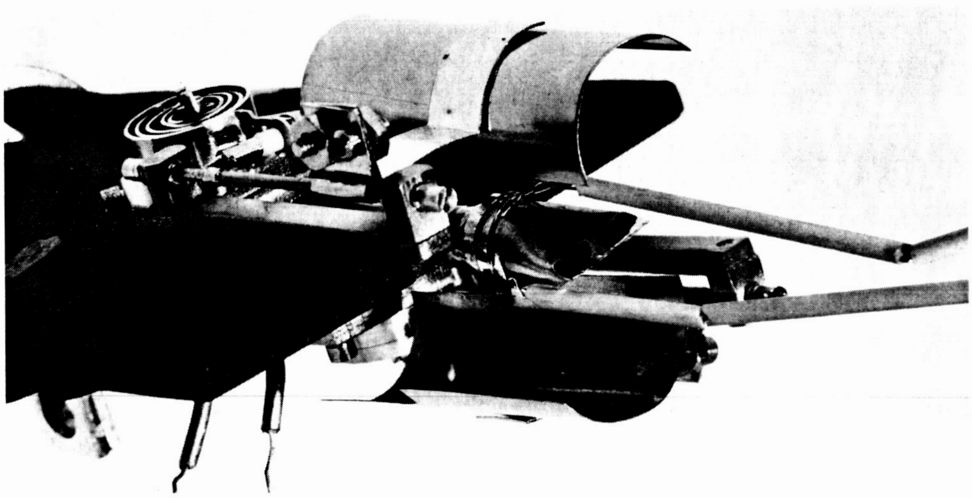
where K is a deflection constant, L is free length, t is thickness, and m is specific deflection.

It is quite evident that an angular displacement can be translated to a linear displacement (chord of an arc) and can, in fact, be translated to various amounts of linear displacement by simply changing the length of the sweeping arm. All other shapes considered gave too little displacement for the amount of surface area they would necessarily shield or blind.

### 2.1.4 Configuration - Adaptability to Various Converters

Of all the converter control concepts described in Section 1.0.4.2, the configuration shown in Fig. 1-4 was chosen as the final model. Figure 1-4 is a conceptual drawing of the control. On the control that was finally made, shown in Fig. 2-17, the only difference is in the rearrangement of the vane and actuating mechanism. The operating principles are identical.

The control consists of a molybdenum base on which are mounted a copper stud which holds the bimetallic actuator coil, the bearings which hold the shaft for the rotating vane, and the mounting saddle which clamps around the reservoir tubulation. The saddle clamp is also copper to provide rapid heat transfer from the tubulation to the control. The vane is made of molybdenum or nickel welded to a shaft which turns between two jeweled bearings. The shaft is driven by the bimetallic actuator coil through a mechanical linkage to amplify the motion. By properly choosing the dimensions, and making an interchangeable saddle mount, the control can be made adaptable for either the JPL or EOS converter. The main support mechanism will therefore fit either converter; however, the vane shape must also



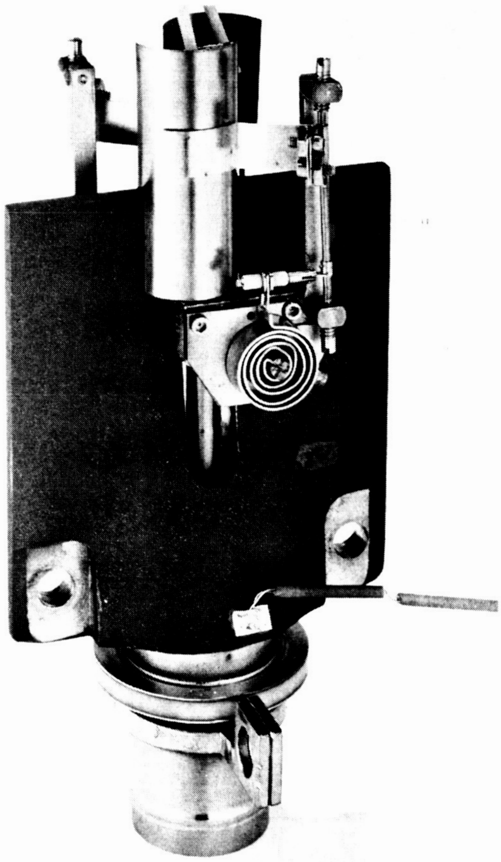


FIG. 2-17 ACTUAL PASSIVE CONTROL

be changed to accommodate each particular geometry. The configuration is most easily mounted on the EOS converter because of the greater accessibility of the reservoir tubulation to the control. There is, however, a space limitation due to the small clearance between the reservoir tubulation and the radiator fin. If these were ever to be made in quantity, the converter would have to be designed to accommodate such a reservoir control. Similar considerations hold for the JPL converter. For example, the present radiation separates the reservoir region from the radiator region of the converter. With the shield in place, it is extremely difficult, if not impossible, to install the actuator mechanism at the heat choke end of the reservoir, and make a mechanical driving arrangement to change the position of the vane which is on the other side of the heat shield.

### 2.1.5 Mechanical Motion Amplification

In order to get the necessary mechanical motion to achieve the emissivity changes shown in Fig. 2-7 within a $\Delta t$ of $\pm 5^{\circ}$, a considerable amount of mechanical amplification is required. The mechanical amplification has been achieved by using a linkage which connects the end of the bimetallic spiral with the driving arm on the axis of the vane shaft. The amplification is equal to the ratio of the radius of the bimetallic lever to that of the radius of the arm on the shaft. With a lever radius of 0.3 inch and an arm radius of 0.060 inch, an amplification of 5 is obtained, which appears to be sufficient for the control operation.

### 2.1.6 Method of Operation and Reliability

The method of operation is most easily visualized by reference to Fig. 1-4 and 1-5. Two identical controls are mounted on each converter, one on one side of the tubulation and one on the other. They are held in place by means of screws which bolt into the opposing halves of the mounting saddle. This clamps the heat transfer block to its source of heat, the reservoir tubulation. The heat, in turn, causes expansion or contraction of the bimetallic actuator element which is mounted on the post connected thermally to the mounting saddle. As the bimetallic spiral expands and contracts, the end swings through an arc thus driving a rod which is terminated in a clevis connected to the arm on the shaft of the control. This shaft is connected to the vanes which swing in and out from around the reservoir tubulation to control its effective emissivity, thereby controlling its temperature.

For reliability, all parts are made of refractory or otherwise suitable vacuum materials. With the present design, the limits on reliability are caused by several factors. In this design only two jeweled bearings were used, namely those on the shaft housing. However, all other moving joints should have jeweled bearings for this high temperature space application. Otherwise, galling or freezing of the joints may take place causing the control to become inoperative. With properly made jeweled bearings in each moving joint, there is no reason why this type control could not be as reliable as the converter itself. The principal factor which would improve the reliability is to have an arrangement on each converter which will accept such a control and thus enable the control itself to become somewhat simpler in its mechanical configuration.

The initial models used copper for the heat transfer block. Experience has shown however, that in spite of the favorable thermal aspects of copper, its poor mechanical properties suggest that a substitute material like molybdenum which has a reasonably high thermal conductivity, but is still quite strong mechanically, should be used instead. This will prevent any mounting or demounting difficulties that could arise due to softening of the copper or stripping of the threads in tapped holes in copper blocks.

#### 2.1.6.1 Temperature Adjustment and Repeatability

In theory, the temperature adjustment can be obtained by merely preloading the bimetallic strip so that it does not begin to move from a fixed stop position until it reaches a certain temperature. Once this temperature is obtained, a control will function normally about its desired operating temperature range. Attempts to do this on the fabricated control were somewhat limited because of other difficulties. On the basis of experience with this control, it is suggested that a different scheme be arranged to improve the ease of temperature adjustment. The repeatability of the control as tested was not as accurate as one would like. The main reason for this lack of repeatability is that the control is being used as a mechanical null instrument. The problem with the bimetallic strip operating as a null device is that at its zero position it has zero torque. As it moves in either direction from the null position it does increase the torque that it applies to the mechanism it is actuating. However, due to starting friction in bearings and the rest of the mechanism sometimes an undesirably high $\Delta t$ has to be achieved before the control begins to move. As mentioned above, this problem no doubt can be obviated by arranging the control so that it is always in a prestressed state and is working not as a null instrument but as a constantly loaded device which has been previously calibrated to move through a certain range over a given temperature variation. The other problem with repeatability is that whereas, with an electrical circuit which has a reference point about which a null is measured, it is very difficult to have a mechanical null reference when there is no available driving power other than the thermal power of the bimetallic device itself. However, with sufficiently sensitive bimetallic elements and suitable mechanical amplifiers as are found in bimetallic thermometers and valve controls, it should be possible to achieve both the temperature adjustment and repeatability.

### 2.1.7 Advantages and Disadvantages of a Passive Control Unit

The principal advantage of the passive control unit is that it absorbs no power at all from the converter and greatly simplifies the overall electrical and mechanical installation problems that arise when a large number of converters are to be installed on a given unit.

One disadvantage is that the problem of mechanically moving the vane to affect the emissivity control of a converter is relatively complicated and requires a relatively sophisticated mechanical design approach. Another disadvantage is that if any of the materials of either the converter or the reservoir control itself change in thermal characteristics, (i.e., if the shields darken, become coated with any other material, or otherwise change their emissivity, or if the reservoir surface itself changes the emissivity), it will have a profound effect on the calibration of the control. With the presently available materials, it is very hard to obtain both mechanical ruggedness and thermal sensitivity in the same unit. One other possible disadvantage is that in a generator assembly using a multitude of converters, it is conceivable that radiation interchange between converters may have a deleterious effect on the calibration of the thermostatic controls which have been previously set under a different set of thermal conditions.

#### 2.1.8 Conclusions and Recommendations

The conclusions that can be gained from this design study are that is possible, and even feasible, to make a passive reservoir control. However, it is strongly recommended that if this type of control is seriously desired, a much more elaborate and detailed study must be made both of the materials to be used and of the mechanical arrangements for achieving the activation of the emissivity control on the converters.

### 2.2 Active Control

#### 2.2.1 Thermal Calculations

The thermal calculations for the active control are much simpler than those for the passive control, in that it is only really necessary to know the amount of power radiated over the entire temperature range. This information is displayed in Fig. 2-6. With this information it is only necessary then, to supply the amount of electrical energy necessary to make up for losses in energy caused by changes in the thermal demands or thermal load on the reservoir. The thermal calculations involved are those involving Eq. 2 which are relatively simple and straightforward. Also, the thermal time constant of the converter itself should be known. To measure it, a recorder was connected to thermocouples at the collector root and the reservoir. The collector root temperature was changed and the time required for the reservoir to react was recorded. Figure 2-18 shows the time relationship of the collector and reservoir temperatures. It is seen from this plot that there is no large time delay in the EOS converter reservoir structure. The addition of the reservoir temperature control sensing unit and heater will have the effect of increasing this thermal time constant slightly; however, that amount is not enough to prevent the active control from working within the required thermal time specifications.

### 2.2.2 Circuit Design

The circuit design consists of taking the signal from a platinum resistance sensor and feeding that into a bridge circuit with the one stage of amplification into a multivibrator circuit where the bridge controls the period of the multivibrator wave. This is fed, in turn, to a square wave generator, whose output is fed back to the heater connected to the reservoir. When the unit is first turned on or when the reservoir needs more heat, the output is a square wave operating at 80 percent duty cycle. As the control comes up to temperature, this duty cycle is cut back until the control is running at about 5 percent duty cycle, where it maintains the temperature constant by the usual feedback mechanism. In addition to this, there is a standby circuit section which enables the control to be turned off and on by a command signal from a remote location. This also allows

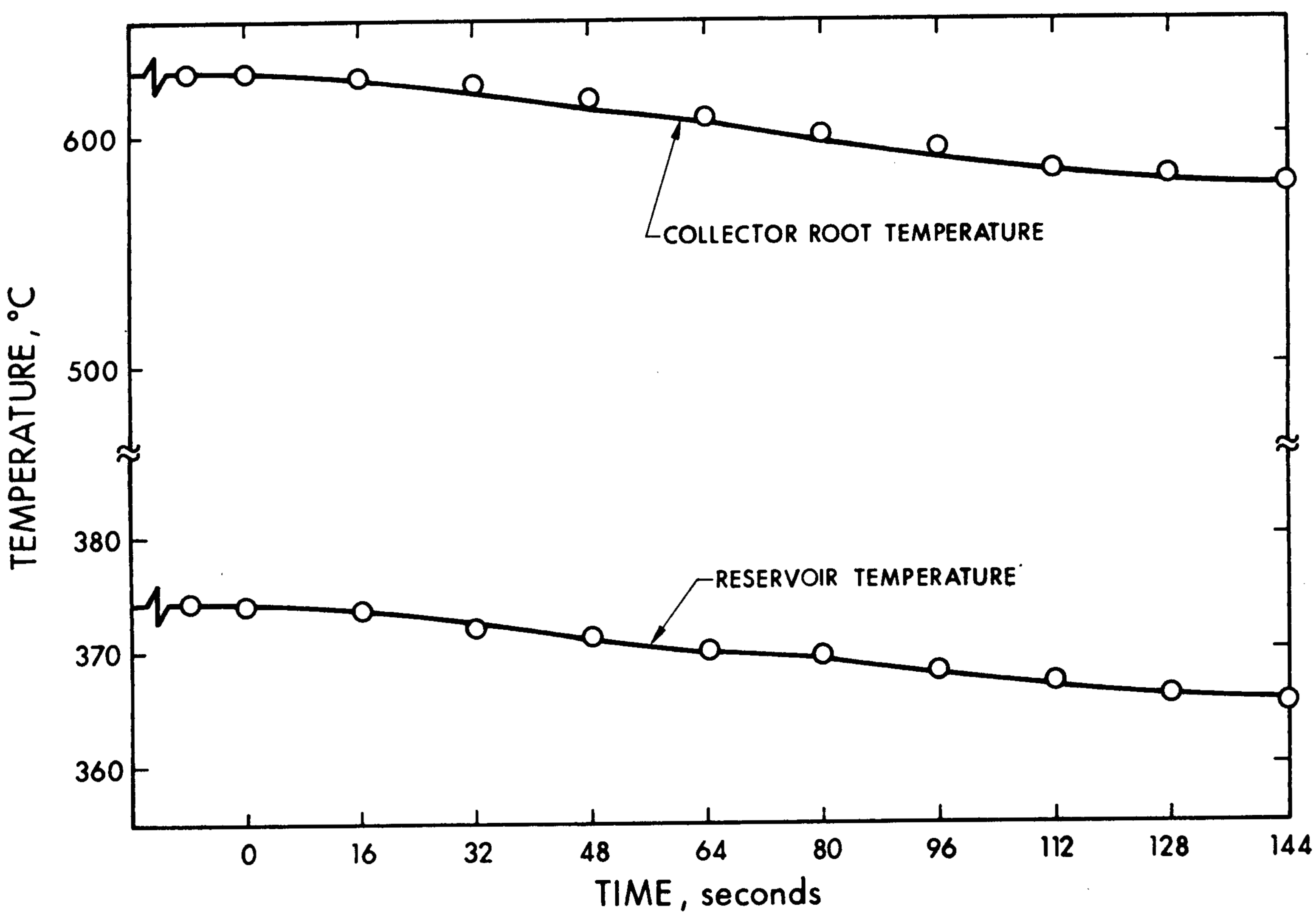



FIG. 2-18 THERMAL TIME CONSTANT OF EOS RADIATOR COLLECTOR, COLLECTOR, AND RESERVOIR

the control to remain idle without absorbing more than a few milliwatts of power from the power source. The main power input is a square wave of 28V amplitude at a frequency of 440 Hz. The schematic of the completed circuit is shown in Fig. 2-19.

#### 2.2.2.1 Location of Electronics with Respect to Converter

Because of the small amount of power, the location of the electronics with respect to the converter is not at all critical. In fact, the control box could be located at distances up to 50 feet from the control with no serious loss in performance. The only precaution to be observed when operating remotely, particularly in the laboratory, is to avoid stray ac pickup on the input which could cause erroneous signals to be fed into the amplifier with subsequent degradation in control characteristics.

#### 2.2.2.2 Lead Loss Calculations

The output of the control is arranged with variable impedance output. The highest current in the heater circuit will be on the 0.5 ohm output tap; for the total 5W output limitation on this control, a maximum of 3.5 amperes would be the current in the leads. This is such a small current that even with wires the size of a No. 18 gage, there will be negligible lead loss and no degradation of performance.

### 2.2.3 Temperature Sensor

The temperature sensor chosen for this control is a platinum resistance thermometer made by the Rosemount Engineering Company. The dimensions and characteristics of this sensor are shown in Fig. 2-20. This particular one was chosen as being capable of operating at 1000°C and therefore, it was felt that it would certainly be quite reliable at the temperature range of 350 degrees. It consists of a platinum case surrounding the platinum wire sensor which is embedded in a vibration proofing material such that the sensor is under

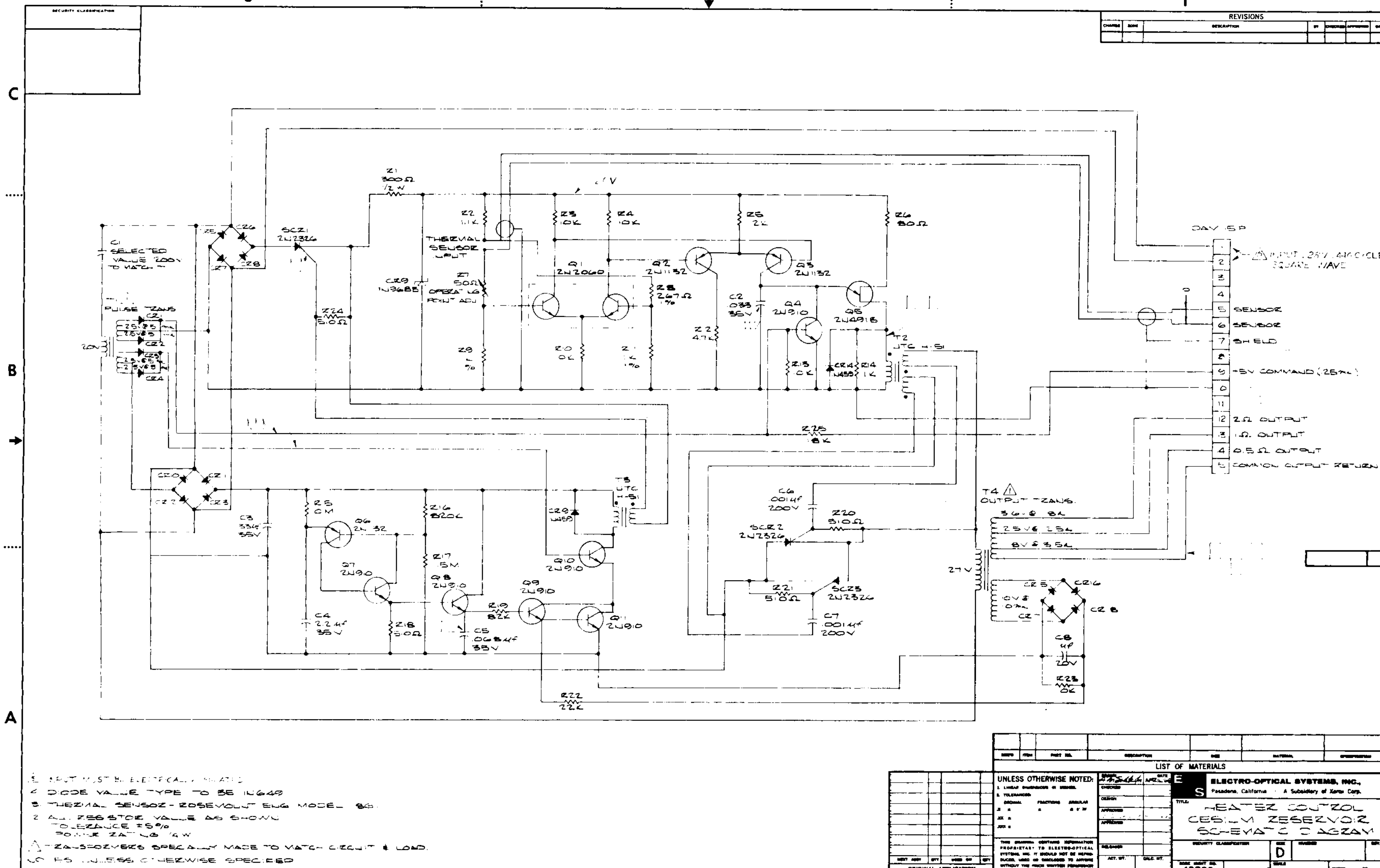



FIG. 2-19 HEATER CONTROL CESIUM RESERVOIR SCHEMATIC DIAGRAM

## SPECIFICATIONS

1. **SCOPE** The Model 118G surface sensor is designed to operate from 260° C to 1300° C. The sensing element is made of pure platinum wire mounted in a strain free manner in a platinum outer case. The sensor may be mounted by spotwelding, cementing, or clamping it to a surface.

2. **DESIGN AND PERFORMANCE SPECIFICATIONS**

2.1 Temperature Range. -200° C to 1000° C

2.2 Resistance Temperature Relationship. Each sensor shall meet the resistance-temperature relationship shown in Table 1 to the tolerances indicated. Other resistance temperature relationships and different interchangeability tolerances can be proposed upon request as a different model number.

2.3 Calibration. Each sensor will be calibrated at 0° C accurate to ± 0.04° C. Additional calibration points and/or individually calculated resistance-temperature tables will be proposed upon request. For higher accuracy (±3° C at 1000° C) calibration at 0° C, 100° C and 260° C are recommended.

2.4. Repeatability. The sensor shall withstand ten consecutive temperature shocks from liquid nitrogen to room temperature trichloroethylene after which calibration at 0° C shall not change more than ± 0.1° C.

2.5 Insulation Resistance. At room temperature with dry external surfaces each sensor will be given a voltage breakdown while placed against a flat conductive plate. The insulation resistance between either sensor lead and the plate shall exceed [illegible] megohms with 100 volts DC applied. For reference, the insulation resistance shall exceed one half megohm at 417° C.

2.6 Time Constant. The time required for [illegible] percent response of an unmounted sensor to a step change in temperature air to #200 Dow Corning 1.5 CT3K [illegible] the sensing surface at 1 fps and at 25 ± 4° C [illegible] seconds. This response time is given [illegible] convenient reproducible laboratory [illegible]. The [illegible] response of the unit will depend upon [illegible] environment in which the sensor is used.

2.7 Self Heating. An unmounted sensor is capable of dissipating an $I^2R$ power of 35 milliwatts with a temperature rise of less than 1° C when submerged in #200 Dow Corning 1.5 CT3K oil flowing transverse to the sensing surface at 1 fps and at 25 ± 5° C. Ref. 2.6. Time Constant

2.8 Vibration. When the sensor and leads are firmly attached to a surface, the sensor shall withstand at least 35 g's peak or 0.5 inch double amplitude from 20 to 2000 cps. The sweep shall consist of 7.5 minutes up and 7.5 minutes down in any axis.

2.9 Compatibility. The sensor is suitable for use in any non-conductive fluid or environment that is compatible with platinum and aluminum oxide.

2.11. Identification. Each sensor shall have a serial number marked in the location shown. In addition a card shall be packaged with each sensor containing the following minimum information:

Rosemount Engineering Company
Model 118G Serial No. ________
Resistance at 0° C ________

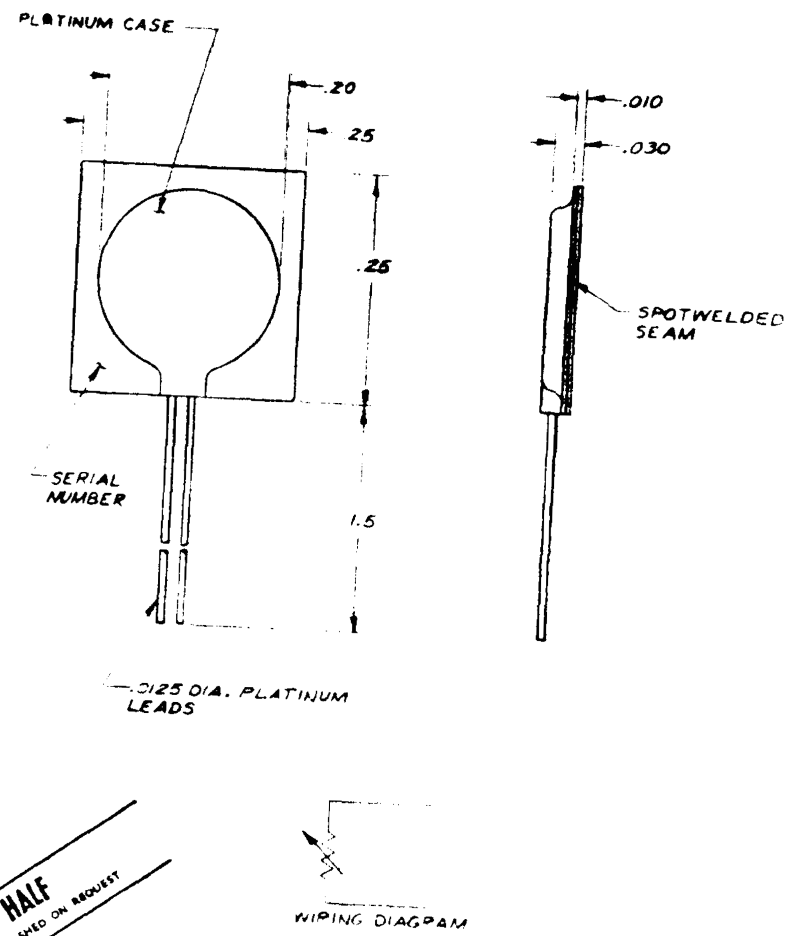
2.12 Weight. The weight of the sensor leads shall be less than 0.10 gm.

2.13. Mounting. The sensor may be mounted by cementing or clamping to a surface. The leads should not be bent nearer than 0.1 inch from the sensor.

3. INDIVIDUAL TESTS. Each sensor shall be examined for good workmanship, conformance to this drawing and shall pass the tests defined or implied by paragraphs 2.2, 2.3 and 2.5. Certified results of these tests shall be recorded on a suitable form and two copies will be packed for shipment with the sensor.

TABLE 1
Resistance Temperature Relationship

| Temperature (° C) | Resistance (ohms) | Interchangeability (± ohms) | ± ° C |
|---|---|---|---|
| - 260.00 | 284 | .20 | 2.5 |
| - 250.00 | 6[illegible] | .25 | 2.0 |
| - 225.00 | 7.00[illegible] | .30 | 1.2 |
| - 200.00 | 17.12[illegible] | .41 | 1.[illegible] |
| - 175.00 | 27.[illegible]42 | .54 | 1.3 |
| - 150.00 | 3[illegible].[illegible]15 | .70 | 1.7 |
| - 125.00 | 49.15[illegible] | .90 | 2.2 |
| - 100.00 | 5[illegible].5[illegible] | 1.10 | 2.7 |
| - 75.00 | 69.79[illegible] | 1.40 | 3.4 |
| - 50.00 | 79.[illegible]50 | 1.60 | 3.9 |
| - 25.00 | [illegible]0.[illegible]1[illegible] | 1.[illegible]0 | 4.5 |
| 0.00 | 100.00 | 2.[illegible] | 5.1 |
| 25.00 | 109.91 | 2.20 | [illegible] |
| 50.00 | 119.76 | 2.40 | 6.[illegible] |
| 75.00 | 129.53 | 2.70 | 6.9 |
| 100.00 | 139.2[illegible] | 2.90 | 7.4 |
| 125.00 | 14[illegible].[illegible]5 | [illegible] | 8.2 |
| 150.00 | 158.41 | [illegible] | [illegible] |
| 175.00 | 1[illegible]7.[illegible]0 | [illegible] | 9.6 |
| 200.00 | 177.11 | [illegible].80 | 10.1 |
| 250.00 | 195.9[illegible] | 4.20 | 11.5 |
| 300.00 | 214.25 | 4.60 | 12.9 |
| 350.00 | 232.29 | 5.10 | 14.4 |
| 400.00 | 240.[illegible]5 | [illegible] | 16.1 |
| 450.00 | 267.52 | [illegible] | 17.8 |
| 500.00 | 284.[illegible]0 | 6.40 | 19.2 |
| 600.00 | [illegible]18.22 | [illegible] | 22.[illegible] |
| 700.00 | 350.59 | [illegible] | 26.3 |
| 800.00 | 381.[illegible]2 | 9.1[illegible] | 30.2 |
| 900.00 | 411.91 | [illegible] | 34.5 |
| 1000.00 | 440.[illegible]5 | [illegible]0.50 | 3[illegible].9 |




REDUCED ONE HALF
A FULL SIZE PRINT WILL BE FURNISHED ON REQUEST

FIG. 2-20 SURFACE TEMPERATURE SENSOR SPECIFICATION DRAWING no mechanical strain. Since it is a pure metal element rather than a thermocouple which consists of two metals, or even two alloys, it is felt that this sensor should have long-term stability and not be subject to drift over periods of many thousands of hours.

### 2.2.4 Configuration Adaptability to Various Converters

The active control is very adaptable to any configuration of converter. All that is necessary is to use the appropriate mounting saddle which mates with the tubulation on the reservoir. For this reason the active control is a much more flexible control than the passive control as far as mechanical mounting problems are concerned. Two configurations are shown for the active control. The simplest one, consisting of a clamp which goes around the tubulation and holds both the clamp in place and the heater plate to the reservoir, is shown in Fig. 2-21. One side of the heater plate has the heater brazed to it, and the other side has the temperature sensor welded to it. The other configuration (Fig. 2-22) uses a saddle mounting similar to those used on the passive control. One side of the saddle mounting contains the heater block, the other side has the sensor attached to it, thus there is no thermal load going through the block on which the sensor is resting. This gives a more accurate measure of the reservoir temperature than would be obtained if it were mounted on the heater plate itself where the possibility of a temperature gradient could arise.

### 2.2.5 Method of Operation and Reliability

To put the active control into operation it is only necessary to attach the sensor and heater plate assembly to the reservoir tubulation and bring the leads out to the electronic control circuit by means of feedthroughs in the vacuum bell jar. The reliability of this control is limited only by the components in the electronic control circuit. Since such components have been shown to have extremely high reliability, i.e., in the Mariner and the Ranger satellites, this thermionic control circuit should have similar reliability.

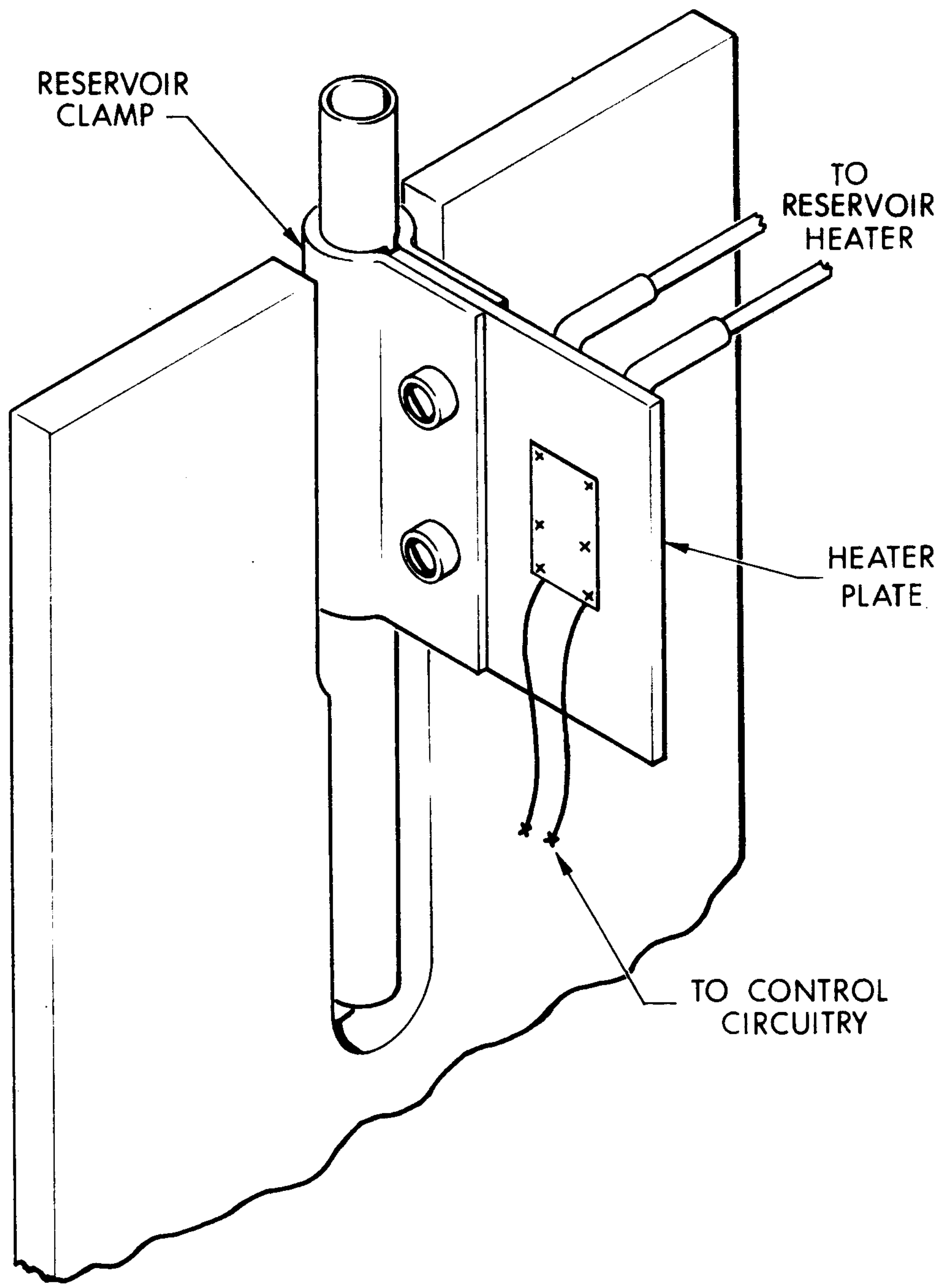



FIG. 2-21 PROPOSED ACTIVE CONTROL

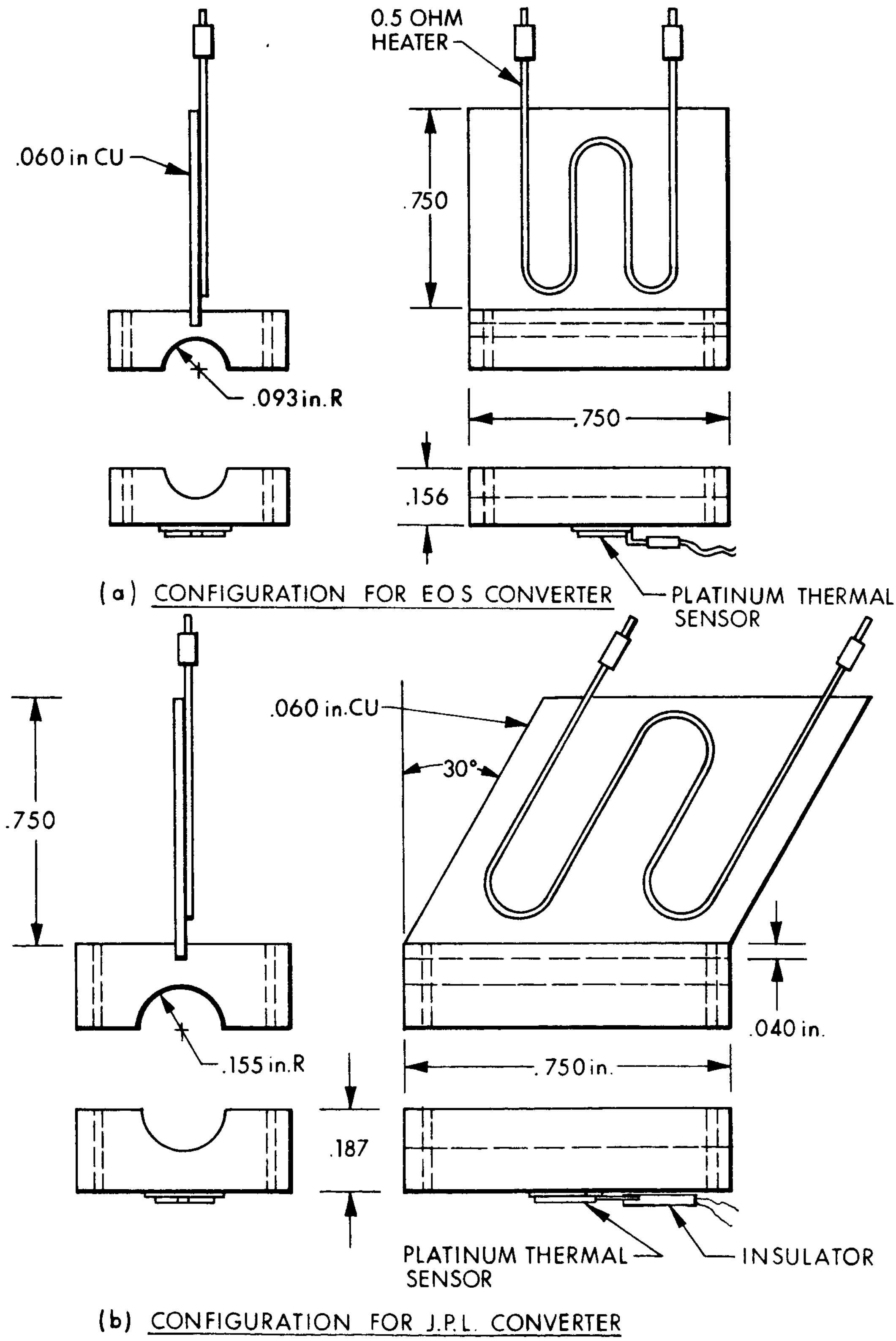



FIG. 2-22 SADDLE SENSOR ASSEMBLY

2.2.5.1 Temperature Adjustment and Repeatability

The temperature adjustment is affected by turning the screw on a potentiometer which is located inside the electronic control box. The temperature can be readily adjusted over the mean operating temperature and a high degree of repeatability is obtained. With the prototype that was made on this program, there is a slight mechanical difficulty in finding the same adjustment point on the potentiometer. This can easily be corrected by a slight change in the mechanical design. Other than that the temperature adjustment is extremely easy and the repeatability is very good.

2.2.6 Command Feature

The circuit has been provided with an external command line which will turn the control circuit on and off. The signal required is a positive, 10V dc level to be maintained while the control circuit is operational. Removal of the signal will put the circuit in the standby condition. Switching the signal on again will put the circuit back into operation. The control signal point has been brought out to a terminal on the plug of the control box.

2.2.7 Advantages and Disadvantages of an Active Control Unit

The advantages of an active control unit are that it functions on an extremely simple principle, it is easy to adapt to a variety of converter configurations, it has a high degree of reliability, temperature adjustment is quite easy and reproducible, and the regulating range can be adjusted from a few degrees to a few 10ths of degrees with suitable adjustments in the circuit. The electronic control can be operated remotely from the region being controlled.

The principal disadvantage of an active control unit is that it does absorb some power from the electrical circuit. For this particular control, the total power consumed is on the order of 5W at full power and it drops to about a half watt after the temperature has become stabilized. In addition, it has a standby feature which will enable it to remain inoperative while it absorbs only about 4 mW.

### 2.2.8 Conclusions and Recommendations

The conclusions reached during the design of the active control is that it is an ideal type of control to be used for cesium reservoirs which require a high degree of temperature control. While it is true that the active control does require some electrical power, the overall simplicity and reliability of the device indicate that this is a small price to pay for this type of temperature control. This is particularly true for laboratory operation of converters. It is recommended that converters in the future have a provision made for easy attachment of the heater sensor unit so that there is no danger of damaging the converter or its delicate pinch-off during the assembly of the control.

SECTION III

CONTROL UNIT FABRICATION AND CHECKOUT

## 3.0 INTRODUCTION

The active and passive control units were fabricated according to the principles outlined above essentially as originally designed. During the course of fabrication and checkout however, there were some indicated changes which were fed back into the fabrication process to result in an improved control.

### 3.1 Passive Control Unit

#### 3.1.1 Fabrication Techniques

The techniques required for fabricating the passive control unit shown in Fig. 1-4 are those used for the fabrication of thermionic converters. That is, most of the materials are either refractory materials, stainless steel, or copper. The usual machining precautions for making the passive control have been observed. There are only two parts of the control which required a different type of fabrication technique. One was the making of the bimetallic spiral and the other was constructing the bearings.

##### 3.1.1.1 Bimetallic Coil Fabrication

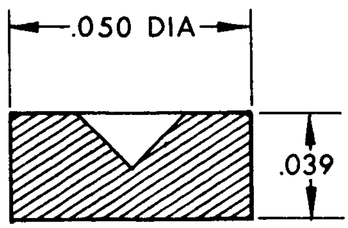
The best procedure for making the bimetallic coil is to decide on a given configuration and have the spiral fabricated by the manufacturer of the bimetallic material. For experimental work, however, this is not feasible and it is more practical to make the spirals in the shop. The spirals are made by cutting thin strips of bimetallic material from bimetallic sheet. The strips are then fastened to a mandrel, a piece of paper inserted behind the strip, and it is wound into a spiral between two surfaces which act as guides. The only critical feature of this operation was that the winding speed should be controlled very carefully so that the spiral is very uniform in its radius of curvature and it has no sharp kinks or bends. The spirals can be made to close inward or open outward as they are heated, depending on which side of the strip the high expansion coefficient material is oriented. After forming, the coils should be heat treated to relieve any mechanical stresses and to insure the uniform operating characteristics over the life of the device.

#### 3.1.1.2 Bearing Fabrication

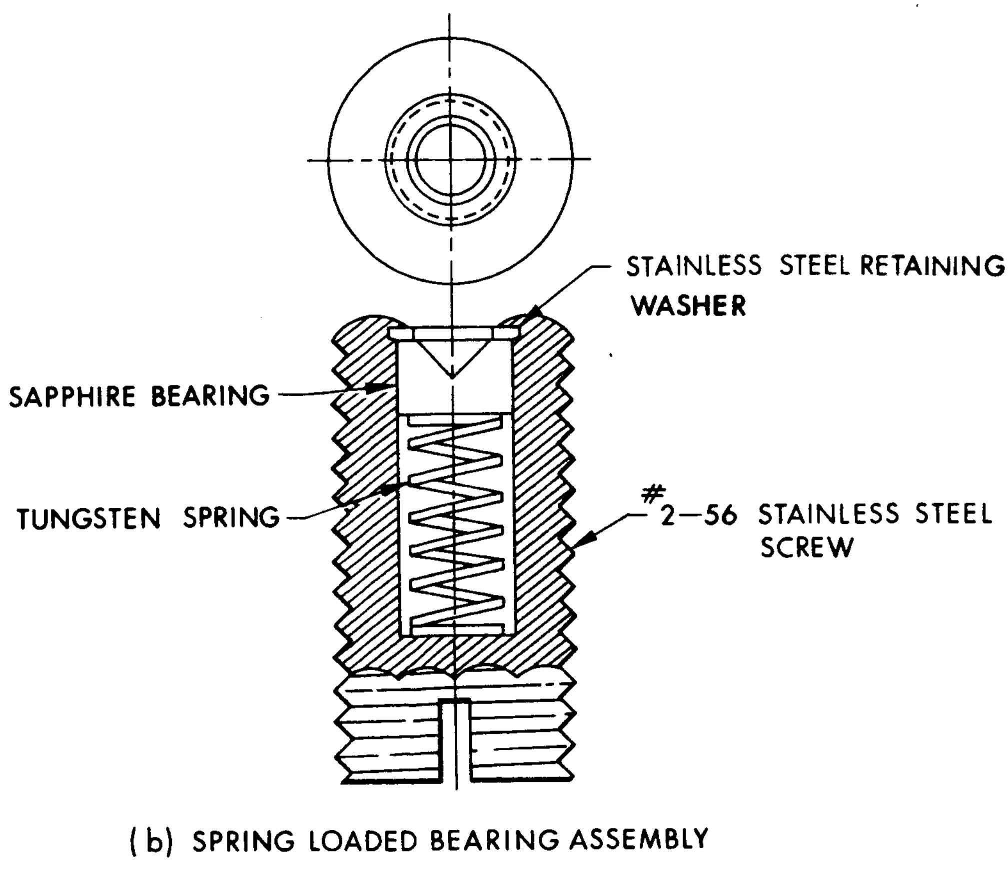
Attempts to purchase jeweled bearings for use in the passive control were not successful because none of the bearing manufacturers made any of these assemblies in materials that are satisfactory for high temperature vacuum use. Therefore, sapphire bearings of the proper size were obtained from the R. H. Bird Company (Fig. 3-1(a)) and acceptable housings were made as follows: small stainless steel screws size 2-56 were drilled out to match the outside diameter of the sapphire bearing. Small tungsten springs were wound to fit inside the drilled screw. These springs will act as a preload for the bearing. The bearing is assembled by inserting the spring in the hole, putting the bearing on top of the spring, and following that with a stainless steel retaining washer which is then held in place by rolling over the end of the screw as shown in Fig. 3-1(b). The principal difficulty in making these bearings is their small size. This small size requires watch making techniques for accurate and repeatable characteristics of the bearing devices. If the bearing assembly is not carefully made, the jeweled bearing itself may not slide properly inside its housing and may stick, thus not acting as a spring-loaded bearing.

### 3.1.2 Handling and Cleaning Techniques

Since all of these materials are standard vacuum materials the usual cleaning and handling techniques apply to the




(a) SAPPHIRE BEARING




(b) SPRING LOADED BEARING ASSEMBLY

FIG. 3-1 SPRING LOADED BEARING

fabrication of this reservoir control assembly. The bimetallic elements after heat treating were cleaned in acid and then followed by the usual ultrasonic cleaning techniques. The bearing assemblies, due to their relatively delicate nature, and the fact that they have many hidden recesses were cleaned only by ultrasonic cleaner techniques in solvents.

#### 3.1.3 Adaptability to Various Converters

The control as shown in Fig. 1-4 is adaptable to various converters merely by changing the saddle mounting which connects the reservoir control to the tubulation. The only problem in interchangeability is one of mechanical interference with the moving parts of the control and various structural elements of the thermionic converter on which it is mounted. Ideally, each converter would have a mounting bracket or pad on which the reservoir control could be mounted. This would solve the problem of adaptability.

### 3.2 Testing

#### 3.2.1 Method

Preliminary tests on mockups were described above in Subsection 2.1.2. The final assembly was tested by mounting it first on an EOS and then on a JPL converter and setting up in the bell jar to observe its behavior. The converter was then operated in its usual fashion with the output voltages of thermocouples monitoring the temperature of the reservoir and a strip chart recorder monitoring the collector.

#### 3.2.2 Criteria and Duration

Each converter ran a minimum of 24 hours in vacuum at temperature. The criteria for judging the performance included the temperature stability and the smoothness of control action.

#### 3.2.3 Results

The test results for the passive control were rather disappointing. For the EOS control the operation was erratic in that a very large $\Delta t$ was required before any motion was observed in the vanes. A temperature record showing the temperature of the reservoir during the control operation is given in Fig. 3-2.

No actual experimental results could be obtained with the EOS reservoir control mounted on the JPL converter because of the mechanical interference with the control operation by the radiation heat shield that is attached to the JPL converter.

3.2.3.1 Individual Converters Without Control Unit

The individual converters without control units were made also without heaters and without any Rokide "C" coating to increase the emissivity on the reservoirs. Without any coating there is a tendency for the reservoir to become too warm. The power input on these particular converters therefore, had to be used as a partial control measure of the reservoir to prevent any overheating.

3.2.3.2 Thermal Time Constant of Control Unit

The thermal time constant of the control unit is of the same order as the thermal time constant of the reservoir itself, since they have about the same thermal mass. However, a thermal lag was introduced because of the fact that a large $\Delta t$ had to build up in order to overcome the starting friction of the bearings. This resulted in an effective increase in time constant over that which would be there if the control were working more smoothly. The thermal time constant, in theory, for a smoothly working passive control should be at least no longer than, and preferably, less than, the thermal time constant of the reservoir itself.

3.2.3.3 Temperature Stability of Control Unit

Because of several factors, particularly the sticking factor mentioned above, the temperature stability of the control unit was not as good as desired. However, in principle, there is no reason why the thermal stability should not be as good as the materials with which the control is made. The only material which

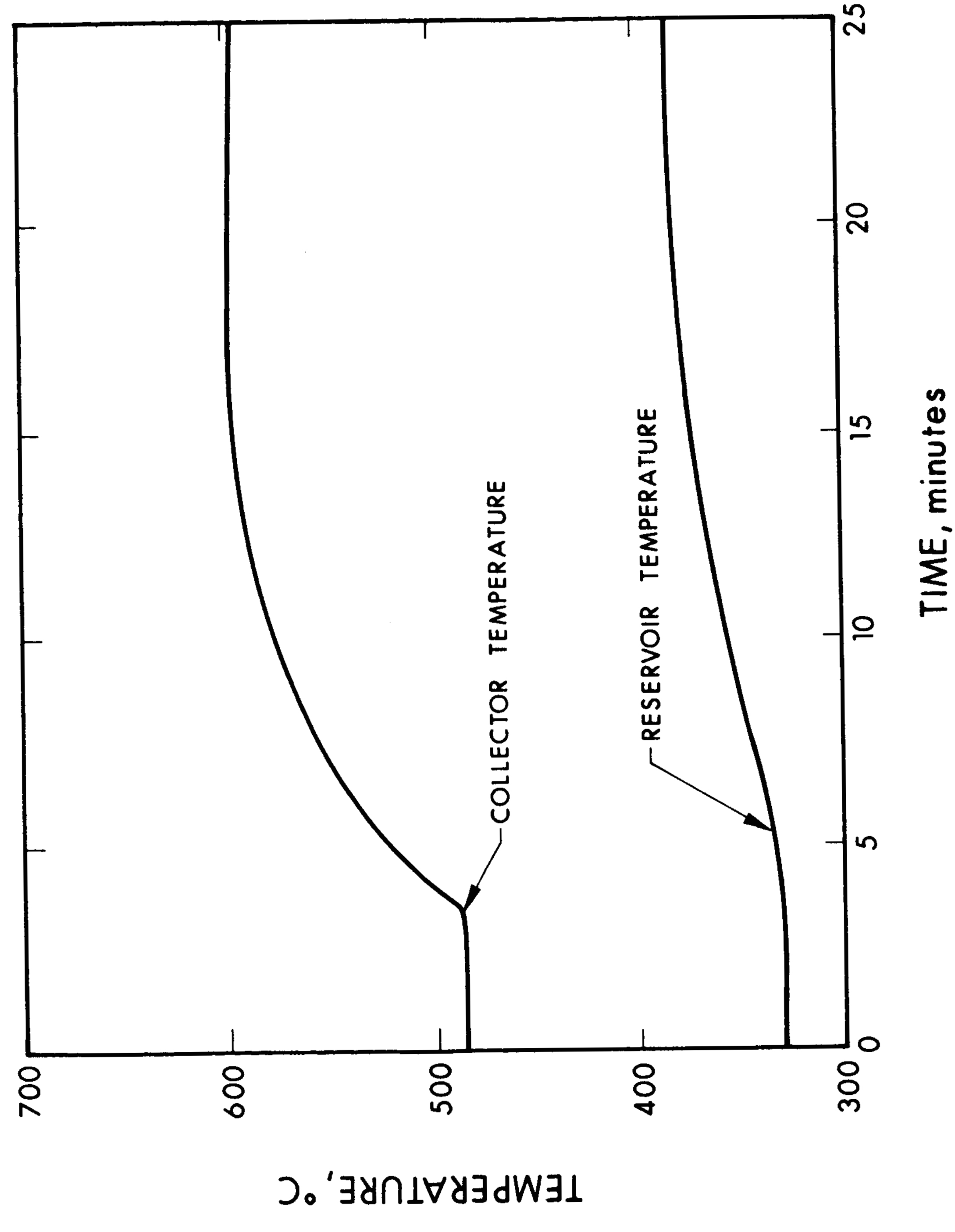



FIG. 3-2 EOS DIODE PASSIVE RESERVOIR CONTROL TEST

will suffer any long term degradation at high temperature over the life of the control would be the bimetallic element. At this time no data are available on the operating characteristics of bimetallic materials near the upper limit of their temperature capability. Long-term tests will have to be run in order to determine what the reliability of these devices really would be.

## 3.3 Active Control Unit

### 3.3.1 Fabrication Techniques

The fabrication techniques required for making the active control were identical with those used for the passive control as far as the heater-sensor block is concerned. The sheathed heater was brazed to the copper saddle element. One side of the copper saddle and the platinum sensor was fastened to the other side of the saddle block. Attempts to braze the platinum resistor to the block were not successful so the mounting technique was changed as follows: a nickel piece was brazed to the copper block and the platinum sensors then spot welded to that. Since the nickel is very thin, there is no danger of any serious temperature gradients being introduced.

The electronic control portion of the active control was constructed using the standard electronic components mounted on circuit boards. These circuit boards are then mounted inside a small aluminum box which will protect and shield the electronic circuits.

A view of the heater and sensor units for both the JPL and EOS converters is shown in Fig. 3-3. Visible in the picture are the heater and sensor units themselves, the insulated leads for the sensor, and a thermocouple for independently monitoring the temperature of the reservoir. The ends of the heaters have special connectors which were developed to protect the delicate heater ends.

A view of the electronic control circuit is shown in Fig. 3-4. The major items of interest in this picture are the control potentiometer which is a trimpot that is adjusted through a hole in

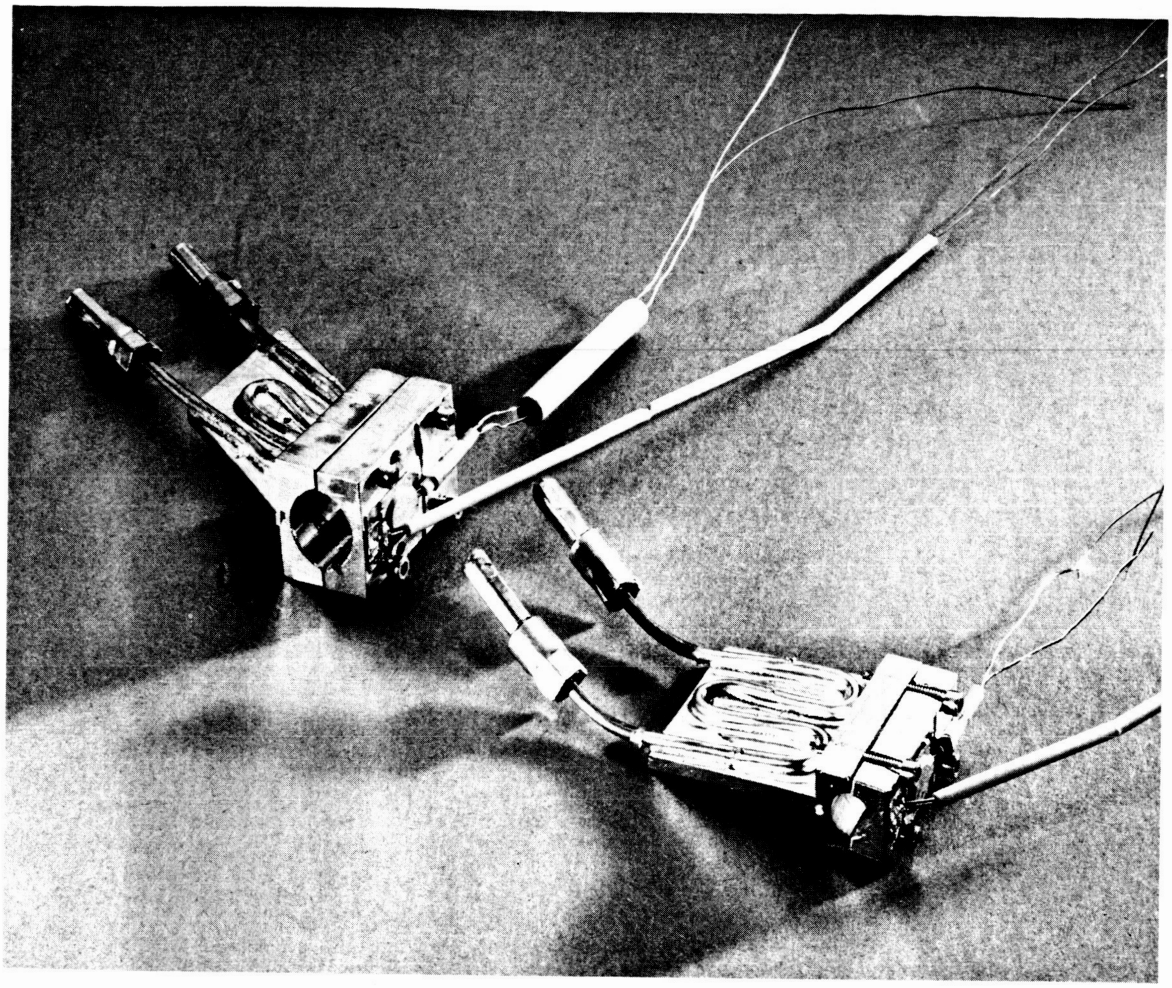


FIG. 3-3 HEATER AND SENSOR UNITS

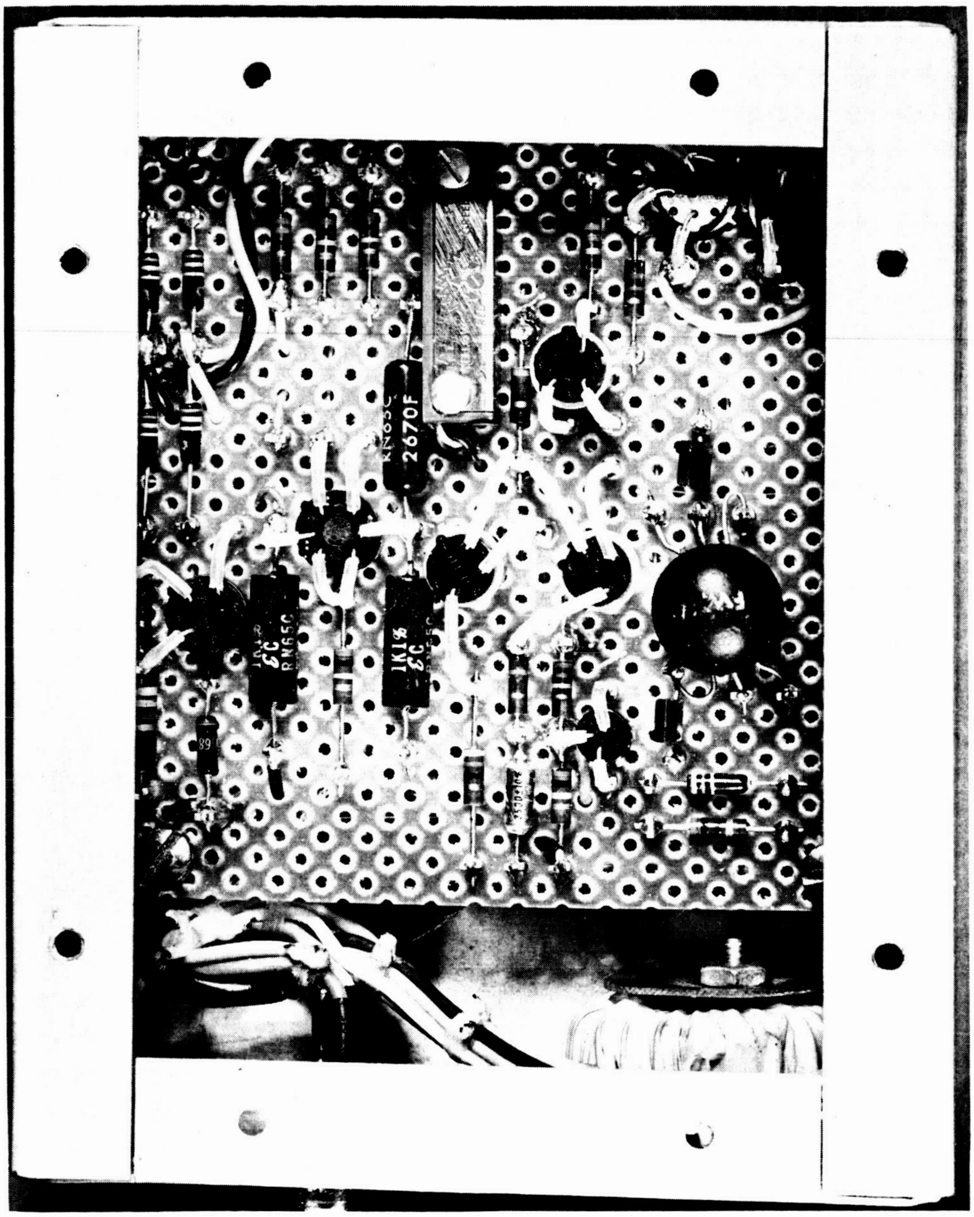



FIG. 3-4 ELECTRONIC CONTROL CIRCUIT

the casing, and the output transformer. The output transformer is a toroidal core type which is wound to provide three impedance taps for different heater requirements. The transformer is bolted to the case as shown in the picture.

### 3.3.2 Handling and Cleaning Techniques

The heater-sensor units for both the EOS and JPL converters were handled in the usual way that thermionic converters are handled. The cleaning techniques used were those of bright dip for the copper followed by suitable rinses, ending up with ultrasonic cleaning in alcohol. Since these parts are quite small, there is absolutely no difficulty in either handling or cleaning them with the usual laboratory equipment.

### 3.3.3 Adaptability to Various Converters

The active control is quite adaptable to any configuration of converter desired. As can be seen in Fig. 3-3 the heater-sensor blocks for both EOS and TEECO converters are identical except for size. There is one other difference and that is that the JPL converter heater is mounted on a plate which is at an angle to the axis of the converter centerline. The reason for this is to avoid mechanical interference with the shield on the JPL converter. However, just as discussed for the passive control the ideal situation is to have provisions already made on any converter for the installation of a reservoir control. In this way, the most reliable results will be obtained.

## 3.4 Testing

### 3.4.1 Method

The active controls were tested by mounting on the converters which were especially made without any heaters. The converter and control unit were then mounted inside the vacuum bell jar in the usual mounting arrangement used for testing the thermionic converter. Thermocouples were used to monitor the temperatures of the reservoir and collector root assembly by recording on a strip chart recorder. Both the temperature range and the time response of the control were measured by varying the circuit reference point and the thermal input to the converter. The circuit performance itself was checked by observing the waveform as the control operated from full power to control power limits.

### 3.4.2 Criteria and Duration

The following criteria were used to evaluate the performance of the control. For changes in the circuit reference point, the thermal time response was used as a measure of the performance of the control capability. For step changes in thermal loading of the diode, the steadiness of the reservoir temperature was used as a criterion. For the evaluation of the circuit, the percent of on-time as measured by an oscilloscope was used as a measure of the operation of the circuit. The tests were run for periods of time long enough to collect the data described in the next section. In addition, a 24-hour test at temperature was conducted to test the stability of the control over a long period of time.

### 3.4.3 Results

#### 3.4.3.1 Time Response

The time response of both the JPL and EOS diodes was measured, for step changes in the circuit reference point. In both cases, the test was started with the reservoir stabilized at the lowest required operating temperature, namely, 325°C. For each run, the reservoir was stabilized at 325°C, the control point adjusted to some upper temperature limit, and the time response observed. The sequence was repeated for each change in temperature. The results of the tests for the two converters are displayed in Figs. 3-5 and 3-6. The time response for the EOS converter is 6 to 7 minutes for the change in temperature over the complete range of 325 to 380°C. This response time is considerably under the 10 minutes allowed for in the

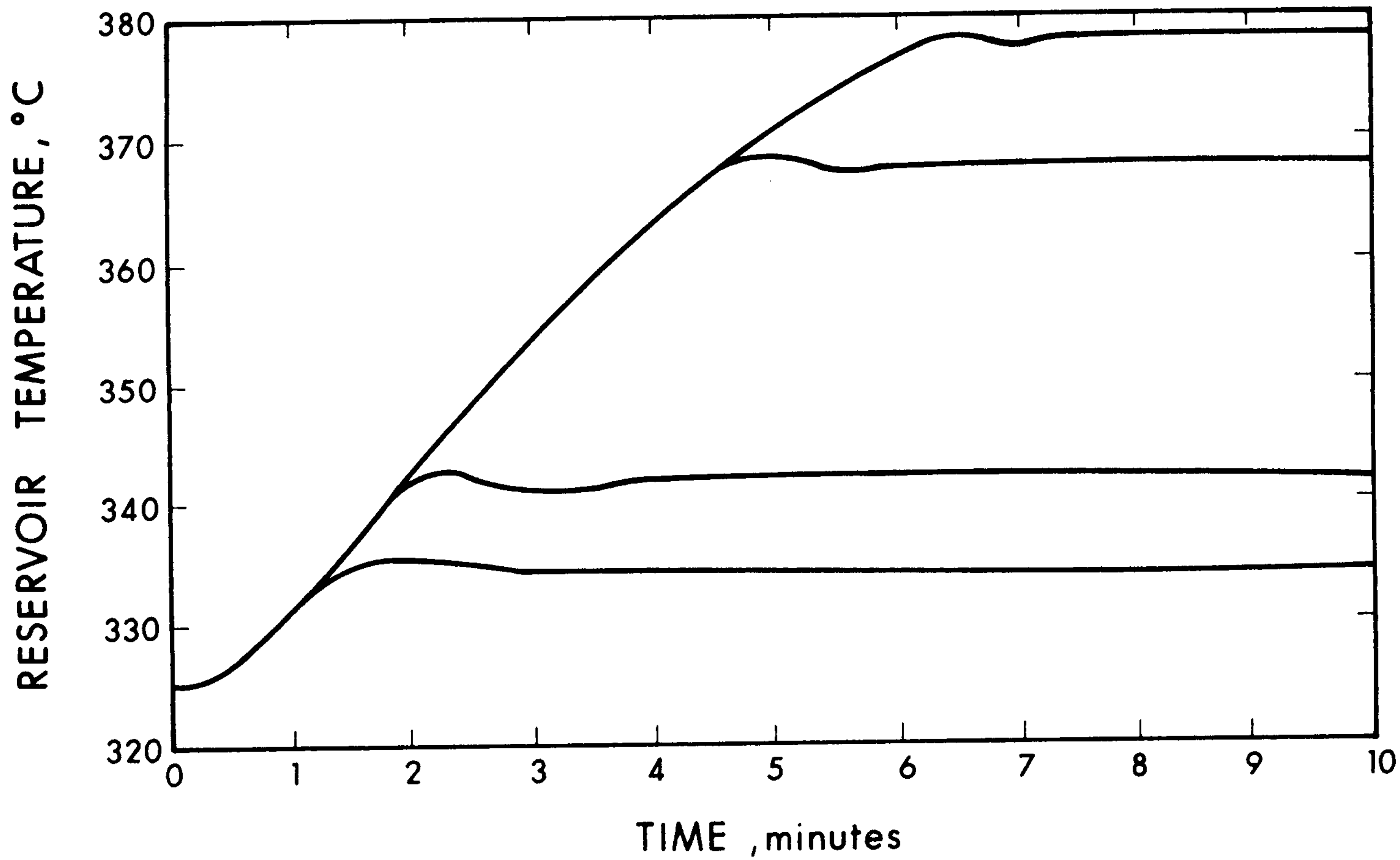



FIG. 3-5 TIME RESPONSE OF ACTIVE CONTROL ON EOS DIODE

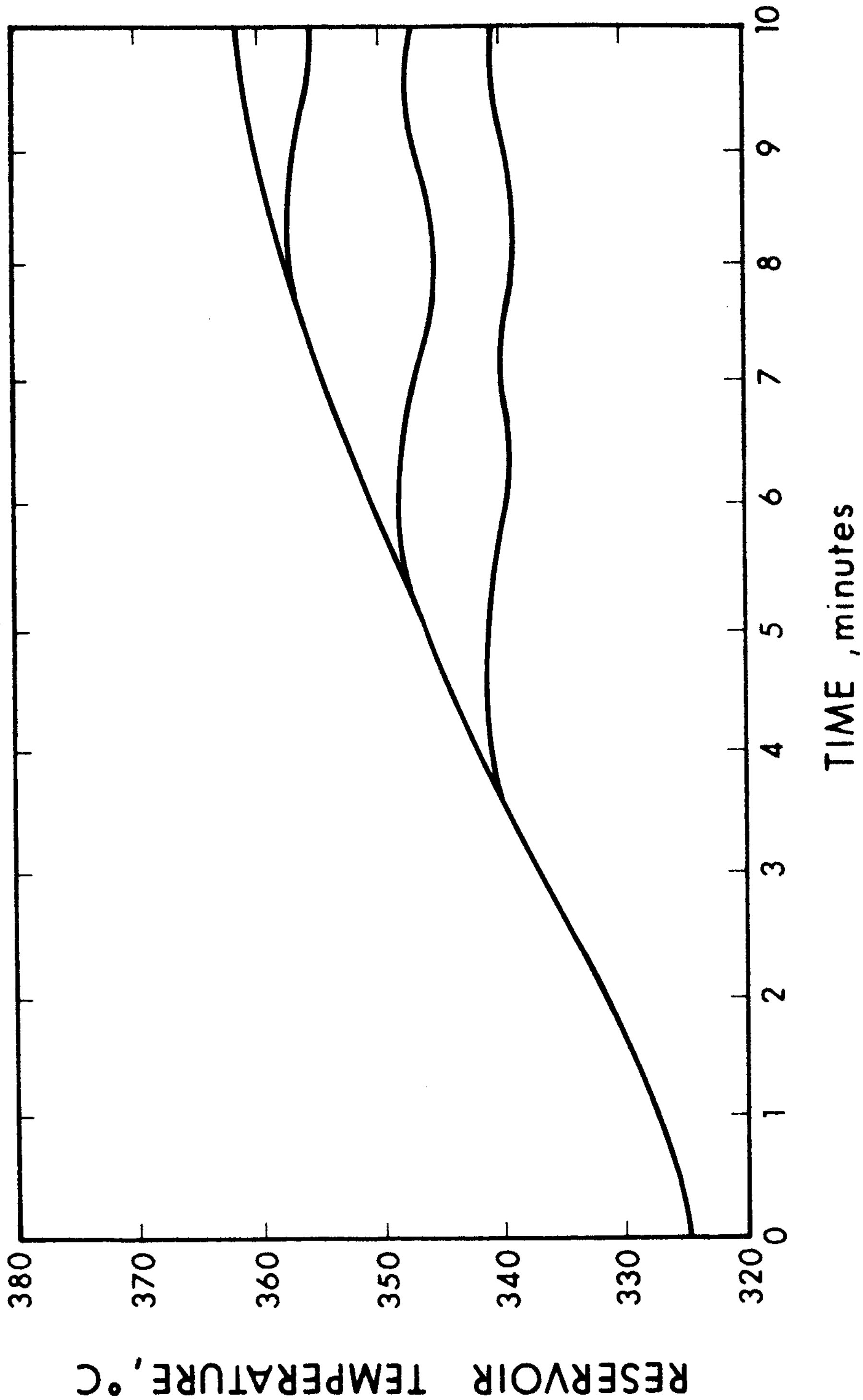



FIG. 3-6 TIME RESPONSE OF ACTIVE CONTROL ON JPL DIODE

specification. The JPL converter, on the other hand, required the full ten minutes to reach 365°C, a span slightly less than a 50 degree span desired for the program. Because of the relatively larger thermal mass of the JPL reservoir and the larger heat path connecting the reservoir to the collector, more power is needed for rapid control of the JPL converter than for the EOS converter. Thus, the time response in this case, was limited by the 5W of power available from the control. Five watts was the stipulated maximum power that the control should utilize in controlling the temperature of the diodes.

#### 3.4.3.2 Load Changes

The converters were tested to see the effect of large load changes on converter reservoir temperature. For the test, the converter was stabilized at a given load current with the reservoir temperature being set at 350°C. The load current was then changed suddenly to a new value and time allowed for the collector to establish a new operating temperature at this current level. At the same time the temperature was monitored. The results of these measurements (Figs. 3-7 and 3-8) show that for the most extreme load variations (from 0 to 60 amperes), there was no discernible change in the reservoir temperature. This indicated that the reservoir was very adequately controlled by this combination of electronic circuit and heater-sensor unit.

#### 3.4.3.3 Circuit Measurements

Prior to making the tests described above, a test of the electronic circuitry control unit was made using an available, though somewhat oversized, plate. A Rosemount platinum sensor was welded to the heater plate to complete the unit. The temperature was measured with a thermocouple which was attached to the plate next to the platinum resistance sensor. The heater sensor plate was then mounted in the vacuum bell jar to simulate vacuum environmental conditions. Electrical connections to the external electronic control

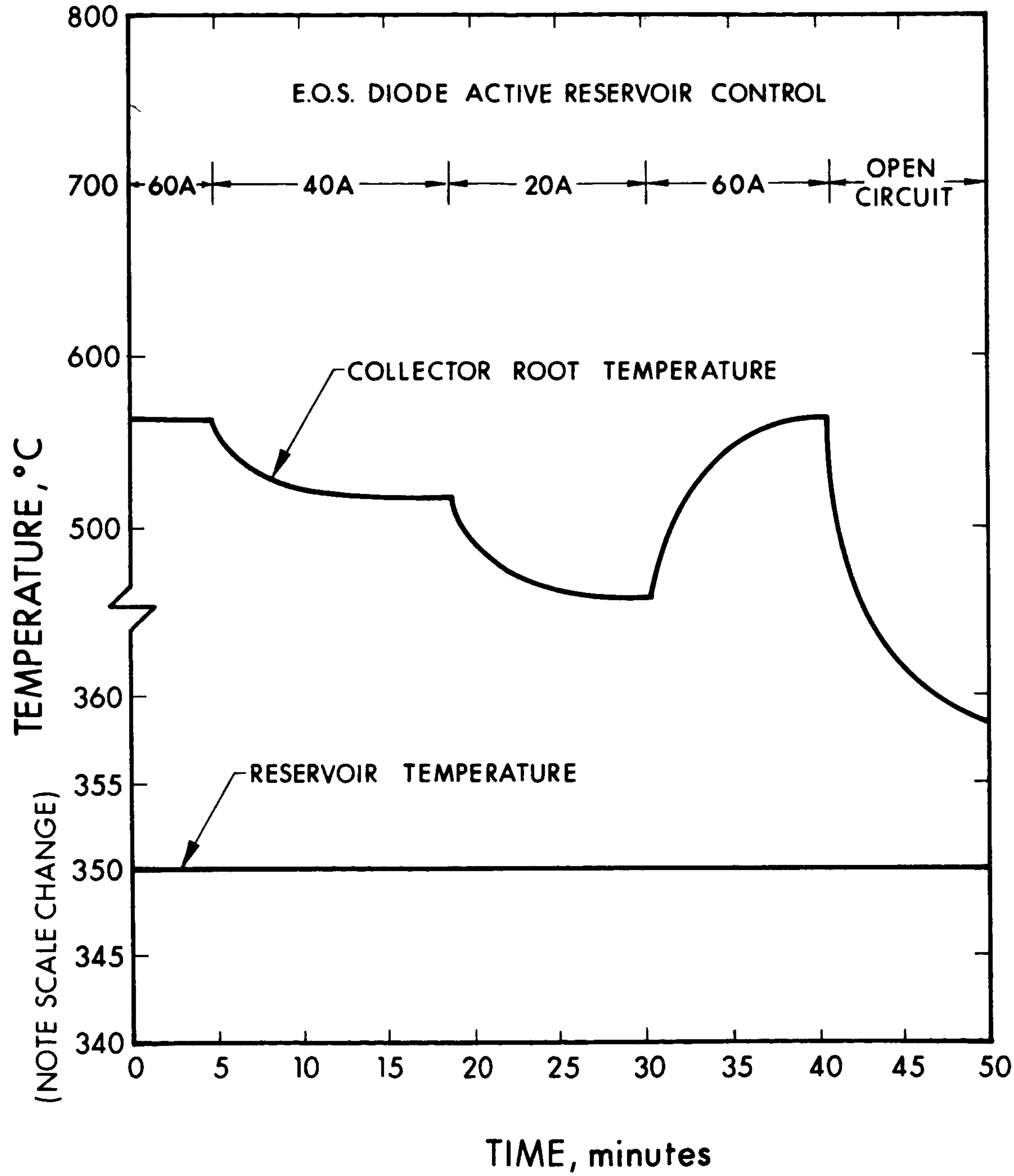



FIG. 3-7 EFFECT OF STEP LOAD CHANGES ON CONVERTER TEMPERATURES

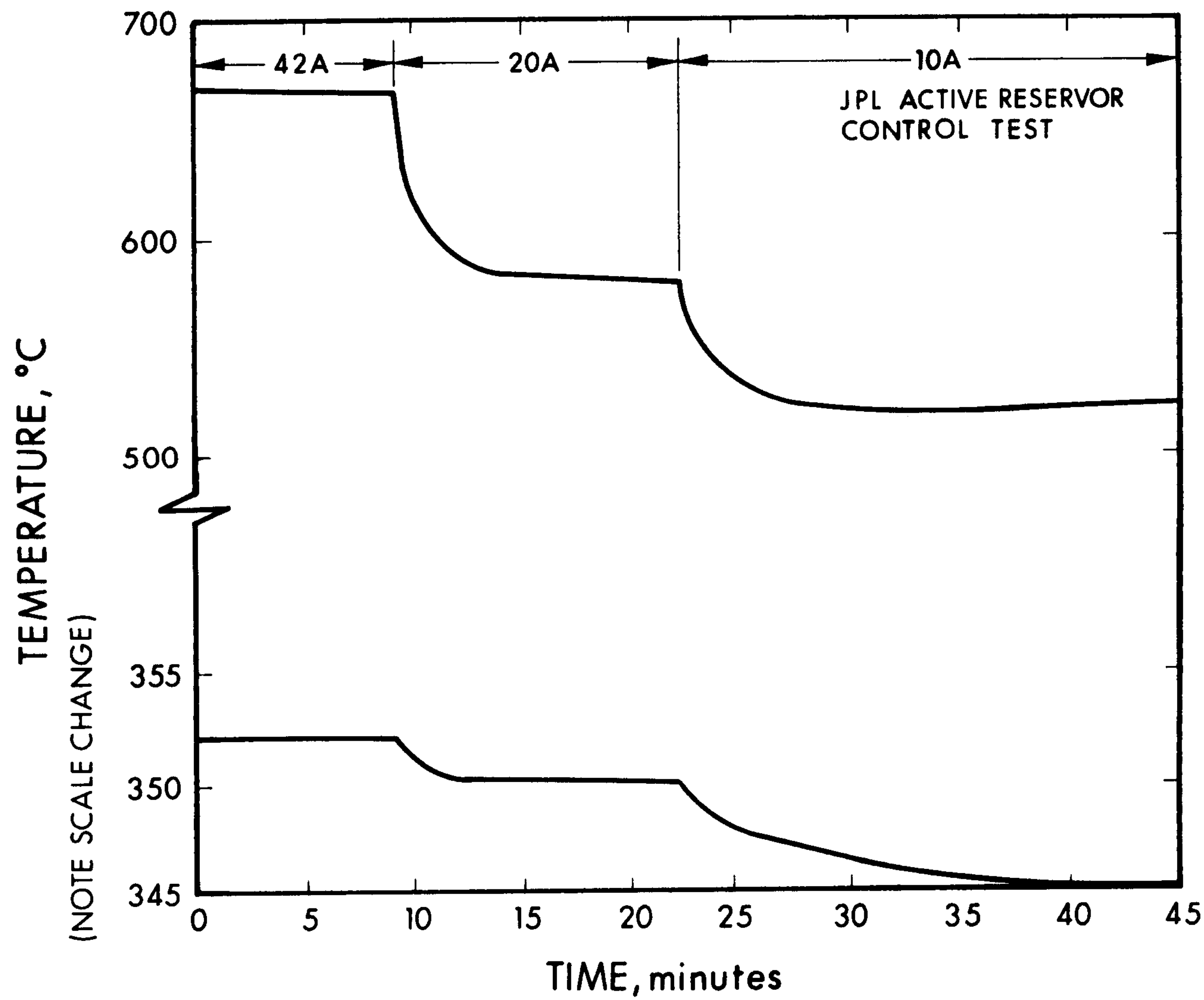



FIG. 3-8 THERMAL RESPONSE OF CIRCUIT PLUS HEATER PLOTS

circuit were made through the vacuum feedthroughs. The complete system was subjected to step function changes in power and the time required for the sensor plate to respond thermally was measured. Fig. 3-9 shows the time-temperature relationship.

This was a test to simulate the actual operation of the converter prior to the time the final heater sensor units were made. The purpose of including these data here is to correlate this test with oscilloscope measurements on the output voltage waveform as the power demand is changed on the circuit. For the top curve in Fig. 3-9, the duty cycle changed from 86 to 50 percent on the output waveform. For the second curve, the change was from 75 to 25 percent duty cycle. Fig. 3-10 shows a photograph of the waveform of the output voltage of the electronic control circuit for different current conditions. These are indicated in the figure and show the behavior of the control circuit over fairly wide temperature ranges. As less and less power is demanded from the control circuit, the leading edge of the control output voltage waveform has increasing jitter. This is shown in Fig. 3-10 by what might be called a band structure of increasing width at each control setting, as shown in the oscillograph. This jitter is due to 60 cycle ac pickup in the laboratory which would not be noticed in a better shielded installation. The pickup however, does not interfere in any way with the operation of the control, nor it in no way reduces the effectiveness of its operation.

#### 3.4.3.4 Weights

The weight of the circuit and heater-sensor assembly are shown in Table 3-I and are exclusive of connecting cable and case. Two items contribute to the weight in excess of the 6 oz stated in the work statement.

1. The output transformer has a tapped output for impedance matching. A single secondary winding transformer would probably weigh between 2 and 2.5 oz, a reduction of 1.3 to 1.8 oz.

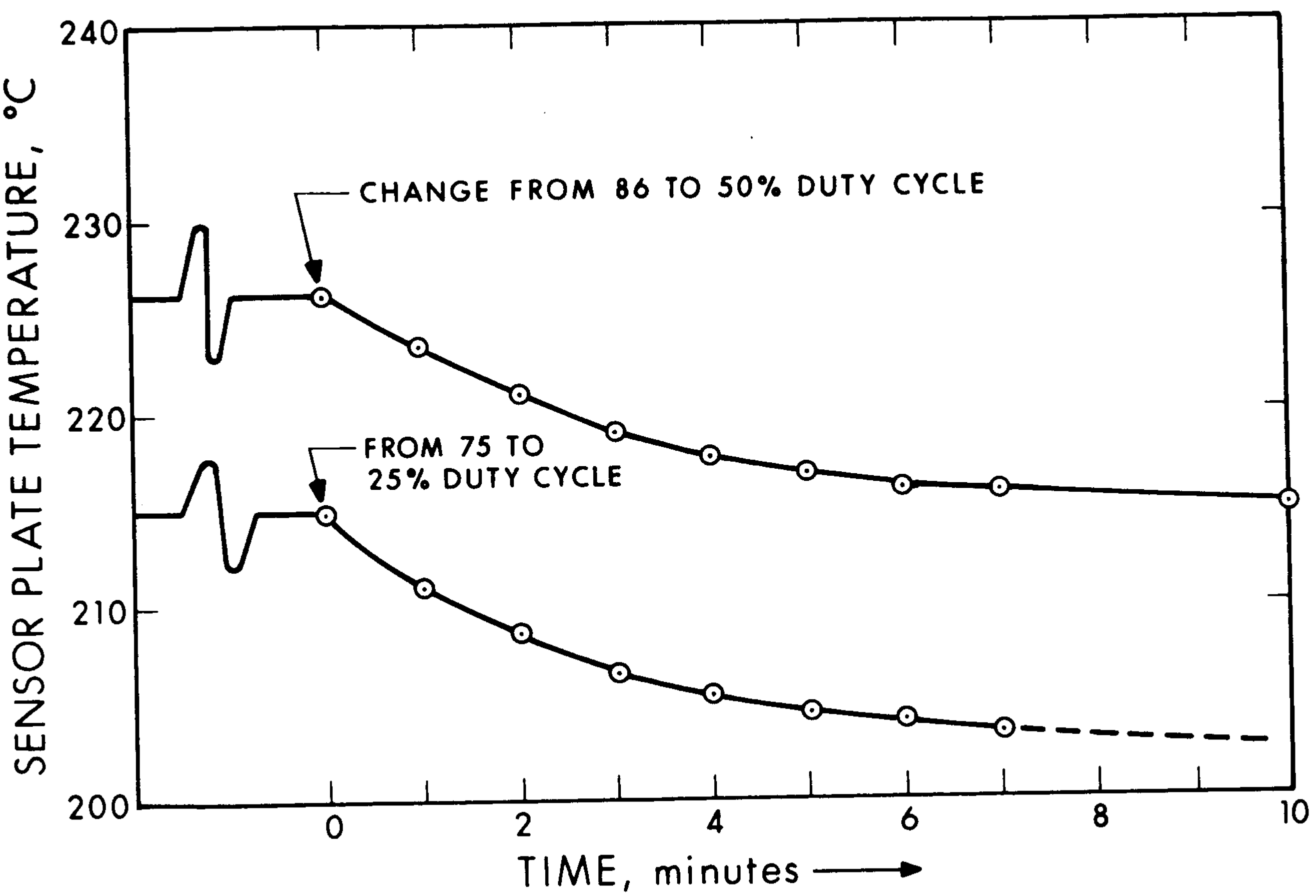



FIG. 3-9 THERMAL RESPONSE OF CIRCUIT PLUS HEATER PLATE

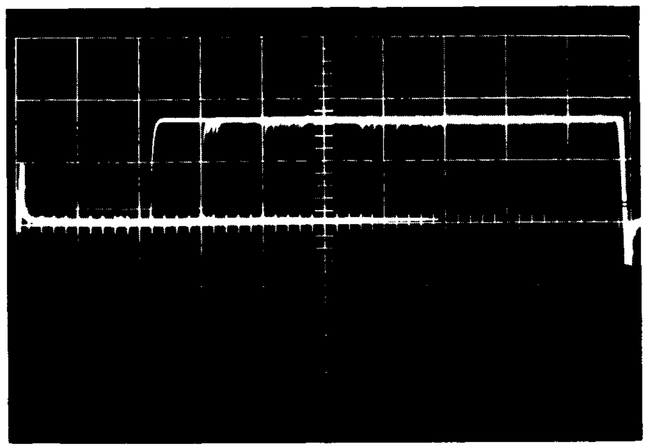


FIG. 3-10 WAVEFORM OF OUTPUT VOLTAGE OF ELECTRONIC CONTROL

2. The timer circuit required for low standby power operation may not actually be needed according to preliminary test results. If not, 1.9 oz additional will be saved.

TABLE 3-I

SUBSYSTEM WEIGHTS

| Item | Weight |
|---|---|
| Heater ckt board only | 1.9 oz |
| Output transformer | 3.8 oz |
| Timer ckt board only | 1.9 oz |
| EOS heater-sensor assembly | 0.5 oz |
| JPL heater-sensor assembly | 0.9 oz |
| Total EOS sensor/circuit | 7.6 oz |
| Total JPL sensor/circuit | 8.0 oz |

The total control weights can be between 3.9 oz without the timer circuit and 6.3 oz with the timer circuit and single winding secondary, in the case of the EOS converter control. Similarly for the JPL, the weight range is 4.3 to 6.7 oz. It thus appears that for a circuit accurately matched to its load and with careful attention to small details the 6 oz weight maximum is easily achievable. By way of contrast the total weight of the passive reservoir control is about 0.3 oz.

3.4.3.5 Adjustments of Operating Temperatures

The adjustment of the operating temperature of the active control is made by turning the screw on the potentiometer shown in Fig. 3-4. This potentiometer was intentionally recessed to the inside of the control so that it would not be disturbed by handling. If it is desired to make this control more accessible, a simple extension shaft can be mounted to this and brought to the outside of the control box.

## SECTION IV

## CONCLUSIONS AND RECOMMENDATIONS

### 4.1 Active Control

As a result of the measurements discussed above, it can be concluded that the active control as designed and demonstrated, more than adequately meets the specifications outlined for its performance. For ease of assembling or disassembling the heater sensor unit on the converter, it would be advisable to provide a mounting pad on the reservoir itself. By providing a specific mounting place, a high degree of reproducibility can be obtained with controls that have been fabricated and calibrated separately from the converter itself.

### 4.2 Passive Control

The passive control has been shown to be capable of providing a moderate degree of control of the reservoir temperature. The principal difficulties are (1) the control actuating mechanism must be located close to the heat source and (2) the converter operating temperature requires that the bimetallic material used for the control actuators are working near or beyond their maximum, long-life ratings. It has also been found that with the low deflection sensitivities of suitable bimetals, some degree of mechanical amplification such as used in thermometers and precision thermostatic controls is required. All moving parts must be mounted in sapphire bearings for high temperature space applications.

By integrating the design of variable emissivity surfaces into the converter reservoir and collector radiator design and by applying high temperature, high vacuum techniques to a sophisticated thermal-mechanical control system, a truly passive reservoir could be attained.

## REFERENCES


1 R. N. Sears, "Fundamentals of Thermostat Materials," Materials Research and Standards, 981-986 Dec 1963

2 S. Timoshenko, "Analysis of Bimetallic Thermostats," JOSA & RSI, 11, 233-255, Sep 1925

3 M. Jakob, Heat Transfer, 1-90, Wiley and Sons, Inc. New York, 1957

APPENDIX I

CONFIGURATION FACTOR STUDIES AND DATA
(Taken from ASD Technical Report 61-119 Part I)

Section VII

# CONFIGURATION FACTOR STUDIES AND DATA

## CONFIGURATION FACTOR EVALUATION

One of the most difficult areas in the analysis of radiation heat transfer is proper calculation of the geometric configuration factor. Basically, the configuration factor $F_{12}$ from $A_1$ to $A_2$ is defined as the fraction of the total radiant flux leaving $A_1$ that is incident upon $A_2$. The configuration factor from a plane point source to a finite surface (commonly known as a differential-finite configuration factor) is obtained by integration over $A_2$, and the mean configuration factor from a finite source (finite-finite configuration factor) is the average of the point configuration factors over the finite source. The integral expression for the differential-finite configuration factor from $dA_1$ to $A_2$ is given by

$$F_{(dA_1 - A_2)} = \frac{1}{\pi} \int_{A_2} \frac{\cos\theta_1 \cos\theta_2 \, dA_2}{S^2} \qquad (203)$$

The integral expression for the finite-finite configuration factor from $A_1$ to $A_2$ is given in the Section III discussion on radiant heat exchange between surfaces.

$$F_{12} = \frac{1}{A_1 \pi} \int_{A_1} \int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{S^2} dA_1 dA_2 \qquad (204)$$

As an example (from Reference 20) consider the two mutually perpendicular surfaces shown in Figure 57. The left-hand corner of the horizontal surface is assumed to be the origin, with the x, y, and z axes as shown. The horizontal surface has overall dimensions of D and W while those of the vertical are H and W. Thus

$$F_{12} = \frac{1}{WD\pi} \int_{A_1} \int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{S^2} dA_1 dA_2 \qquad (205)$$

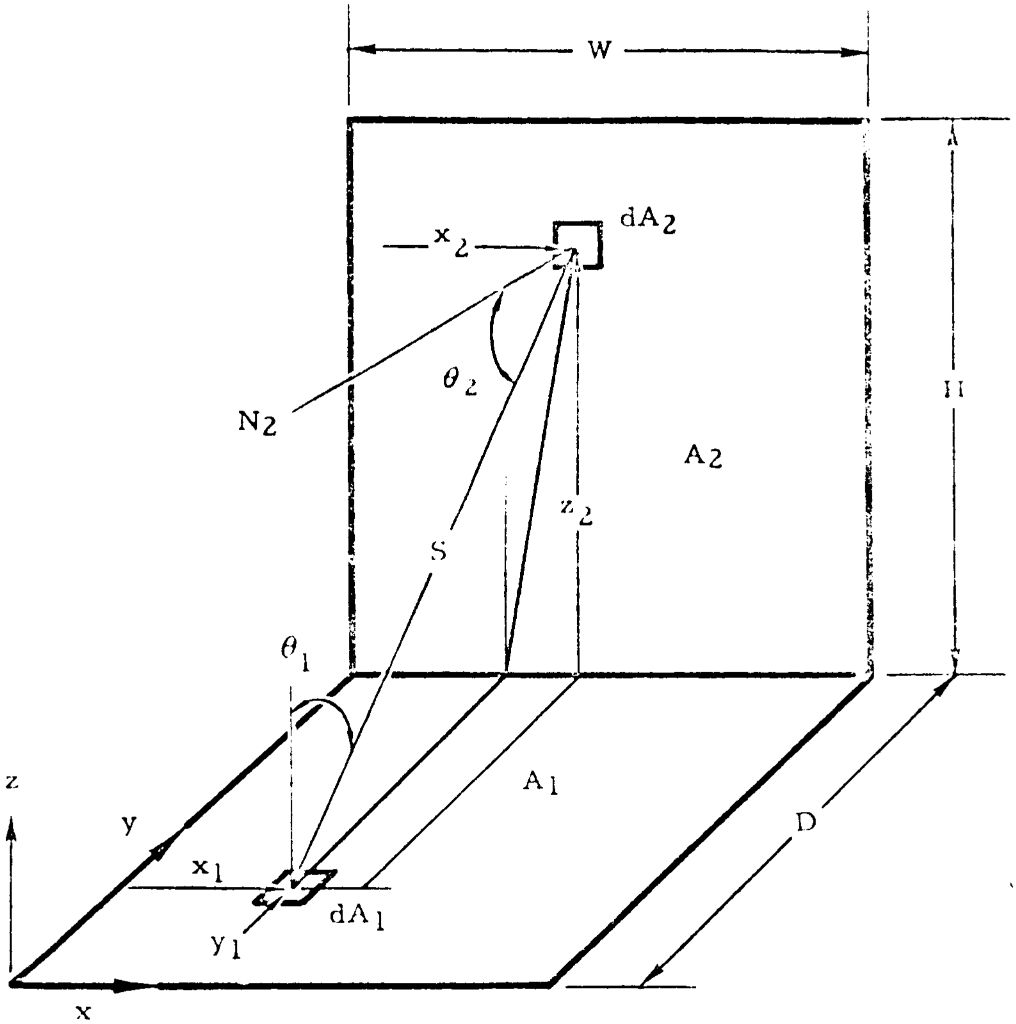



Figure 57. Geometry for Calculation of Configuration Factor for Two Mutually Perpendicular Surfaces

where $\cos\theta_1 = \frac{z}{s}$

$$\cos\theta_2 = \frac{D-y}{s}$$

$$s = \sqrt{(x_2 - x_1)^2 + (D - y)^2 + z^2}$$

and

$$dA_1 = dx_1\, dy$$

$$dA_2 = dx_2\, dz$$

therefore

$$F_{12} = \frac{1}{WD\pi} \int_0^H \int_0^D \int_0^W \int_0^W \frac{z\,(D - y)}{\left[(x_2 - x_1)^2 + (D - y)^2 + z^2\right]^2} dx_1 dx_2 dy dz \tag{206}$$

Integrating Equation 206 yields

$$F_{12} = \frac{1}{WD\pi} \left\{ \frac{1}{4} \left[ (D^2 - W^2 + H^2) \ln (D^2 + H^2 + W^2) - (D^2 + H^2) \ln (D^2 + H^2) - (D^2 - W^2) \ln (D^2 + W^2) \right] \right\} \tag{207}$$

$$- \frac{1}{WD\pi} \left\{ \frac{1}{4} \left[ (H^2 - W^2) \ln (H^2 + W^2) - D^2 \ln D^2 - H^2 \ln H^2 + W^2 \ln W^2 \right] \right\}$$

$$+ \frac{1}{WD\pi} \left[ HW \tan^{-1} \frac{W}{H} + DW \tan^{-1} \frac{W}{D} - W \sqrt{D^2 + H^2} \tan^{-1} \frac{W}{\sqrt{D^2 + H^2}} \right]$$

It can be seen that the integration process is often tedious, even for simple shapes such as in the example. In fact, for most cases the integration cannot be solved analytically and other means must be used to obtain the answer. Under these circumstances the following approach can be utilized:

1. If the areas in question can be assumed infinite in one direction, there are several very simple and rapid methods available with which to obtain the configuration factor.

2. If step 1 does not fit the problem, the next step is to use tables and charts which are available for specific configurations. These are discussed in this section and provide solutions to a number of different configurations, with the help of form factor algebra.

3. If the previous steps are not adequate, there is available an IBM program which calculates the configuration factor between any two plane areas if they are in the form of parallelograms.