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A NARROW FIELD-OF-VIEW, HIGH RADIANT HEAT FLUX SENSOR FINAL REPORT

Contract NAS8-11994
G.O. 8733

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FOREWORD

This report was prepared in partial fulfillment of the requirements of Contract NAS8-11994. Delivery of three breadboard and three prototype heat flux sensors comprises the remainder of the contractual requirements. Delivery of the sensors has been completed prior to the date of this report.

This contract was administered by the Astrionics Laboratory, Research and Development Laboratory, Marshall Space Flight Center, NASA. Mr. Harlan Burke was the contract technical monitor.

ABSTRACT

A prototype, radiant heat flux sensor was designed. Fabrication, calibration and delivery of three of these prototypes to NASA MSFC has been completed.

The heat flux sensors are high responsivity, short time constant radiometers designed to operate reliably in the severe environs of rocket engine exhaust plumes. The sensors are designed to measure very high radiant emittance levels over a narrow field of view.

The sensors are described in this report and detailed drawings of the sensor and its components accompany it. In addition, the research and development which led to the design is discussed.

CONTENTS

INTRODUCTION

The measurement of radiant heat flux from high intensity sources has become increasingly important with the advent and expansion of the space age. For example, the design of the boattail region of a vehicle requires an accurate knowledge of the heat radiated from the exhaust plumes of the rocket engines which propel the vehicle. Because of the structural, and consequently the radiative, complexity of these plumes, it is difficult to accurately predict theoretically the quantity of radiant energy from them. Hence, accurate measurements are needed.

Specialized radiometers are required for measurements of this type. Commercially available radiometers typically have rather wide fields-of-view which usually are not well defined. In actual measurement situations, for example, on rocket engine static test stands and on flight vehicles, it frequently happens that indeterminate amounts of the plume are obscured by intervening structural members. It may also be that the plume is deflected, as is usual in static test configurations. This will have pronounced effects on the radiation from the overall plume, the majority of which would lie within the field of view of standard radiometers. For meaningful measurements in such situations, or where information is desired about the radiation from a particular portion of a heterogeneous plume, it is clearly necessary to restrict the field of view of the radiometer.

Other important characteristics of a radiant heat flux sensor for measurements of this type include: sufficiently high signal amplitude to obviate noise problems in connection with signal conditioning equipment and sufficiently rapid response to provide an accurate measure of radiation intensity even when the latter is varying slowly with time.

For those rocket exhaust plumes which contain particulate matter, the radiation is spectrally continuous. This is true, for example, of plumes of engines using the liquid propellants LO_2/RP-1 or aluminized solid propellants. In addition, the molecular species present in most exhaust plumes radiate in several portions in a wide wavelength interval. Therefore, to accurately measure the amount of radiation from such sources, it is essential that the radiometer used have uniform spectral responsivity over a wide range.

The immediate vicinity of large rocket engine exhaust plumes is a strenuous one for instruments of any type. In addition to very high acoustic and vibration levels, high heat transfer rates are present. The latter area is of particular concern for a flight instrument where water cooling is not possible. Thus a radiant heat flux sensor designed for this type of usage must be very rugged mechanically and must have thermal protection adequate to ensure satisfactory operation under high heat loading.

The prototype heat flux sensors developed and fabricated under this contract are designed to operate satisfactorily under conditions such as the above and in particular to meet the specific requirements for performance listed in the contract quidelines.

ILLUSTRATIONS

HEAT FLUX SENSOR

SENSOR DESCRIPTION

The prototype heat flux sensor is comprised of a reflective-refractive optical system and a thin foil thermocouple detector. The folded optical system serves to define the field-of-view of the instrument while increasing the irradiance at the detector. The components of the optical system and the detector are mounted in a compact metal housing, which, in turn, is covered by a thermal protective material. Radiant energy is admitted to the sensor via a sapphire window which is recessed in a cylindrical contamination shield through which a gaseous nitrogen purge is exhausted. Figure 1, 2 and 3 are photographs, including an exploded view, of the uncoated sensor while Fig. 4 is a photograph of a thermally protected sensor. EWR 926935-1 is an assembly drawing of the prototype sensor.

The overall dimensions of the sensor are approximately 6-1/2 by 4 by 2 inches. Its weight with thermal protection is 3.8 pounds; without the protective coating it is 2.9 pounds.

Electrical connection is made through a two-pin receptacle at the rear of the sensor housing. Pin B is the positive terminal. A length of cable terminated by a snap-on connector is supplied with the sensor.

An AN fitting, also at the rear of the sensor, provides for admission of the nitrogen purge gases. An orifice in the fitting decreases the 750 psi supply pressure to 50 psi within the housing and adjusts the flowrate to 3 standard cubic feet per minute.

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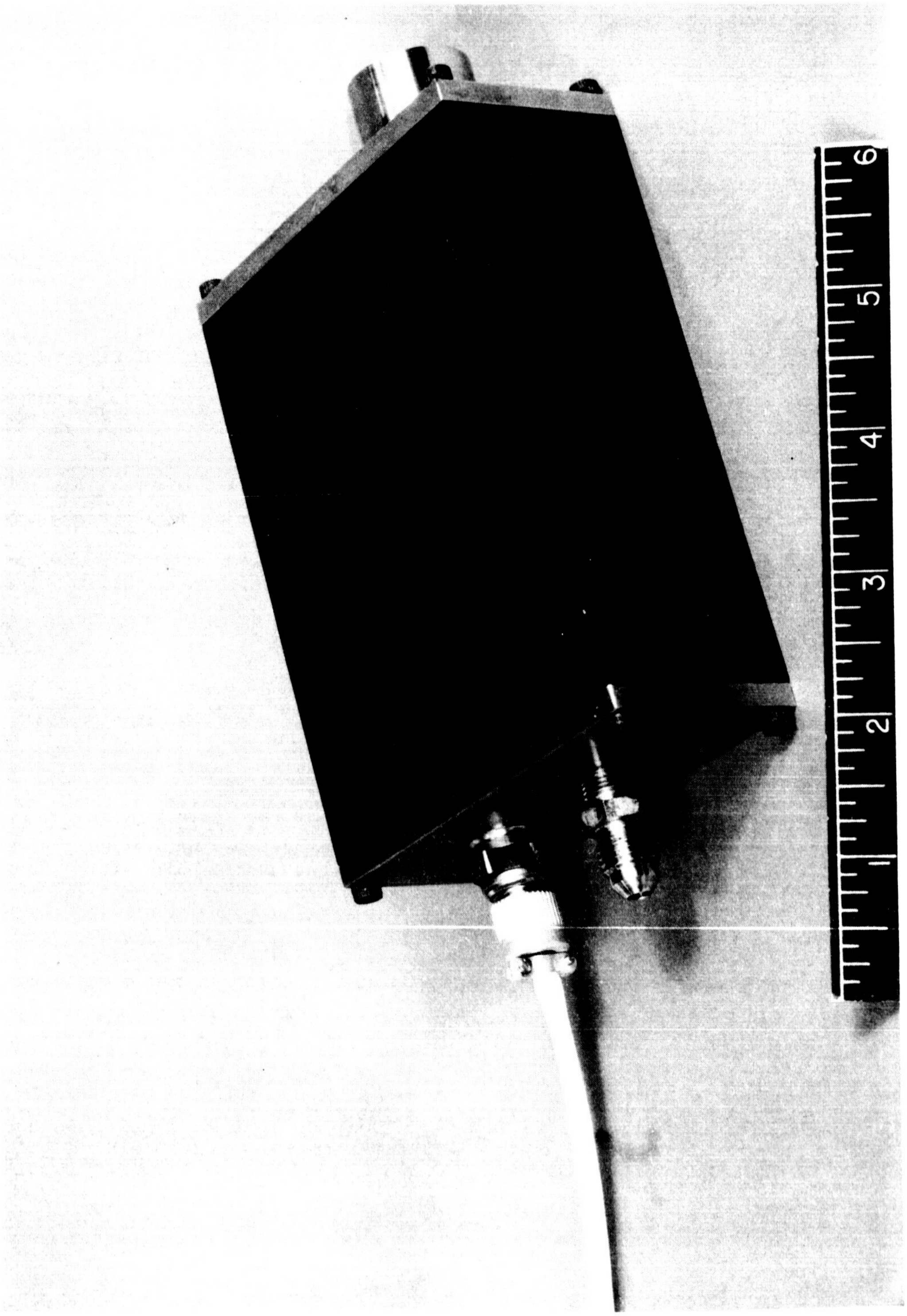

Figure 1. Prototype Heat Flux Sensor

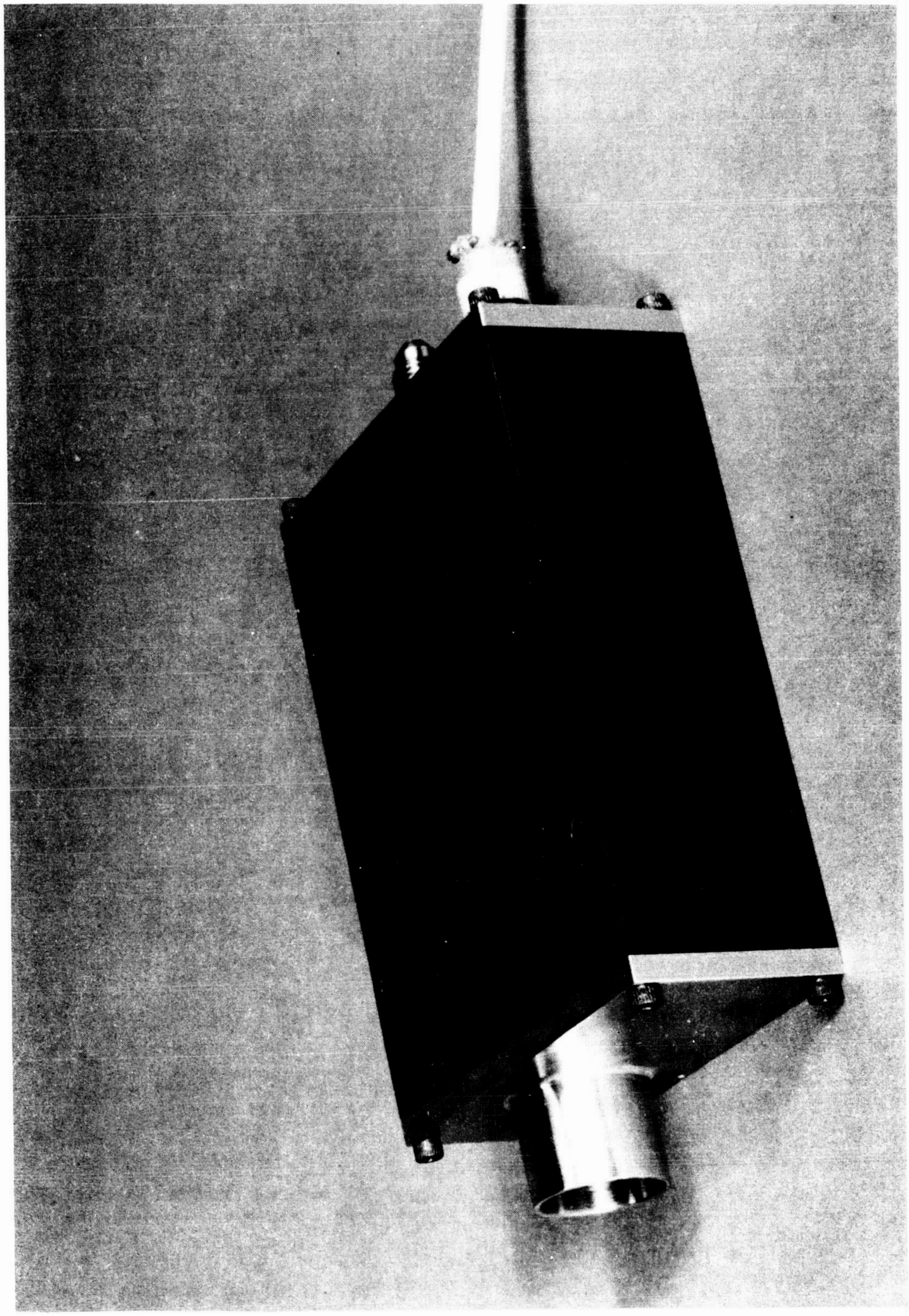

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Figure 2. Side View of Sensor

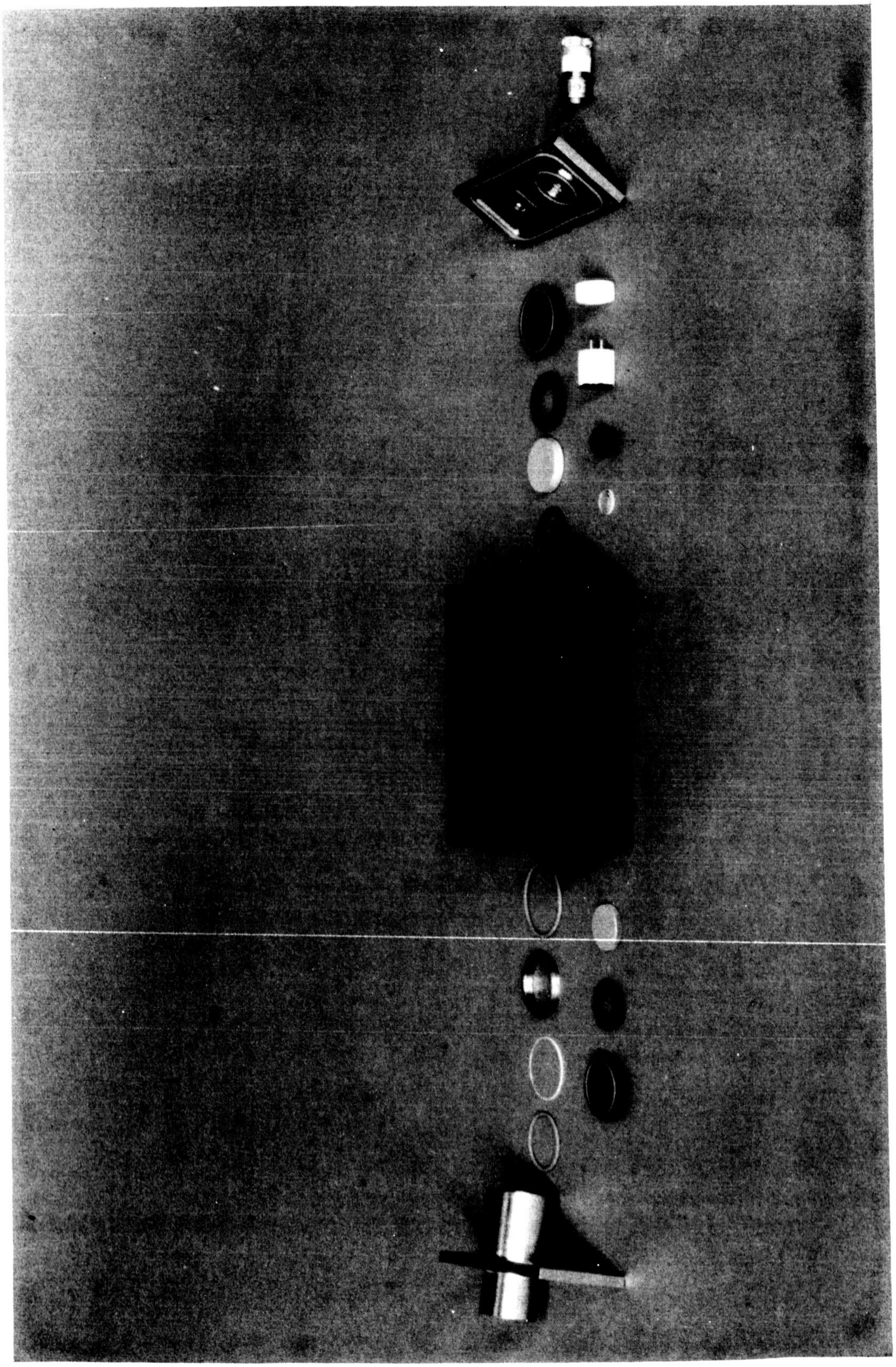

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Figure 3. Exploded View of Sensor

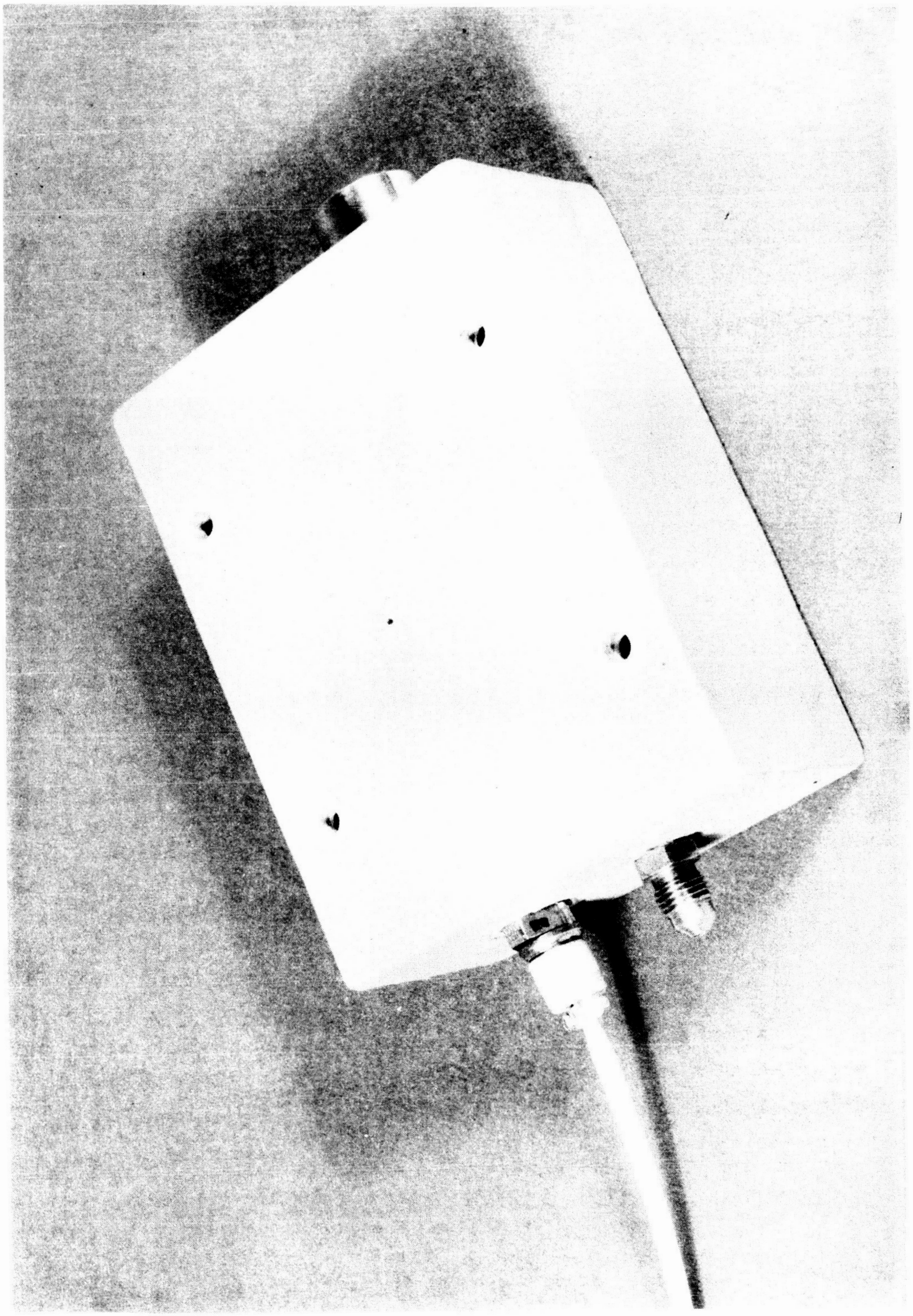

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Figure 4. Sensor With Thermal Protective Coating

Four bolt holes through the sensor housing in a direction transverse to its long dimension are provided for mounting the sensor.

SENSOR PERFORMANCE

Calibrations and other tests were performed on the prototype heat flux sensors to determine their performance characteristics. The results are given in this section and compared with the contract quidelines.

Sensor output voltages vs source radiant emittance level is shown in Fig. 5, 6, and 7. In all cases, the responsivity is greater than the guideline limit value of 10^{-4} volts $watt^{-1}$ $centimeter^{2}$. Depature from linearity is less than ±3 percent of the full scale value.

The above calibrations were performed using a series of five intermittent exposures of several seconds duration at each radiant emittance level. To determine the stability of the output over longer periods of time, the sensors were exposed to the calibration source radiating at a level of 250 watts $centimeter^{-2}$ for periods up to 10 minutes. The change in voltage output over this period was less than 0.3 percent, well below the guideline limit value of 2 percent at 200 watts $centimeter^{-2}$ for 3 minutes. The stability test was performed both with the gaseous nitrogen purge on and off. There was no measurable change between these two operating states.

The contract guidelines define the time constant as the time to reach 63.2 percent of the final output voltage when the sensor is subjected to a step change in radiant emittance from 0 to 50 watts $centimeter^{-2}$.

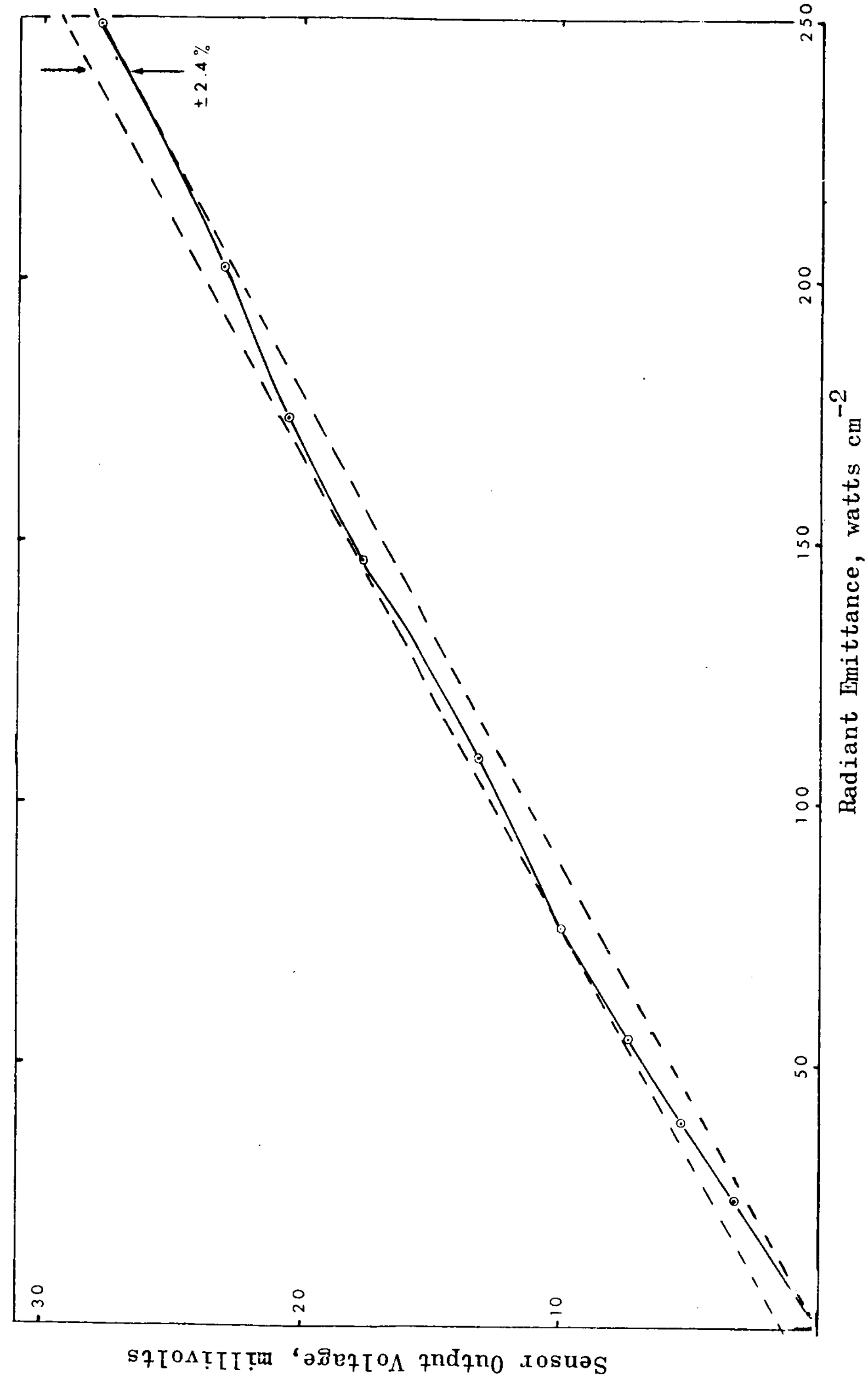

Figure 5. Calibration of Sensor No. 1

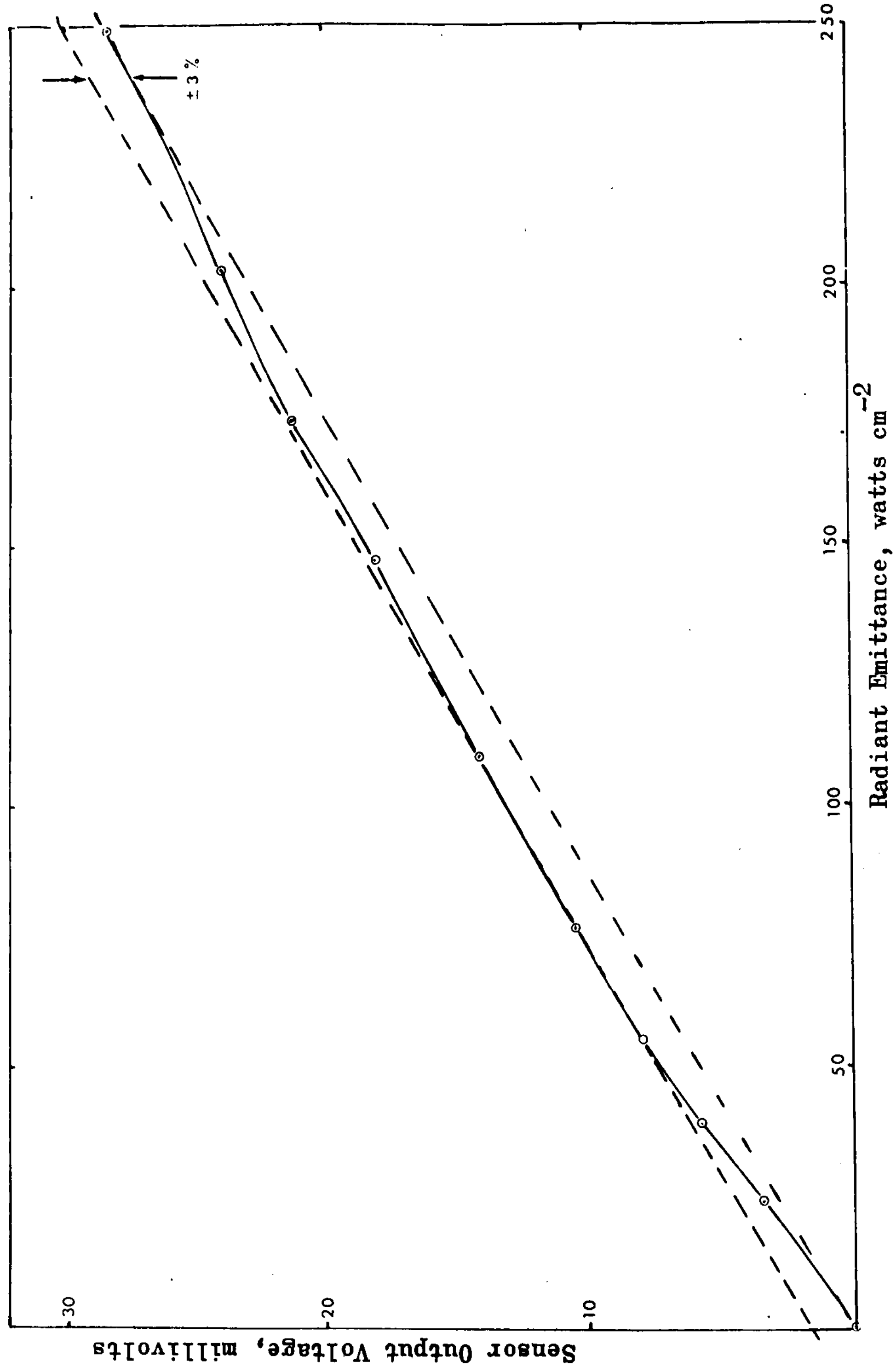

Figure 6. Calibration of Sensor No. 2

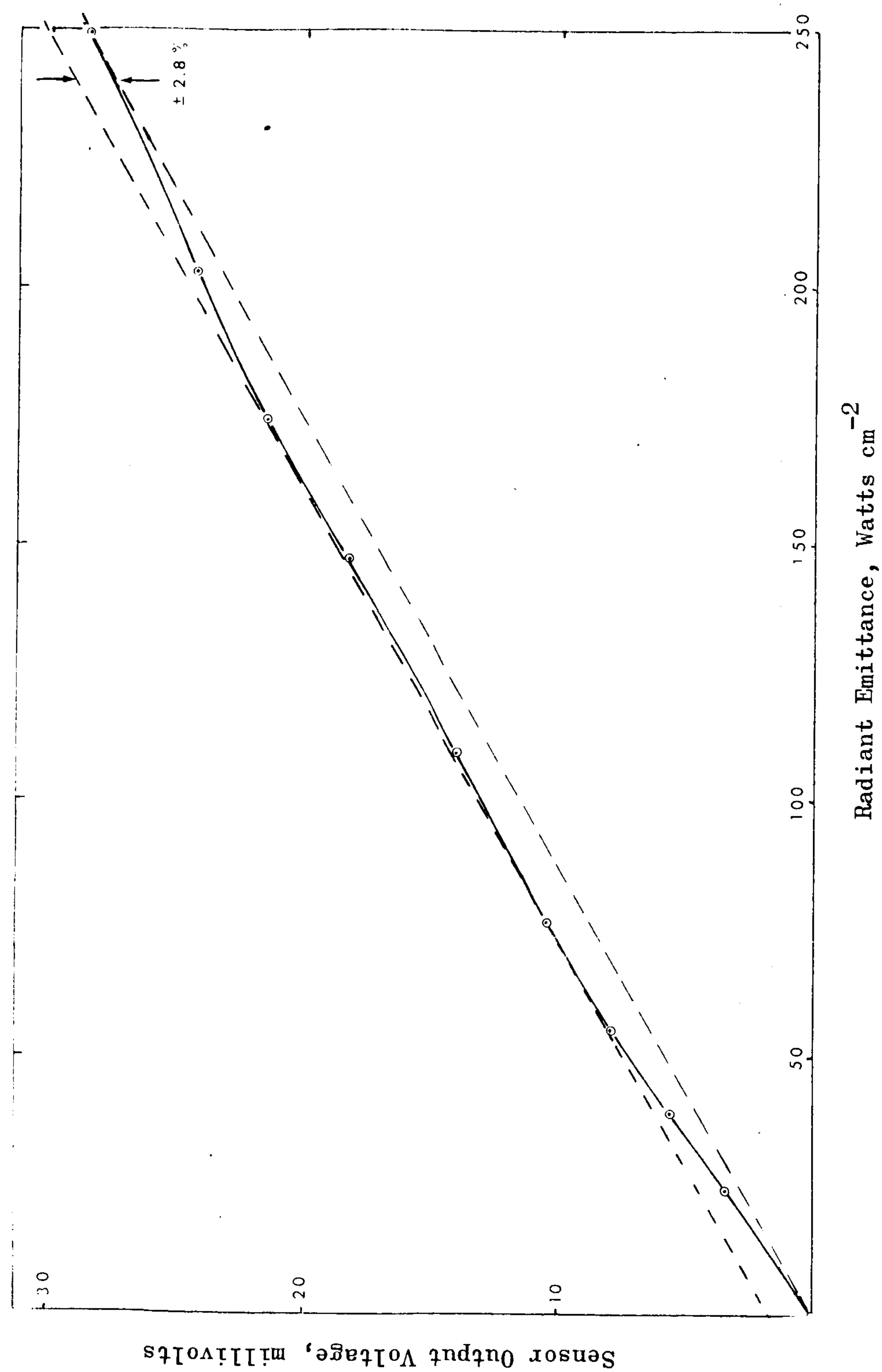

Figure 7. Calibration of Sensor No. 3

Measurements were made for step changes over a wide range of levels and the results are presented in Fig. 8, 9, and 10. For all levels of steps including 50 watts centimeter^{-2}, the time constant is less than the guideline maximum value of 200 milliseconds.

The measured angular field of view of the prototype sensor is shown in Fig. 11. It is given in terms of the relative responsivity of the sensor as a function of the angular deviation from the optical axis of a "point" source. The field of view is here defined as the "total field of view," and is discussed more fully later in this report. The measured value of 6.16 degrees lies between the guideline limit values of 6 and 8 degrees.

An acetylene torch was used as a soot generator in the test for anticontamination protection. Specifically, the test was that detailed on page 11 of NASA MSFC drawing number 50M60219. This involves directing the torch at the sensor viewing port from a distance of 2.5 inches at three different angles for a total of 3 minutes. Sensor purge flow for the tests was 3 standard cubic feet per minute at 750 psi. Responsivity measurements made immediately before and after such tests showed a decrease of less than 1 percent due to contaminants deposited on the sensor window.

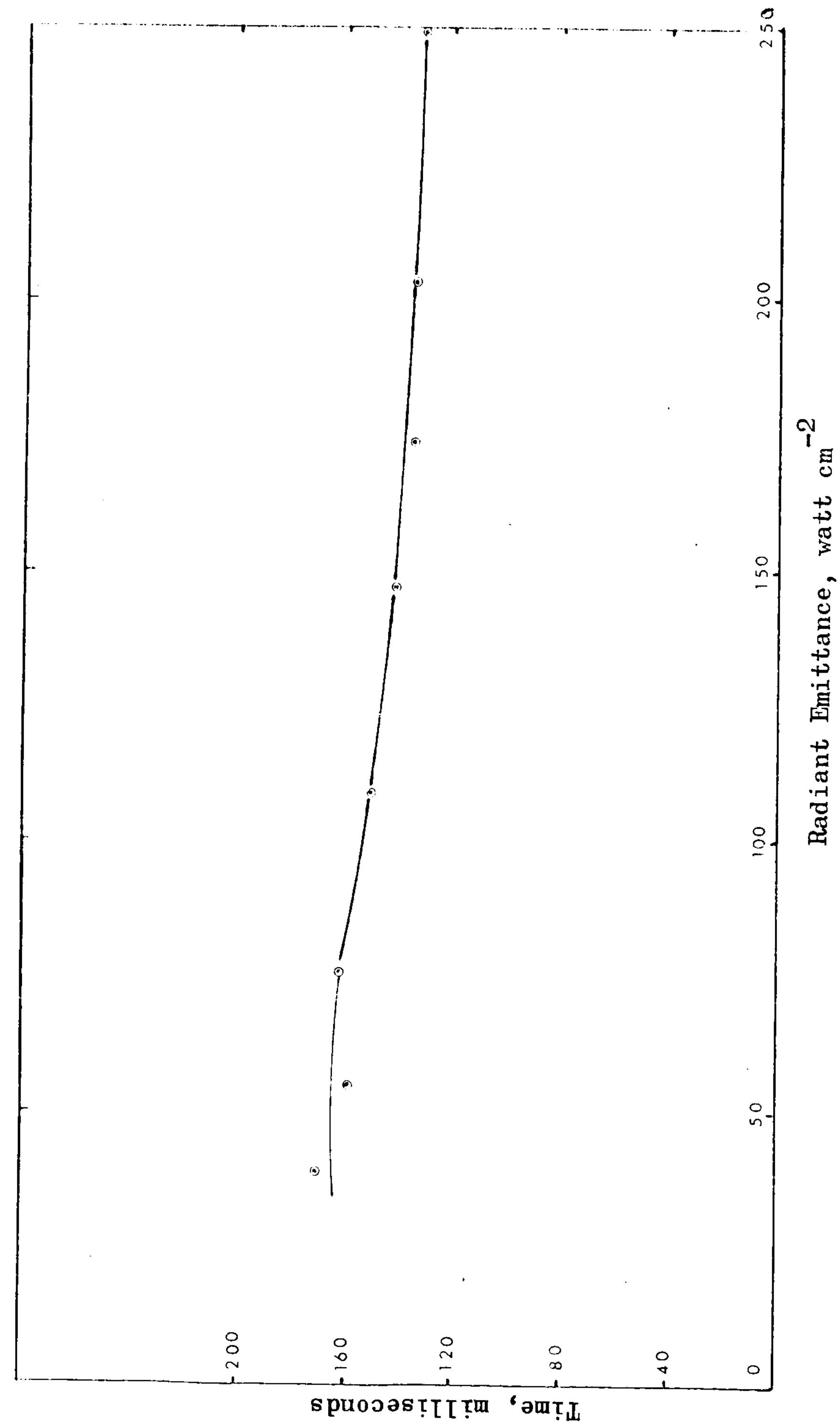

Figure 8. Time Constant of Sensor No. 1

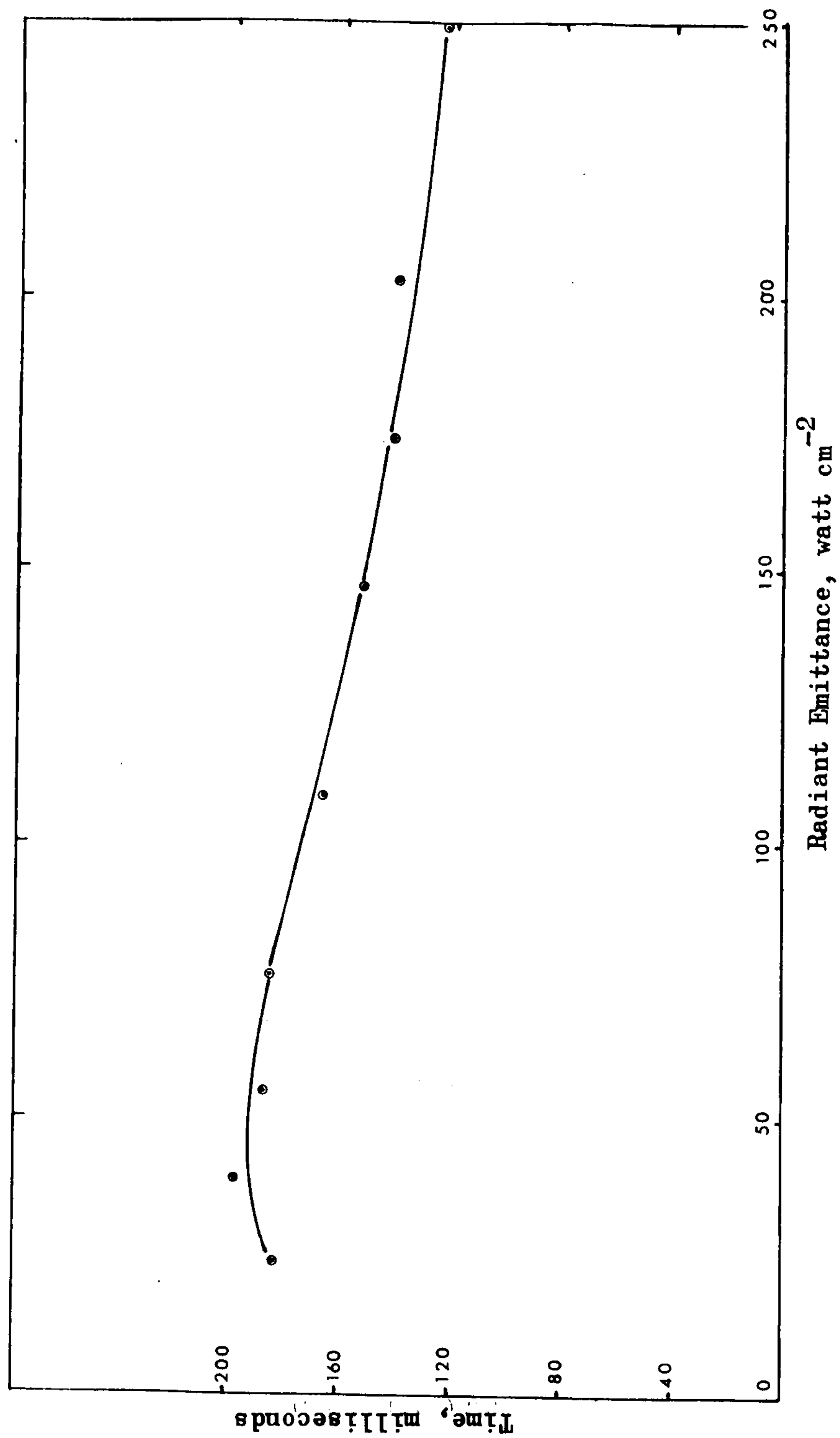

Figure 9. Time Constant of Sensor No. 2

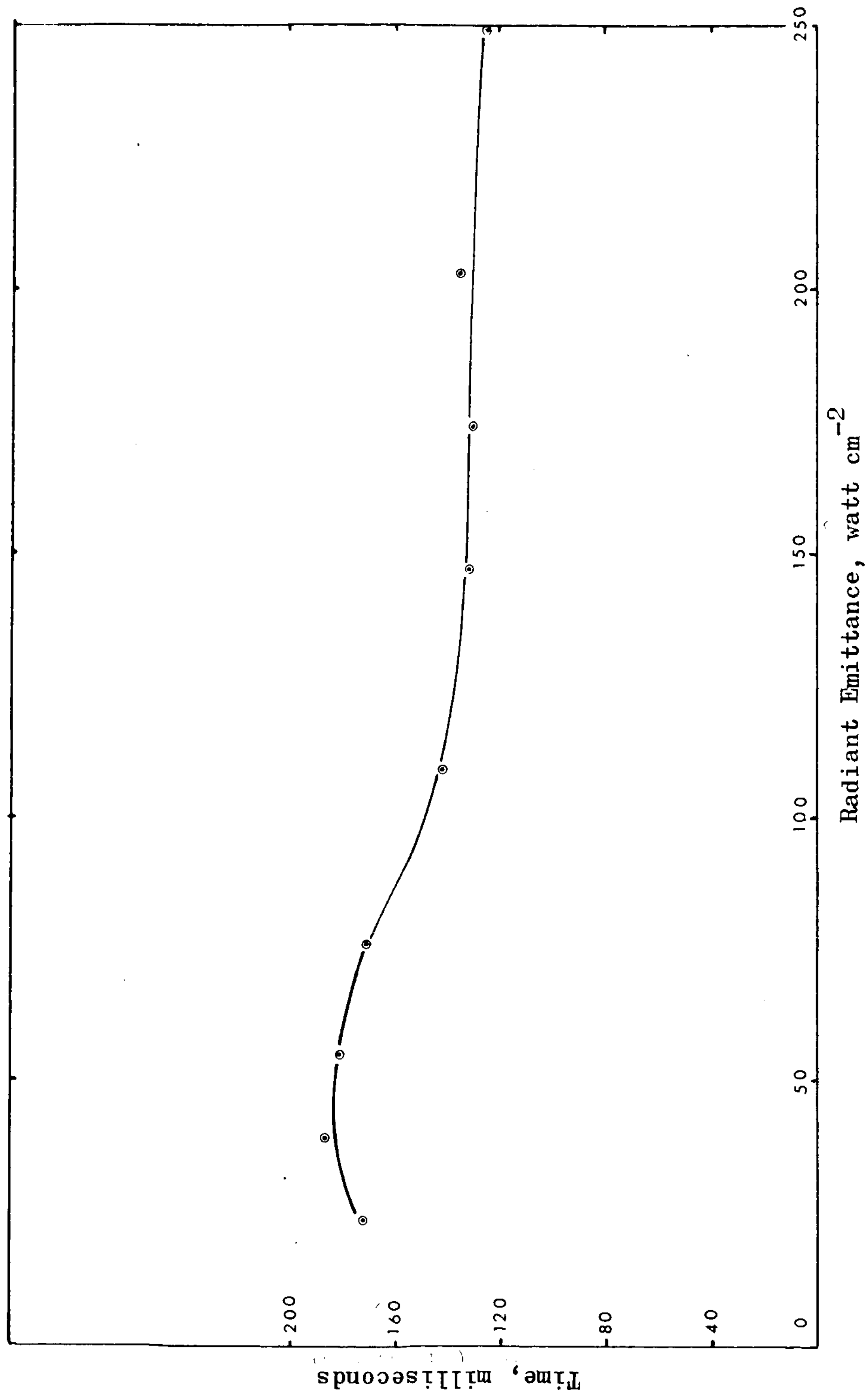

Figure 10. Time Constant of Sensor No. 3

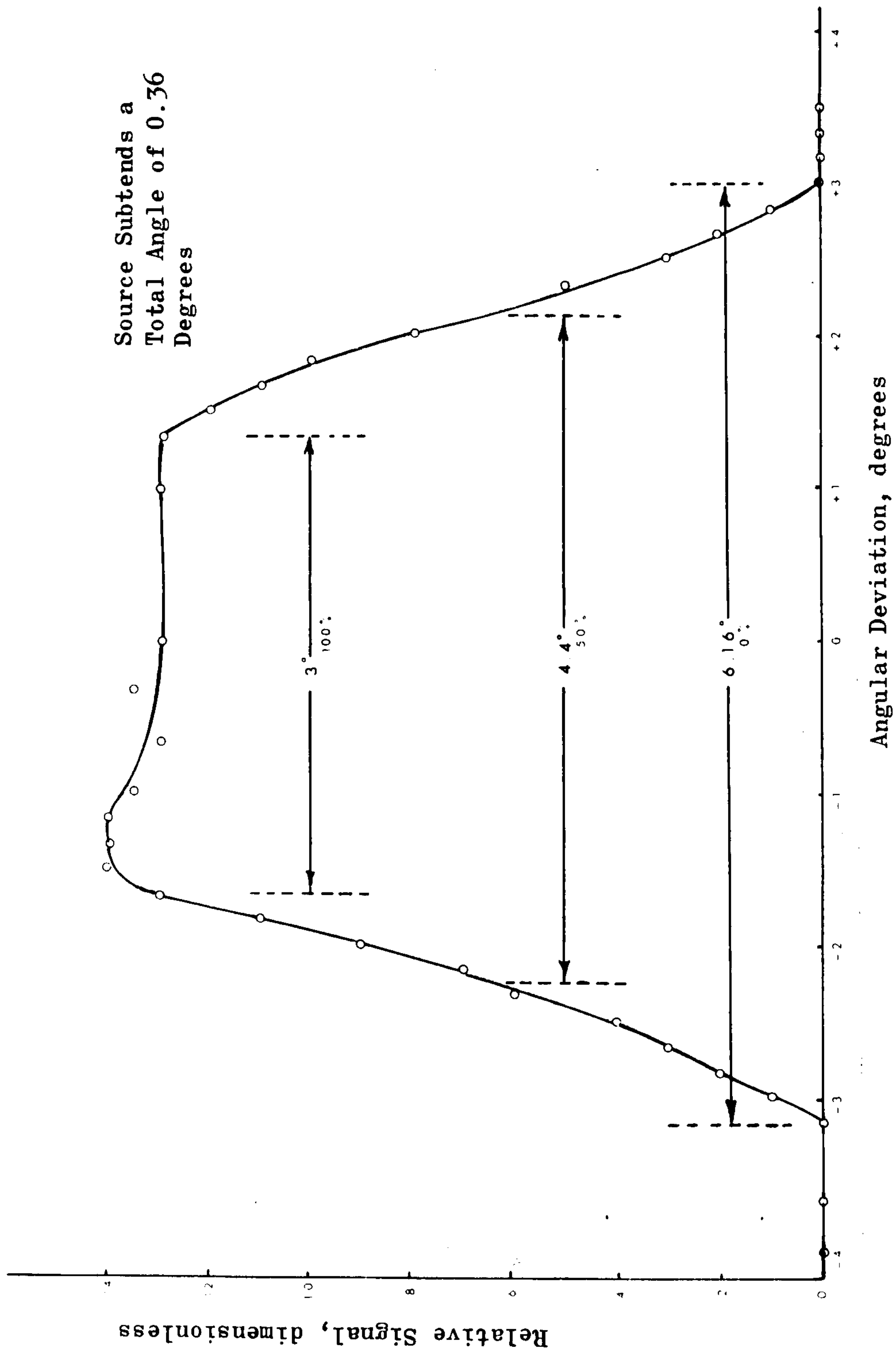

Figure 11. Angular Responsivity of Prototype Sensors

CONCLUSIONS

A rugged, compact, high radiant heat flux sensor has been developed and tested. Its measured performance characteristics are such that it meets or exceeds the operational requirements as set forth in the contract guidelines. Three of these prototype sensors have been delivered to NASA MSFC.

RECOMMENDATIONS

In the course of the research on and development of the prototype heat flux sensors, several areas of possible improvement became apparent. For reasons of time and money these areas could not be investigated more fully under the present contract. They are mentioned here as areas where further investigation might prove fruitful in leading to an optimal design of a high radiant heat flux sensor of the present type.

As in the design of most instruments there are tradeoffs which can be effected in the heat flux sensor. There is, for example, a tradeoff between responsivity and time constant, between responsivity and sensor size (and hence, weight), and between responsivity and field-of-view. Thus discussion of increase in responsivity could be read, decrease in weight or decrease in field-of-view. Although size and weight are not mentioned in the design guidelines, it is possible that minimization of these characteristics of the sensors may be of great importance in flight models.

DETECTOR

The foil used in the prototype sensor detectors is 10^{-4} inch thick constantan, the thinnest available at the time of purchase. Vendor foil rolling capabilities are constantly improving and it appears that thicknesses of 6×10^{-5} inches are feasible now. Use of the thinner foil may result in a 50 percent increase in responsivity or, alternatively, a decrease in sensor size.

To obtain even thinner foil electroetching proves useful. Preliminary investigations were conducted in this area with evidence that increases in responsivity could be obtained.

Further investigation of substitute materials for the Chromel P and constantan used in the present sensors may prove especially fruitful. A gold-nickel alloy, which demonstrated higher thermoelectric power than the above combination, was used in experimental detectors. At some thicknesses it provided a responsivity which was definitely higher than the comparable constantan. It should also be investigated in the very thin forms now available. Other materials may provide an even greater increase in responsivity.

OPTICAL SYSTEM

Coaxial optical system of the reflective and reflective-refractive types were analyzed to determine whether sensor size reduction over the present Z shaped optical configuration was possible. Due to difficulties in shielding the detector from the direct incidence of radiation from outside the field of view of the sensor, this approach did not appear promising. However, the desired size reduction might be possible using an all refractive system. Such a system was not used in the prototype sensors because of the difficulty in meeting the field-of-view requirement over the desired wide wavelength interval. However, it would be possible to maintain the field of view within the design guideline limits over that portion of the sprectrum in which the vast majority of the radiant energy is present. This slight relaxation of the field of view requirements could result in an appreciable size and weight reduction.

SENSOR HOUSING

The sensor housing might well be reduced in weight by careful attention to this factor. In particular, redesign of the gaseous nitrogen purge flow system through the housing may effect sizeable weight savings.

THERMAL PROTECTION

Tests conducted in the most strenuous environment to which the sensor will be exposed may reveal that the thickness of the thermal protective material could be safely reduced with consequent weight savings. In addition, where use is planned for less than the extreme thermal environment, the thermal protection may be tailored specifically to that situation, again with resultant weight savings for particular applications.

HEAT FLUX SENSORS - RESEARCH AND DEVELOPMENT

As pointed out earlier, the high heat flux sensors developed under this contract have unique requirements. Such considerations as severe thermal environments, precisely limited field of view, very high source energy levels and high sensor responsivity, to name several, place stringent requirements on a successful design. Therefore, research and development in a number of areas was a necessary preliminary to sensor design.

This section of the report contains a discussion of those investigations and their relationship to sensor design. An attempt is made to discuss all such areas of investigation, whether or not the results were incorporated in the design of the prototype high heat flux sensors. The discussion is organized generally according to the functional components of the sensor.

GENERAL DISCUSSION

In addition to meeting specific operating requirements, it is necessary that the sensors be calibrated. Clearly such calibration comprises an essential part of the development and evaluation of the sensors; as such, it is important that the calibration extend over the entire sensor operating range from 0 to 250 watts cm^{-2}. Hence, the availability of a source capable of very high radiant intensities was essential to the successful conduction of the program. A Rocketdyne developed 1/4-inch diameter, high temperature blackbody (Ref. 1) was intended for use in this calibration.

For a valid calibration, two criteria must be satisfied, namely: (1) the sensor entrance pupil must lie within the field of view of the blackbody to assure a uniformly radiant calibration source for all points in the entrance pupil and (2) the blackbody aperture must fill the field-of-view of the sensor. Since the aforementioned Rocketdyne blackbody has a field-of-view of 6.5 degrees, essentially the same as that of the sensor, it is apparent that the entrace pupil can be no larger than the blackbody aperture. In fact, a diameter of 1/4 inch was chosen for the preliminary optical system.

While an optical system of this size leads to a very compact sensor, it places extremely high responsivity requirements on the detector. It was originally hoped that it would be possible to use very high thermoelectric power materials for the detector to achieve such detector responsivities; however, as the investigation of available thermoelectric materials progressed, it became apparent that fabrication difficulties with the materials in the form needed for the detector were too great to allow such consideration within the scope of the program. Therefore, it was decided to remain with more or less conventional, and readily available, materials for the detector. Hence, it became necessary to increase the "gain" of the optical system to achieve the required overall responsivity of the sensor. A diameter of 3/4 inch was selected for the collecting optics as sufficient to meet this need.

This increase in diameter presented the need for a correspondingly larger blackbody. To fulfill this need, a Rocketdyne 2-inch, 100 watt cm^{-2} source (Ref. 2) was successfully modified to incorporate a 1-inch diameter aperture and to operate at radiant emittance levels to 250 watt cm^{-2}.

DETECTOR DEVELOPMENT

The detector proposed and used for the heat flux sensors is the foil type originally described by Gardon (Ref. 3). Detectors of this type are well suited for use in the high heat flux sensor for a number of reasons: their spectral response is broad since they respond to the total energy absorbed; they are self generating transducers and, hence, independent of power supplies; their responsivity is nearly independent of the ambient temperature since they are differential thermocouple devices; their responsivity and time constant can be tailored to fit specified values; and they are inherently rugged mechanically.

Since the foil detectors are thermocouple devices their responsivity is inherently low. Several possible methods of increasing this parameter were investigated.

Responsivity and Time Constant

Seebeck Coefficient. A literature search for materials with high Seebeck coefficient was conducted. The vast majority of references examined were in connection with thermoelectric power generation where problems of device fabrication are completely different than those of the heat flux sensor detectors. However, due to the intensive investigations in this area a number of materials which have very high Seebeck coefficients are known. For example, values as high as 400 microvolts degree^{-1} have been measured for such materials as tellurium, lead telluide, bismuth telluride, doped germanium and silicon. However, these semiconductor materials appear to be universally brittle and extremely difficult to fabricate in such forms as foil and small diameter wire such as are needed for the foil detector. Such fabrication techniques as powder metallurgy, which is commonly used in thermoelectric power generation devices, are simply not applicable. Consequently, attention was turned to those metals which were more likely to be available in the form needed.

The original materials used by Gardon were copper and constantan. As a substitute for copper, it was decided to use Chromel P which was readily available in the form needed and had a Seebeck coefficient of 25 microvolts $degree^{-1}$ as compared to only 2 or 3 for copper.

Bismuth is a good thermoelectric material and suggests itself as a substitute for constantan. However, the temperatures the foil must reach to generate the required output signal of 25 millivolts would be very close to the melting point of the bismuth, particularly if the temperature of the detector body should rise appreciably. In addition, a 91% gold - 9% nickel alloy was obtained in the form of foil and preliminary tests run with detectors fabricated using it. Those tests performed using it indicated a promise of performance superior to that of the constantan eventually used in the prototype sensors. Unfortunately, time and funds did not permit a complete evaluation of the material. Hence, constantan was selected as the detector foil material and was procured in the thinnest foil attainable.

Foil Thickness. As an example of the rapidity with which progress is being made in the rolling of thin foil, two and one half years ago when constantan foil for a similar detector was sought (Ref. 4), the thinnest foil available was 2×10^{-4} inches. At the beginning of the program reported here, the presently used 1×10^{-4} inch foil was the thinnest, while near the end of the program, foil as thin as 0.7×10^{-4} inches supposedly became available. Again insufficient time remained to procure such foil for evaluation.

In an effort to further reduce the thickness of the foil obtained commercially, an attempt to roll the material using a small hand rolling mill was made. No more than a 5 percent reduction in thickness was obtained using the method on 1 x 10^{-4} inch thick constantan; hence, further rolling efforts were abandoned.

An investigation of the possibility of using electrical etching of the foil was also conducted. Here experiments were conducted largely on 1 x 10^{-3} inch thick gold-nickel alloy in an effort to obtain thicknesses comparable to that of the constantan. In general, it was found that substantial thickness reductions could be obtained. However, it proved very difficult to maintain a uniform foil thickness. In addition, the process of etching appeared to affect the thermoelectric properties of the foil. It is felt, however, that a more comprehensive investigation of this technique for reducing foil thickness is warranted, particularly when further reduction in thickness by rolling becomes increasingly difficult.

Foil Irradiation. A previous investigation of the foil detector (Ref. 4) demonstrated that different shapes of irradiated detector foils often yielded superior responsivity and time constant values. It was decided in this program to use a circularly symmetric configuration attached completely around its periphery. This was for reasons of ruggedness, fabricability and reproducibility. However, the idea of improvement via different configurations was pursued further by investigating the effect of partial irradiation of a circular foil. In particular, an analytical solution to the problem of the irradiation of a centrally located circular area with diameter less than that of the total foil was found. It was found that improvement could be made in both responsivity and time constant, particularly the latter. Therefore, this feature was incorporated in the prototype heat flux sensors where the irradiated spot diameter is 30 percent that of the detector foil.

Foil Absorptive Coating. The constantan foil in its natural state has a low emissivity and consequently absorbs incident radiation poorly. Hence, an investigation was undertaken to evaluate various foil blacking materials. The evaluation consisted of coating the same detector, or on occasions similar detectors, successively with different materials and performing a sequence of calibrations under otherwise identical conditions. The coatings evaluated were: three different commercial optical black paints, soot generated in two ways, and a colloidal graphite suspension.

In general, the soot was slightly superior to the graphite suspension, while the paints exhibited excessively long time constants. However, the soot did not adhere well to the foil. It was readily displaced by gas flows of moderate velocity and by mechanical shock. Therefore, the graphite suspension was used for the prototype sensors.

Responsivity increases of 250 percent were typical of those achieved by the addition of detector coatings while time constants increased less than 10 percent.

Foil Convective Losses. The equations describing foil detector behavior are usually written based on the assumption that heat loss from the irradiated foil by other than conductivity through the foil to the peripheral heat sink is negligible. In practice, radiative and convective losses occur. Since the maximum foil temperature is several hundred degrees centrigrade, radiation losses are expected to be small; furthermore, there is little that can be done to reduce these losses.

Convection losses can be controlled, however, and the possibility of improving detector performance by this method was investigated.

Two techniques were used to reduce convective losses. These were: the use of a partial vacuum and the use of low thermal conductivity gases such as argon and xenon.

It was found that responsivity increases of more than 30 percent could be obtained with the vacuum and argon atmosphere and up to 70 percent with the xenon atmosphere. However, in all cases this apparent gain was almost completely offset by a corresponding increase in time constant. Because of the minimal net improvement achieved by altering the gaseous environment of the foil, and the concomitant difficulties in preserving such altered environment for extended periods of time, air at 1 atmosphere is used in the prototype radiometers.

If the calibration of such a sensor is to remain constant, it is clear that the gas pressure at the detector must remain approximately constant even though external conditions change drastically. Therefore, provision is made for the maintenance of the pressure by sealing the detector in the sensor housing. Minor pressure variations such as would occur with the temperature changes the sensor may encounter were found to produce no effect on responsivity or time constant.

Fabrication

The principal problem encountered in the fabrication of the detectors lay in the attachment of the thin foil to the relatively massive detector body. A strong, continuous welded attachment was desirable for structural, thermal and electrical reasons. The following welding techniques were explored as to applicability: electron beam, laser, ultrasonic, and electrical resistance. According to the welding experts consulted all of the first three techniques looked promising, but all required extensive development and testing for this particular application

Experimental evaluation of electrical resistance welding was conducted using a capacitor discharge welder. Successful attachment was achieved by using a series of overlapping spot welds generated under the following conditions: tungsten electrodes, electrode force of 3 ounces, and discharge energy of 8 watt seconds.

OPTICAL SYSTEM

There are two principal functions of the optical system of the high heat flux sensor. These are to collect sufficient radiant energy so that with limited detector responsivity, the total sensor responsivity requirements can be met. A second important function is to precisely define the field-of-view of the sensor.

In this program, field-of-view has been taken to mean the "total" field-of-view (Ref. 5), that is, that field outside of which the sensor is insensitive to radiation. The use of this definition follows naturally from the emphasis placed on the precise knowledge of the area from which the measured radiation originates. Were the more usual "mean" field-of-view used, there would be, in the case of an extended radiation source, an ill-defined quantity of radiant energy entering from outside the field of view. This is clearly an undesirable situation.

Because of the use of this definition, the field-of-view is not measured from the center of the objective optical element. Rather, in the case of the prototype sensors, it is measured from a point on the optical axis 1.82 inches in front of the end of the window protective shield. This difference is of importance only in the case of sources located very close to the sensor. These would, in general, include calibration sources.

An all refractive optical system was first considered for the heat flux sensor. The change of refractive index with wavelength for the objective lens causes corresponding changes in the sensor field-of-view. Because of the wide wavelength interval over which the sensor is to operate this problem is severe. Efforts to design a two-element lens of sapphire and magnesium oxide sufficiently, color corrected over the 0.4 to 6.0 micron wavelength interval to maintain the field-of-view within the guideline limits of 6 to 8 degrees were unsuccessful. Therefore, a combination reflective-refractive system was incorporated in the prototype sensors.

The objective mirror diameter of 0.75 inches was determined as the size necessary to furnish sufficient detector irradiance to meet sensor responsivity requirements with the Chromel-constantan detector.

The sensor optical system consists, then, of an objective mirror and a field lens. To reduce the overall size of the sensor, the optical system is folded to form a Z shaped configuration.

A rather thorough examination of the efficiency of a coaxial reflective-refractive optical system was conducted. It was hoped to appreciably reduce the overall size of the sensor in this manner. Unfortunately, the problem of shielding the detector from direct radiation from outside the sensor field-of-view while maintaining a compact configuration proved intractable in the time allotted to the investigation.

SENSOR TESTS

Calibration

The importance of heat flux sensor calibration has been stressed previously. In order to satisfy the calibration requirements for this program, the Rocketdyne 2-inch blackbody was modified for higher temperature operation. This was accomplished by reducing the size of the radiating element, incorporating two more radiation shields and reducing the aperture to 1 inch in diameter.

These modifications enabled the attainment of source radiant emittance levels in excess of 250 watts cm^{-2} with source field-of-view and size sufficient for the calibration of the prototype radiometer.

The calibrations are performed as follows: the heat flux sensors are positioned so that the blackbody aperture fills the field-of-view of the radiometer with an area of uniform radiance. A shutter is interposed between source and sensor. The source is then brought to a specific radiant emittance level, the shutter opened and the sensor output recorded as a function of time. Thus, the sensor time constant as well as the responsivity may be determined.

The radiant emittance of the blackbody is obtained by measuring its brightness temperature using an optical pyrometer which, in turn, has been calibrated using an NBS certified tungsten strip lamp. The true temperature of the blackbody is calculated using Wien's law and the emissivity of the blackbody. The latter is estimated using an approach basically that of DeVos (Ref. 6, and 7). The emissivity and true temperature are then inserted into the Stefan-Boltzman equation to determine radiant emittance.

Field-of-View Tests

The field-of-view of the heat flux sensor was measured by using a radiation source whose area subtended an angle which was small with respect to the sensor field-of-view. This source was then moved across the sensor field-of-view and the relative response of the sensor measured as a function of angular deviation from the optical axis of the sensor. As mentioned previously, the test results indicate a total field-of-view within the range allowed by the guidlines.

SENSOR LINEARIZATION

The calibration of the prototype sensors revealed a small but distinct nonlinearity (Fig. 5, 6, and 7). A brief investigation of the feasibility of linearizing this output by the use of nonlinear resistors was undertaken. Several commercial, voltage variable resistors were obtained and their characteristics examined at voltage levels comparable to those of the sensor output signal, i.e., 25 millivolts. In this very low voltage region, the variable resistors were found to be constant and, hence, of no use in removing sensor nonlinearity.

ANTI-CONTAMINATION

Incident radiation is admitted to the heat flux sensor through a sapphire window. Provision is made for protection of the window from particulate contaminants which may be present in the vicinity of rocket engine exhaust plumes. Protection is provided by a cylindrical shield which projects 2 inches beyond the window and through which a gaseous nitrogen purge is allowed to exhaust.

The limitation of gaseous nitrogen flowrate to 3 standard cubic feet per minute caused some difficulty in the design of the protection system. The initial purge systems had a ring of high velocity nitrogen jets exhausting to form a cone in front of the sapphire window. This design proved ineffective even at flowrates far in excess of the allowed value.

The second approach used a ring of nitrogen outlets arranged to provide a sheet of nitrogen flow directed toward the optical axis in a plane parallel to the window. This arrangement was somewhat more effective but still inadequate. The next step was to decrease the linear velocity of the nitrogen jets by providing more of them and to add increasing lengths of cylindrical shielding in front of the window until satisfactory protection was effected.

THERMAL PROTECTION

It is required that thermal protection be provided for the uncooled* heat flux sensor for durations of 180 seconds in an environment with heat transfer rates to 100 watts cm^{-2}. Because of the finite duration involved, an ablative material suggests itself as the most efficient thermal protection. Consultation with experts in the field of ablative materials resulted in the suggested use of a silica filled silicone rubber, 1/4-inch thick. This material will survive the high heat transfer rates for the specified duration while adhering tenaciously to the sensor housing in the face of shear stresses exerted by high velocity gases. After use in a strenous environment of this type, the charred insulting material may be removed and another layer deposited over the uncharred insulation remaining.

*Although some cooling is provided by the nitrogen purge flow, it is negligible compared to the heat input at the above transfer rates.

ACKNOWLEDGEMENTS

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