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Heat Flux Instrumentation for Hyflite Thermal Protection System

Grant No. NAG3-1643

Final Report

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Final Report

December 30, 1994

Virginia Tech Contract CF-4648-426381

Heat Flux Instrumentation for HYFLITE Thermal Protection System

for

NASA Lewis Research Center
Cleveland, Ohio

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SUMMARY

Tasks performed in this project were defined in a September 9, 1994 meeting of representatives of Vatell, NASA Lewis and Virginia Tech. The overall objective agreed upon in the meeting was "to demonstrate the viability of thin film techniques for heat flux and temperature sensing in HYSTEP thermal protection systems". We decided to attempt a combination of NASA's and Vatell's best heat flux sensor technology in a sensor which would be tested in the Vortek facility at Lewis early in 1995. The NASA concept for thermocouple measurement of surface temperature was adopted, and Vatell methods for fabrication of sensors on small diameter substrates of aluminum nitride were used to produce a sensor. This sensor was then encapsulated in a NARloy-Z housing. Various improvements to the Vatell substrate design were explored without success. The basic NASA and Vatell sensor layouts were analyzed by finite element modeling, in an attempt to better understand the effects of material properties, dimensions and thermal differential element location on sensor symmetry, bandwidth and sensitivity. This analysis showed that, as long as the thermal resistivity of the thermal differential element material is much larger (10X) than that of the substrate material, the simplest arrangement of layers is best. During calibration of the sensor produced in this project, undesirable side-effects of combining the heat flux and temperature sensor return leads were observed. The sensor did not cleanly separate the heat flux and temperature signals, as sensors with four leads have consistently done before.

Tasks 7 and 8 discussed in the meeting will be performed with a continuation of funding in 1995. The following is a discussion of each of the tasks performed as outlined in the statement of work dated September 26, 1994. Task 1A was added to cover further investigation into the NASA sensor concept.

TASK 1

NASA Lewis has carried on development work with thin film heat flux and temperature sensors for several years. All the designs they have developed use a thin film thermocouple for surface temperature measurement, instead of the resistance temperature sensor used by Vatell. This thermocouple is formed between one of the two end terminals of the heat flux sensor and a third terminal, which is made of a material with a different thermoelectric potential. Thus the NASA sensor measures heat flux and temperature with only three leads, instead of the four used by Vatell sensors.

Vatell had explored using thermocouples for surface temperature measurement, but abandoned them in favor of resistance temperature sensors (RTS) because the temperature resolution obtained with the latter was consistently better. However, it is clear that a flight test sensor should have the smallest number of leads possible, so we agreed for this project that a surface thermocouple would be incorporated if possible. On a flight vehicle, a 25% reduction in sensor connections could have a measurable impact on the total weight of instrumentation.

A surface thermocouple was added to the Heat Flux Microsensor design by editing the stencil masks used in the sensor fabrication process. The surface thermocouple is produced by overlapping a new platinum-rhodium trace on one of the platinum extensions from the heat flux sensor. The two patterns are shown in Figure 1. The thermocouple voltage is measured between the lead extending from the new trace and the heat flux sensor lead it overlaps.

In replacing the RTS with a thermocouple it is important to understand the overall effects on instrumentation connected to the sensor, as well as on its performance. There is essentially no reduction in the requirement for reference circuits. While the RTS must have a current source, the thermocouple must have a source of reference potential. These circuits are approximately equivalent in complexity. There is no reduction in amplifier or data acquisition requirements.

However, there is a unique problem in thin film thermocouple sensors because the thermoelectric differences between bulk materials and thin films must be accounted for[1]. Figure 2 shows the <u>entire</u> thermocouple circuit. There are two unwanted thermocouple junctions at the points where wires are connected to the thin films, one exhibiting the thermoelectric potential difference between bulk platinum and thin film platinum and the other exhibiting the potential difference between bulk platinum-rhodium and thin film platinum-rhodium. Even if these thermocouples are at the same temperature, their potentials may be different, no matter what extension lead material is used. To accurately account for the potential of these thermocouples, the temperature at the connection point would have to be known, as well as the thermoelectric potentials for each material over the operating temperature range. A method for determining the thermoelectric characteristics of these materials is discussed later, under Task 3.

In addition to the problem of unwanted thermocouple potentials, there is a possibility of interference between the signals of the thermocouple and the heat flux sensor on the common lead. Test results with the sensor fabricated on this project have verified this.

The problem of unwanted thermocouple potentials can be solved by making both leads of a sensor out of the same material and positioning the leads close together so they will be at the same temperature. In the Vatell design, this is done with both the heat flux sensor and the RTS. All four leads (thin film and solid) are platinum. It might be possible to combine one lead of the Vatell RTS with one of of the thermocouple array to produce the temperature difference. During this study we realized that two thermal differential layers might not actually be required. If sensors could be made with only a single thermal differential layer, one step of the fabrication process could be dropped, and a potential source of adhesion problems eliminated.

The numerical model of the Heat Flux Microsensor is a two dimensional cross-section of the sensor which includes one thermocouple pair placed on a portion of a substrate as shown in Figures 4 and 5. The variations of the model used to study the effect of thermal differential layer arrangement on operation are shown as Models 1 through 6 in these figures. A uniform heat flux boundary condition q" at the top surface is indicated in all cases. All other surfaces are perfectly insulated except in models 5 and 6, where a convective boundary condition is indicated on the top surface.

To evaluate the performance of each arrangement, the temperature difference ΔT between T_1 and T_2, as indicated in the figures, was monitored. The temperature difference is generated by the incident heat flux q", set at 1 W/cm^2, in all cases.

Model 1 was used to determine the effect of substrate thermal conductivity, κ_{sub}. As long as κ_{sub} is at least 10 times higher than the insulating layer's thermal conductivity, κ_{ins}, there is very little or no effect. The ΔT generated in all these cases was .02 °C. When κ_{sub} is less than 10 times κ_{ins} the ΔT generated is less. As κ_{sub} approaches κ_{ins} the temperature difference goes to zero.

With Model 2 we examined the effect of the thermal differential layer over T_1. There was no effect on the steady state ΔT generated, only a very slight decrease ($<5\mu$sec) in time response compared with Model 1.

The arrangement of Model 3 generated no steady state ΔT. A very small ΔT was generated ($<.007$ °C max.) for short times, however this ΔT approached zero after .01 seconds.

The effect of lateral thermal transport on ΔT was evaluated with Model 4. This effect was found to be less than 0.1%.

Models 5 and 6 were constructed to evaluate the symmetry of the sensor, i.e. whether the same magnitude of ΔT is generated with heat flowing into or out of the sensor surface. The result was that both arrangements generate the same ΔT, opposite in sign, as models 1 and 2 respectively.

TASK 2

During the meeting of September 9 it was decided that the sensors fabricated for this sub-contract would be installed in housings of NARloy-Z. NARloy-Z is the material which has been adopted by NASA for cooled thermal protection panels. It is believed to be best for the extreme temperature differences of a liquid hydrogen cooled panel in hypersonic flight. We requested a sample of NARloy-Z at the beginning of this project, but NASA had great difficulty in obtaining it. A rough cut portion of a forged plate 3/4" thick was finally supplied by Rockwell International on December 6.

Vatell and NASA subsequently agreed on the design for a sensor housing which could be installed in a counter-sunk hole in the panel. The housing has a tapered head as shown in the upper view of Figure 6, and is threaded for application of a nut to secure it and produce good thermal contact. The inside contour of the housing is the same as that of Vatell's HFM-6 series housings and can therefore accommodate a standard substrate. The inside of the housing behind the ceramic substrate is threaded to provide a mechanical grip for the potting material. The lower part of Figure 6 is a sectional view of the sensor and potting material installed in the housing, with the leads exiting the back. This view also shows that the potting material fills the void between the flat on the side of the substrate and the inside diameter of the housing.

TASK 3

We investigated the use of E-type thermocouples as a replacement for S-type thermocouples, to increase voltage output of the heat flux sensor. This bulk thermocouple produces 58.5 μV/°C, as opposed to 6 μV/°C for S-type. The E-type thermocouple is a combination of two alloys; nickel-chromium (Ni / 10%Cr) and constantan (Cu / 45%Ni). Since sputtering is a physical deposition process, the thin films it produces may not have the same composition as that of the alloy target or source. The yield rates of each component metal can be used to estimate the required composition of a target for producing a desired thin film alloy. The yield rate is the number of atoms of a particular material that are ejected from a surface per incident ion. However, other poorly understood surface interactions contribute to the yield of particular materials. A slight change in alloy content can have a profound effect on the thermoelectric potential of a film. In addition, as discussed earlier, the bulk thermoelectric properties of an alloy are not likely to be the same as the thin film properties.

of Thin-film Temperature and Heat Flux Sensors for Aerospace and Hypersonic Propulsion Systems."

TASK 4

If aluminum nitride sensor substrates similar to the current Vatell design are directly inserted into thermal protection tiles, it will be necessary to fill the space between the flat side of the substrate and the cylindrical hole in the tile. This may be difficult to do after the sensor is installed. During the September 9 meeting we recognized this potential problem and proposed to look into methods for restoring the cylindrical shape of the substrate after the sensor is completed.

We investigated seven high temperature ceramic adhesives for forming a cylindrical filler over the flat side of the substrate. None of them had enough adhesion to the aluminum nitride plug to allow finish machining to a final shape after cure. We thought that it might be possible to mold a ceramic adhesive to the final shape, and attempted this using an HFM-6 housing coated with release agent as the mold. The result was that the ceramic adhered to the housing, despite the release agent, and not to the substrate. For this to work, a special adhesive will probably have to be formulated for the aluminum nitride substrate.

Another possibility for instrumentation of the thermal protection tile systems would be to make a plug of the tile material to serve as a housing for the sensor. The plug would then be inserted in the tile, possibly after the tile was mounted on the vehicle. If this can be done, filling of the void over the substrate flat could be part of the procedure for cementing the substrate in the plug.

TASK 5

The NARloy-Z material was received so late in the contract that we did not have time to thoroughly investigate depositing insulation materials on its surface. There has been an ongoing effort at Vatell to develop these types of coatings for a variety of substrate material applications. The method which has been successful in the past has been to plasma coat the metal surfaces with layers of aluminum oxide. This method is plagued by adhesion problems. It would be much more advantageous to deposit thin film insulating layers directly on the metal. Vatell has succeeded in sputtering 5-6 micron layers of aluminum oxide on highly polished metal surfaces. The adhesion of these layers has been quite good, but the electrical isolation from the base metal has not been consistent. Vatell is continuing to work on improving this method as well as to investigate alternative methods such as e-beam and laser deposition and thermally growing oxide layers from bond coatings. This method is used in the gas turbine industry. New equipment will probably be required, depending on the process used and the size of the panels to be insulated.

TASK 6

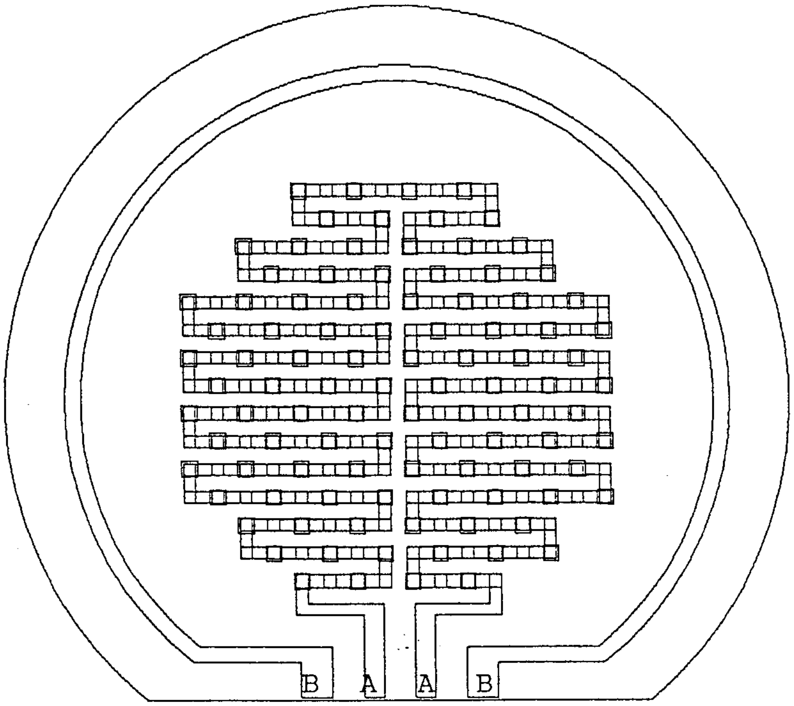
A sensor based on the Vatell HFM-6, and incorporating the NASA Lewis thermocouple concept in place of an RTS has been assembled and calibrated. During calibration we experienced some difficulties with this sensor design. The output of the heat flux sensor depended on whether the thermocouple lead was floating, grounded or connected to a heat flux lead. The signals produced in these three cases are shown in Figure 8. Also, the signal from the thermocouple is affected by the connection of the other lead of the heat flux sensor. Signals for the three cases are shown in Figure 9. The lowest noise signal was obtained with the second heat flux lead floated at the instrument plug. Even this signal does not appear correct, however. There appears to be cross-talk between the signals, perhaps attributable to the shared lead. The thermocouple signals should behave like the RTS signals of a similar sensor, as shown in Figure 10, but they do not. The signals shown in Figure 9 do not indicate surface temperature alone.

We performed a radiation calibration of the heat flux sensor using a quartz spot heater, with the thermocouple shorted to the heat flux lead. The magnitude of the heat flux produced by the spot heater was measured using a commercial Gardon gage calibrated at the Arnold Engineering Development Center. The average sensitivity of the sensor over the calibrated heat flux range of 9.26 - 43.98 W/cm^2 was 7.149 μV per W/cm^2 with a standard deviation of 20%. We did not measure the temperature dependence of the sensor sensitivity because the surface temperature measurement could not be relied upon. An Information Sheet and a Handling Sheet which contain additional information about the sensor are included at the end of this report.

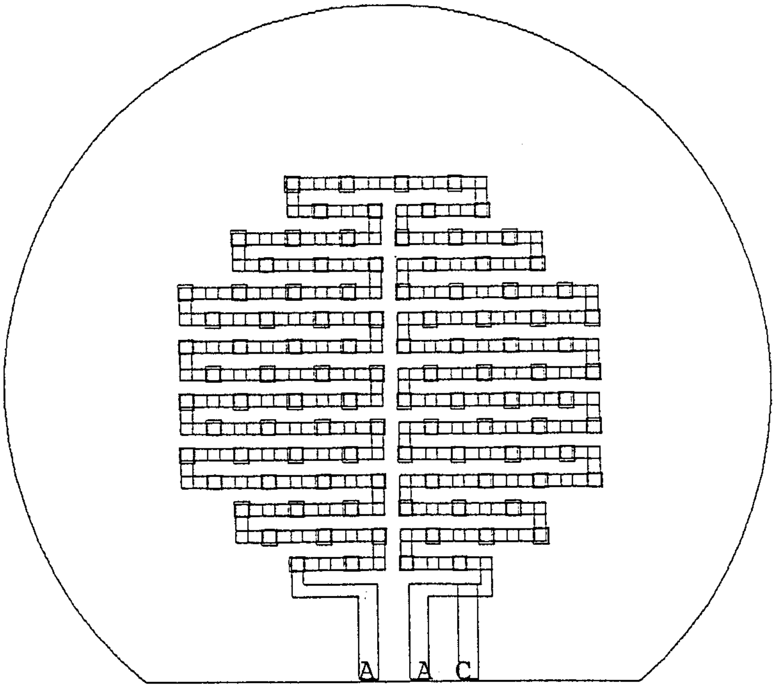
REFERENCES

1. "Transparent Thin Film Thermocouple", Yust, M. and Kreider, K., Thin Solid Films, Vol. 176, Electronics and Optics, 1989, pp. 73-78

2. "Unsteady Surface Heat Flux and Temperature Measurements", Baker, K.I. and Diller, T.E., Proceedings of the ASME National Heat Transfer Conference, Atlanta, GA - August 8-11, 1993

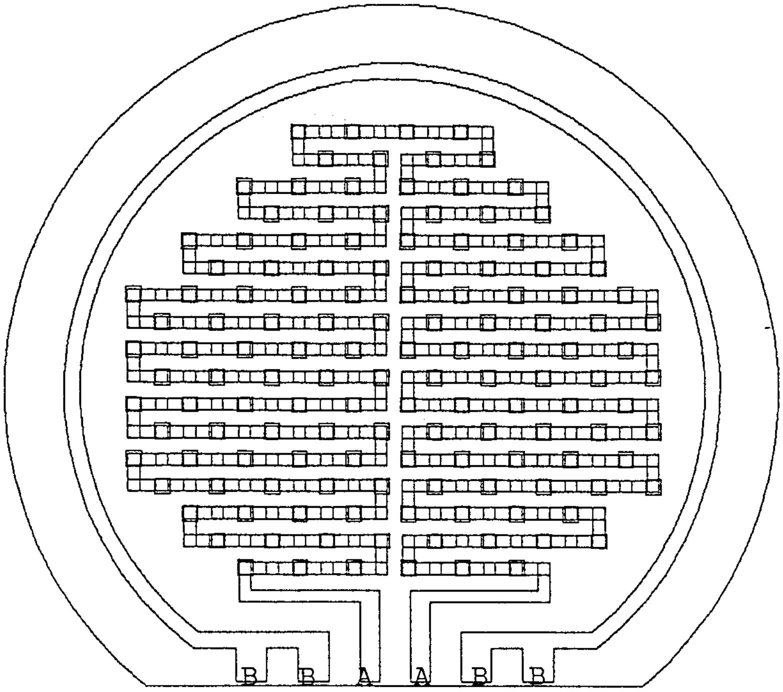


A -heat flux leads
B -resistance temperature leads



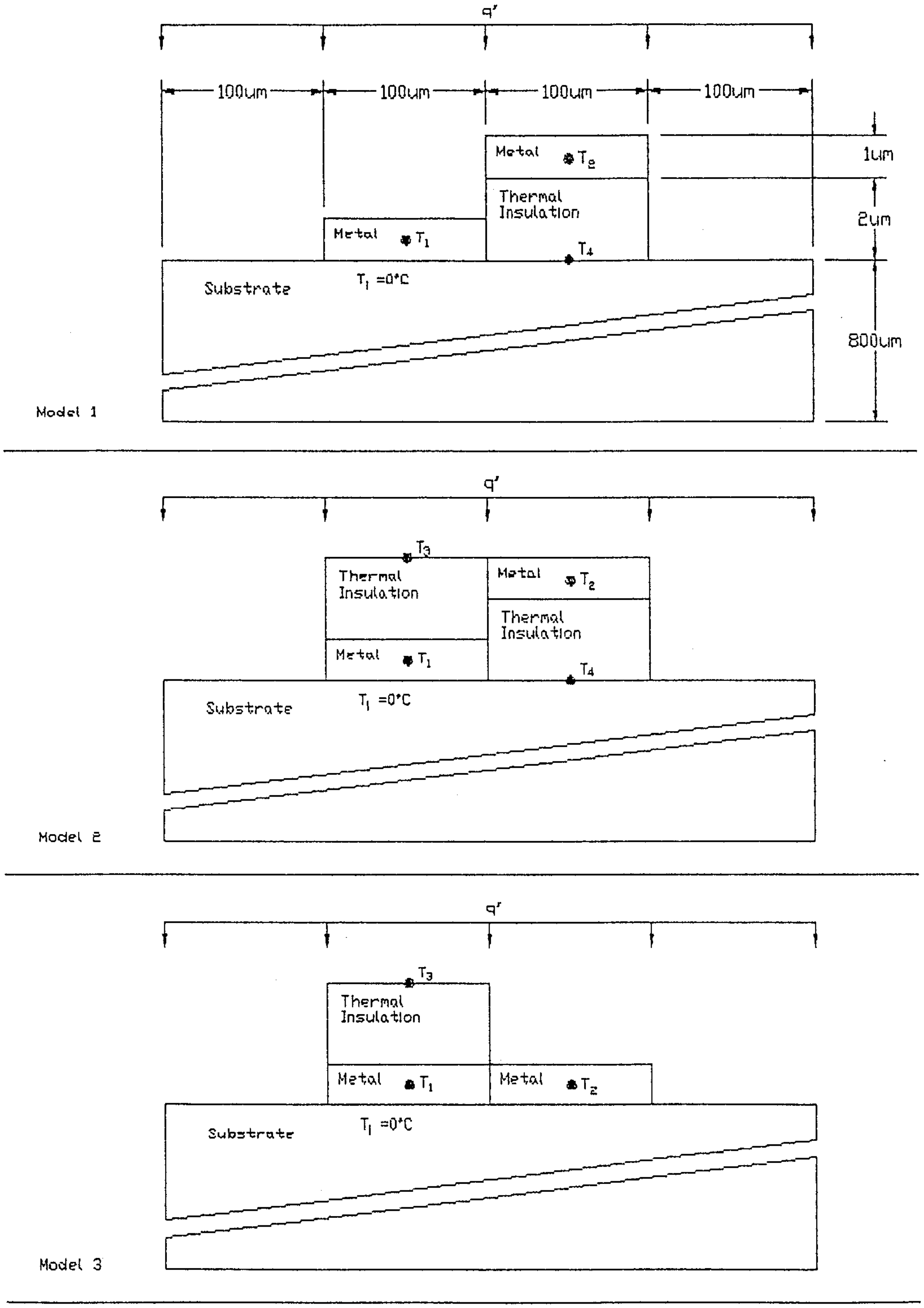
A -heat flux leads
C -TC lead (third lead)

Figure 1



A -heat flux leads
B -resistance temperture leads (4)

Figure 3


q'
100um
100um
100um
100um
Metal
T2
1um
Thermal Insulation
2um
Metal
T1
T4
Substrate
T1 =0°C
800um
Model 1
q'
T3
Thermal Insulation
Metal
T2
Thermal Insulation
Metal
T1
T4
Substrate
T1 =0°C
Model 2
q'
T3
Thermal Insulation
Metal
T1
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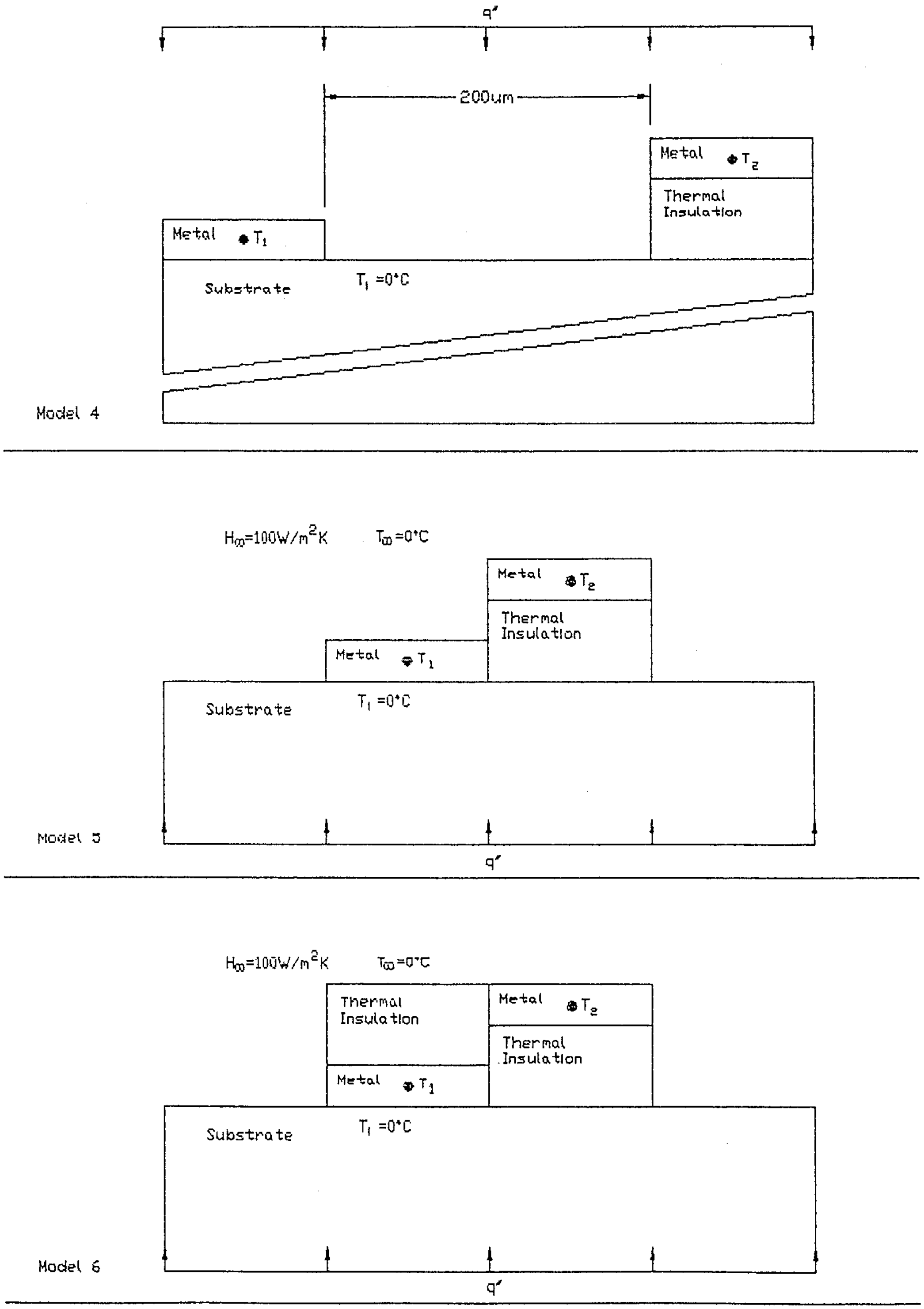
T2
Substrate
T1 =0°C
Model 3

Figure 4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Metal
T_2
Thermal Insulation
Metal
T_1
Substrate
T_i =0°C
Model 4
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T_∞=0°C
Metal
T_2
Thermal Insulation
Metal
T_1
Substrate
T_i =0°C
Model 5
q″
H_∞=100W/m^{2}K
T_∞=0°C
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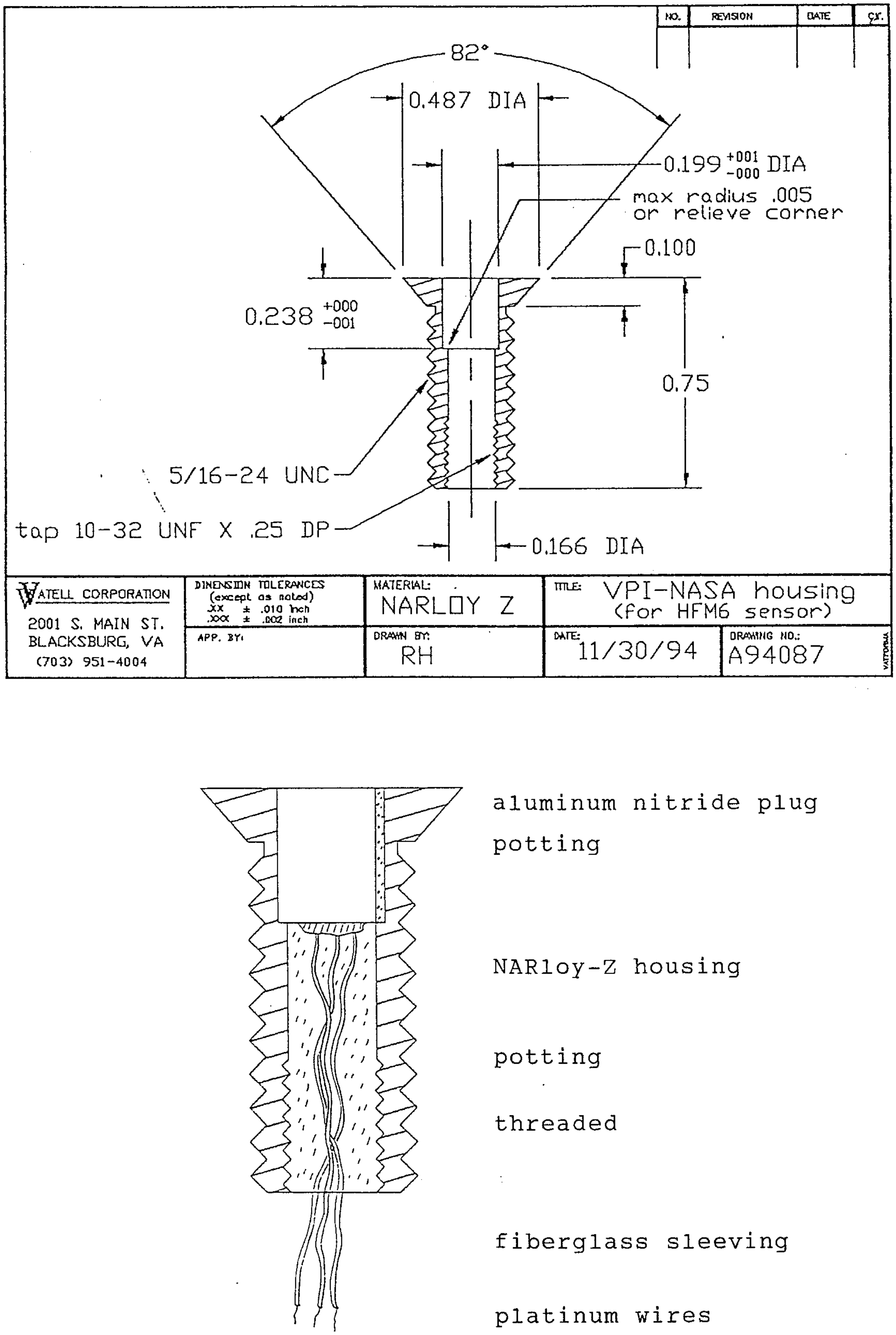
Metal
T_2
Thermal Insulation
Metal
T_1
Substrate
T_i =0°C
Model 6
q″

Figure 5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tap 10-32 UNF X .25 DP
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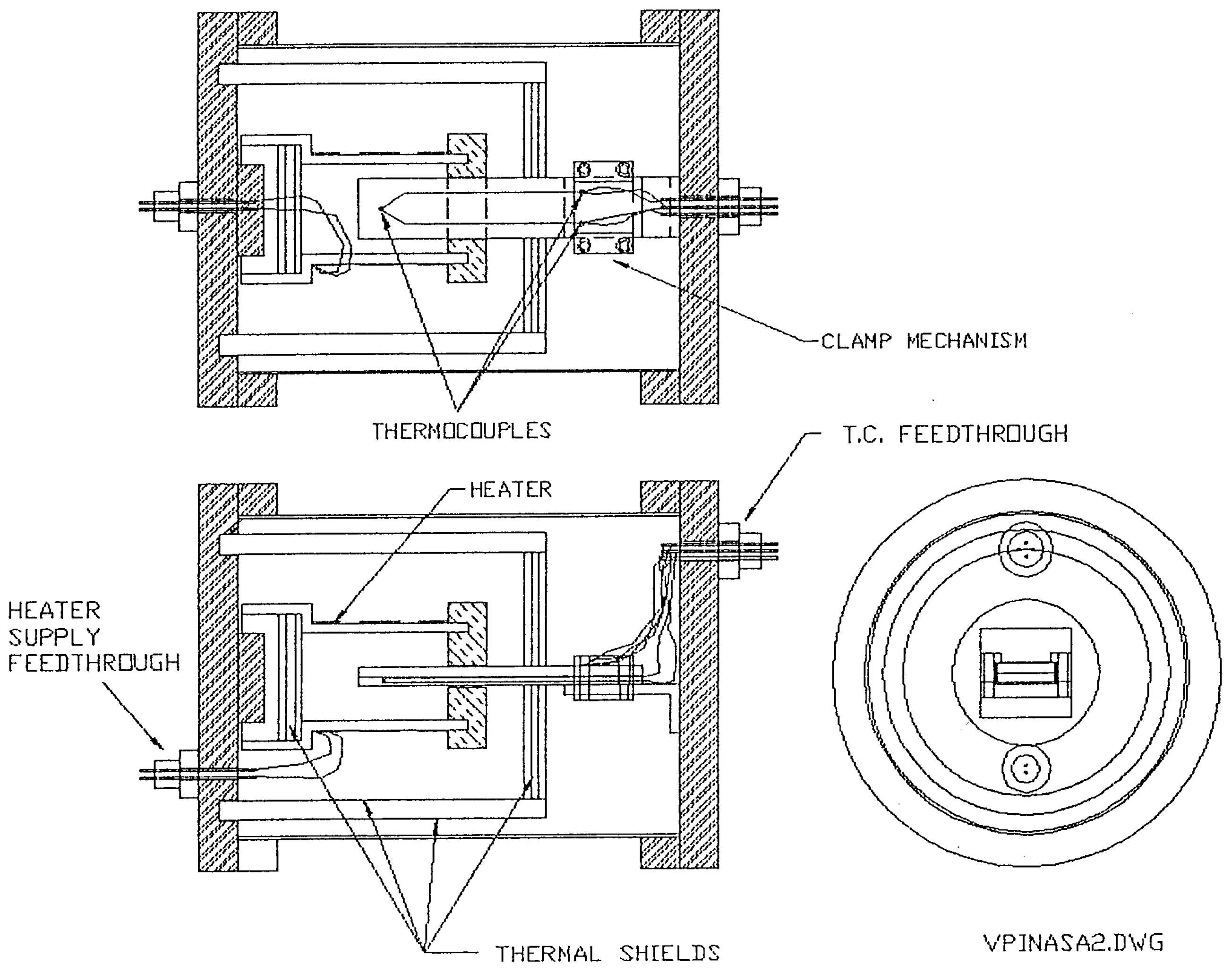
WATELL CORPORATION
2001 S. MAIN ST.
BLACKSBURG, VA
(703) 951-4004
DIMENSION TOLERANCES
(except as noted)
.XX ± .010 inch
.XXX ± .002 inch
APP. BY:
MATERIAL:
NARLOY Z
DRAWN BY:
RH
TITLE:
VPI-NASA housing
(for HFM6 sensor)
DATE:
11/30/94
DRAWING NO.:
A94087
aluminum nitride plug
potting
NARloy-Z housing
potting
threaded
fiberglass sleeving
platinum wires

Figure 6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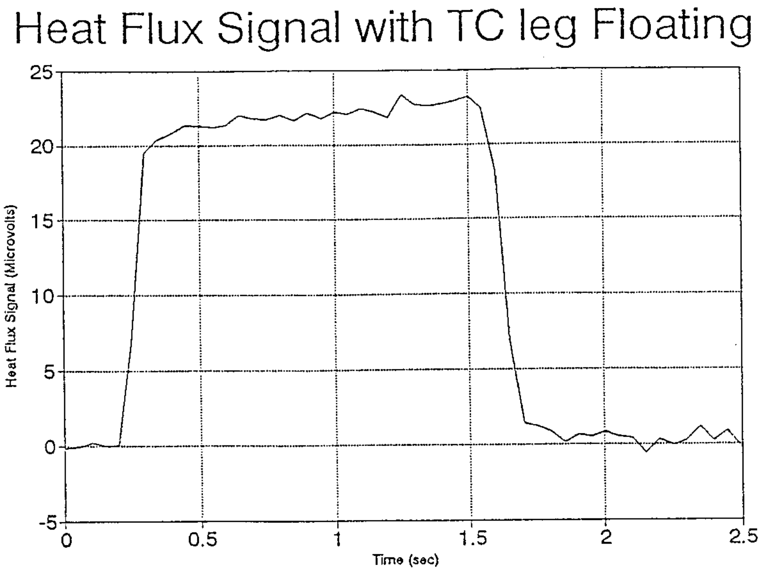
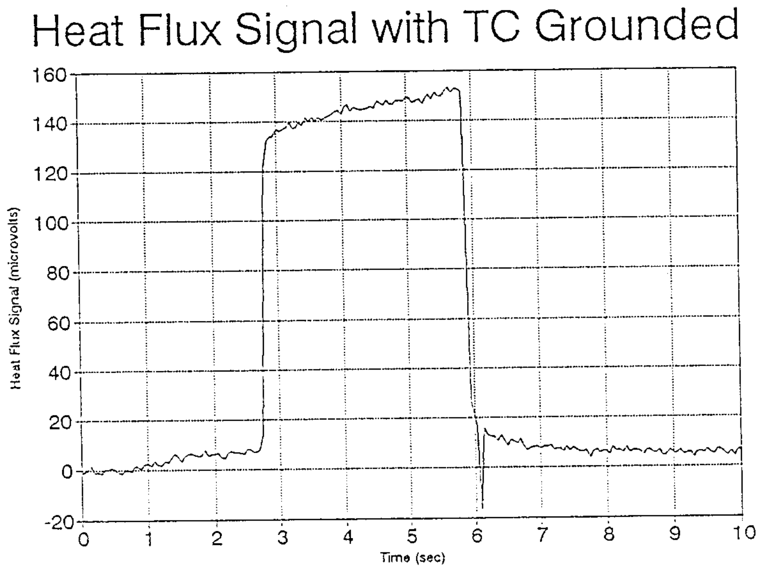
T.C. FEEDTHROUGH
HEATER
HEATER
SUPPLY
FEEDTHROUGH
THERMAL SHIELDS
VPINASA2.DWG

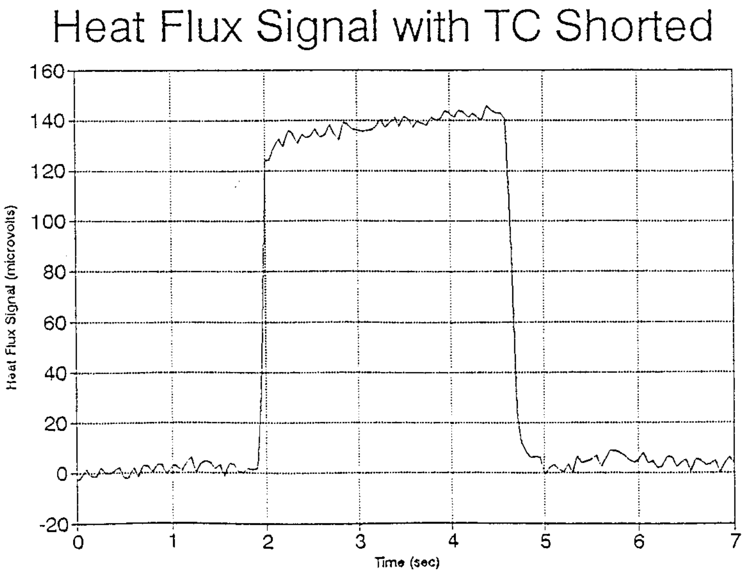
Figure 7



Heat Flux Signal with TC leg Floating

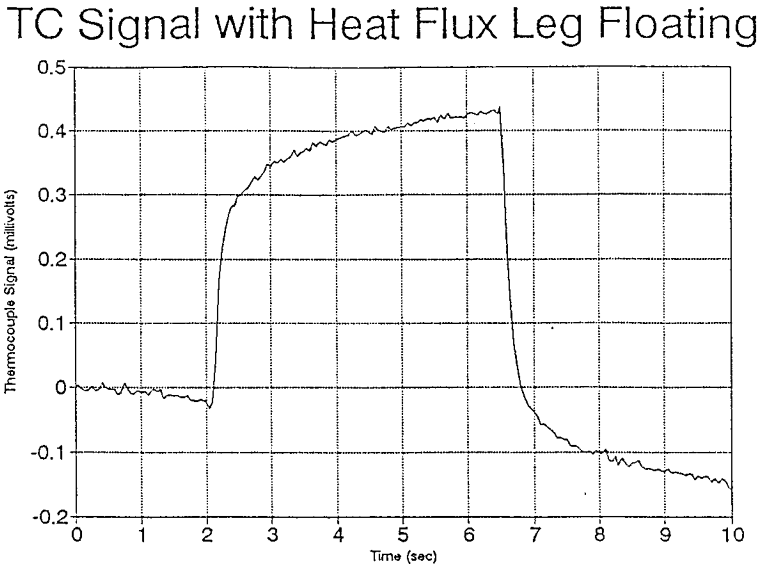


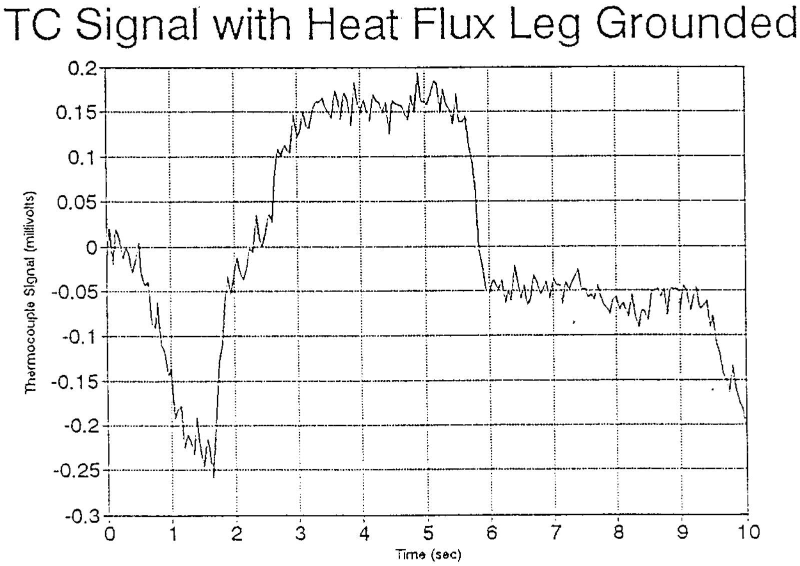
Heat Flux Signal with TC Grounded



Heat Flux Signal with TC Shorted

Figure 8


TC Signal with Heat Flux Leg Floating


TC Signal with Heat Flux Leg Grounded

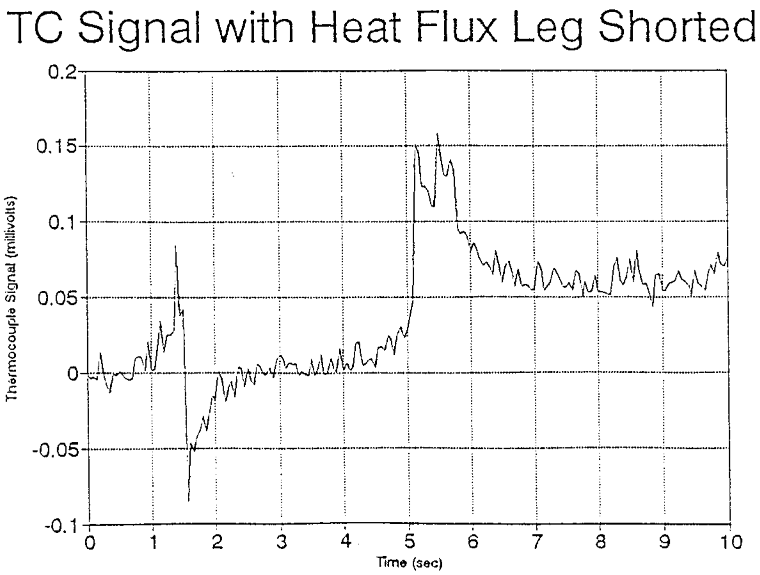
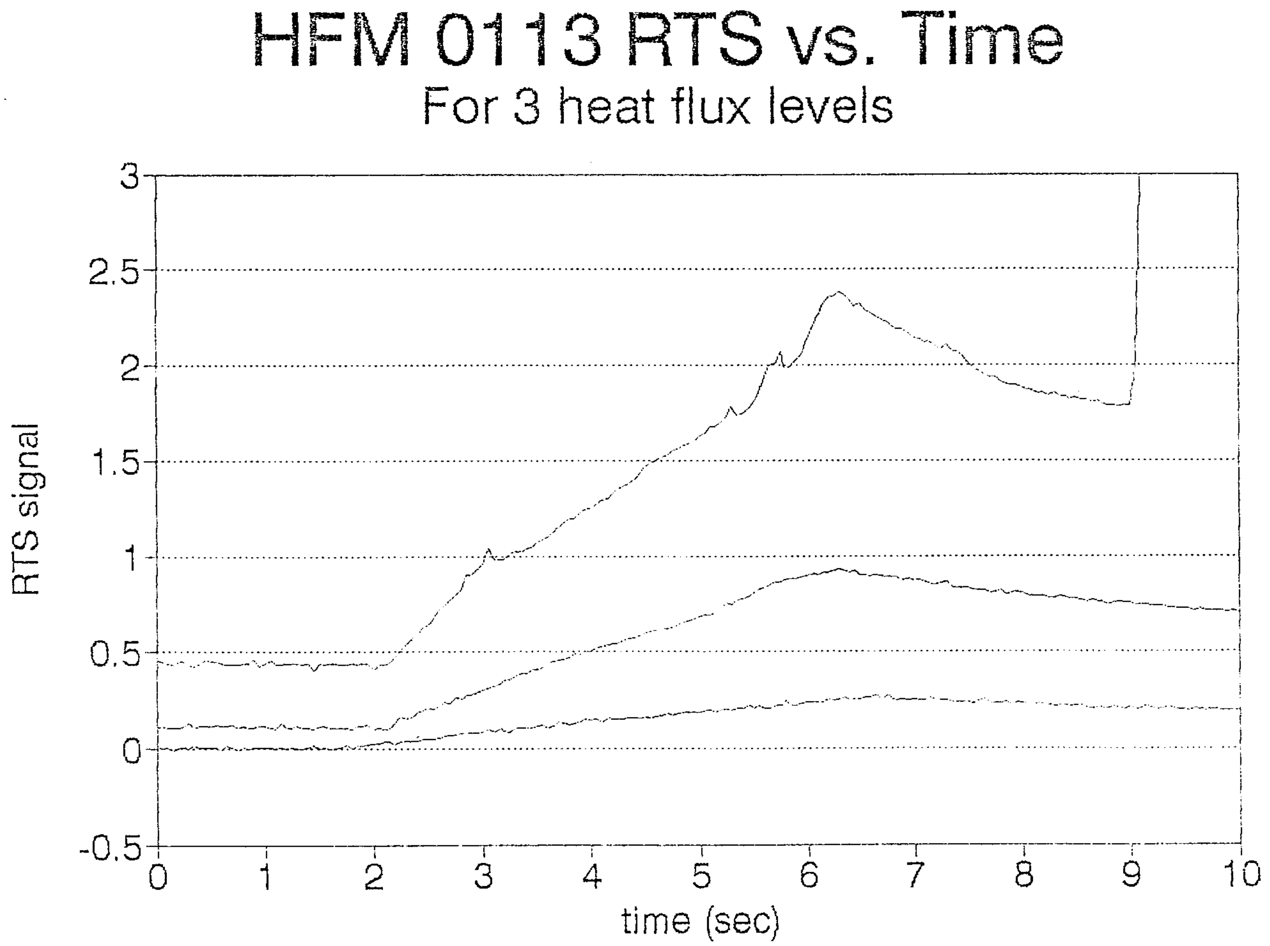

TC Signal with Heat Flux Leg Shorted

Figure 9


HFM 0113 RTS vs. Time

For 3 heat flux levels

Figure 10

INSTRUCTIONS FOR HANDLING AND USING
THE VATELL HEAT FLUX MICROSENSOR

Read these instructions before unpacking or installing this product !

Handling

Careful handling will prevent damage and prolong the life of your Heat Flux Microsensor. While this sensor is designed to withstand temperature extremes, it must be protected from excessive physical shock and stress during handling. In particular the leads which make connections within the potting material to the thin films on the sensor surface must be protected from excessive tension or repeated flexing. If the leads break, contact the manufacturer for further instructions.

The substrate material is aluminum nitride, a ceramic. It is potted into a NARloy-Z housing using a ceramic based adhesive. Avoid any contact to the exposed face of the ceramic with any sharp objects.

Always handle the sensor by the housing or the connector, never by the face or lead wires.

Upon removing the sensors from the box, please check the sensor resistances to assure they are consistent with the Information Sheet.

Mounting

It is important to achieve good thermal contact between the housing and the surface in which it is installed. Ideally the housing should be evenly held in compression around its perimeter. This can be achieved by clamping it in a countersunk hole that matches the contour of the head of the housing. The housing can be held in place with a threaded nut. Care must be taken when tightening the nut because the copper threads can be stripped easily. Contact the manufacturer for recommendations.

Make sure that the mounting does not apply any forces to the wires and that the temperatures around the leads and connector are not excessive. Strain relief should be used on the wires to support the weight of the connector.

Product Return for Repair or Replacement

Before returning this product for any reason, contact the manufacturer at the address below for instructions.

Vatell Corporation
P.O. Box 66
Christiansburg, VA 24073
(703) 961-2001 Fax 703-953-3010

If you have any other questions about the sensor, please call the number at the bottom of the Information Sheet.

HEAT FLUX MICROSENSOR INFORMATION SHEET

SERIAL NUMBER: 0115

SENSOR TYPE: HFM-6A-AlN-D🗎

SENSOR	CALIBRATION EQUATION	UNITS	R (Ω)
HFS (V,T)	Q = V/ (G*S) where S = 7.149 μV per W/cm^2 (average)	watts/cm^2	12.2 k @22°C
TC (V)	T = V/ (G*S) where S_{TC} (μV/°C) could not be determined	°C	@ 0°C
(R)	N/A	°C	298.9 @22°C

KEY:
- V - amplified voltage
- G - gain setting for that sensor
- T - temperature indicated by surface TC
- R - resistance of sensors

Heat Flux Measurement: The instantaneous voltage from the amplifier is entered into the above equation with the appropriate gain to provide the instantaneous heat flux (temperature dependence could not be determined).

Temperature Measurement: If the calibration of the thermocouple could be determined, the voltage from the amplifier and the appropriate gain would be entered into the above equation. The thermoelectric sensitivity, S_{TC}, of the thermocouple pair needs to be determined by calibration.

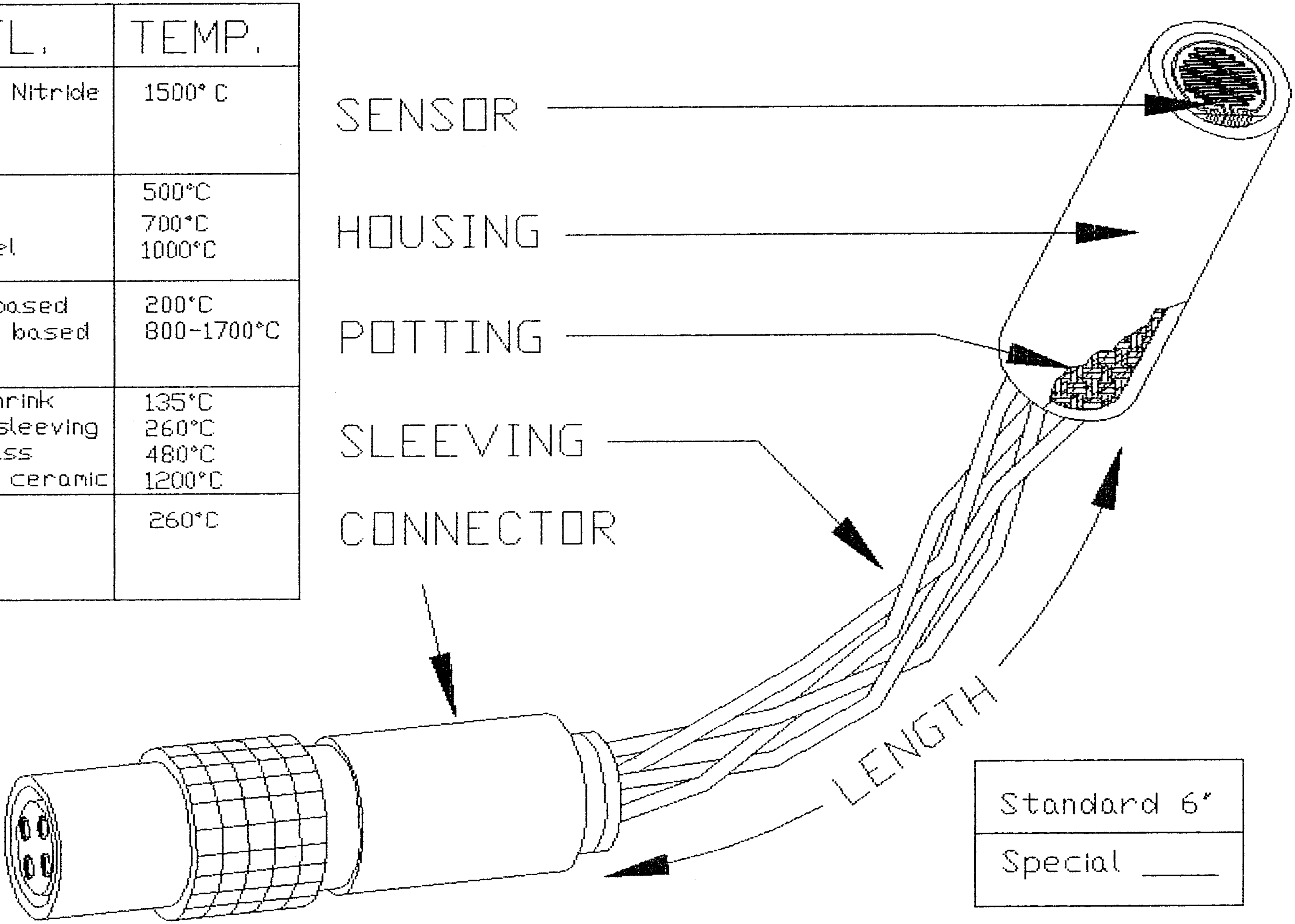
FURTHER INFORMATION

Sensor Description:	Pattern:	dense square heat flux sensor
	TC elements:	platinum vs. platinum-rhodium
	Surface TC:	platinum vs. platinum-rhodium
	Sensor coating:	sputtered aluminum oxide
	Substrate:	aluminum nitride (k = 150 W/m K)
Heat Flux Limits:	No known limits in either direction	
	Maximum heat flux calibrated:	43.98 W/cm^2
Temperature Limits:	Long term:	800°C
	Short term:	1200°C
	Maximum temperature tested:	320°C
Connections:	HFS lead connections:	silver pads
	HFS wire connections:	platinum wire - fiberglass sleeving
	TC lead connections:	silver pins
	TC wire connections:	platinum wire - fiberglass sleeving

VATELL CORPORATION

Phone: (703) 231-3892 Fax: (703) 231-3327

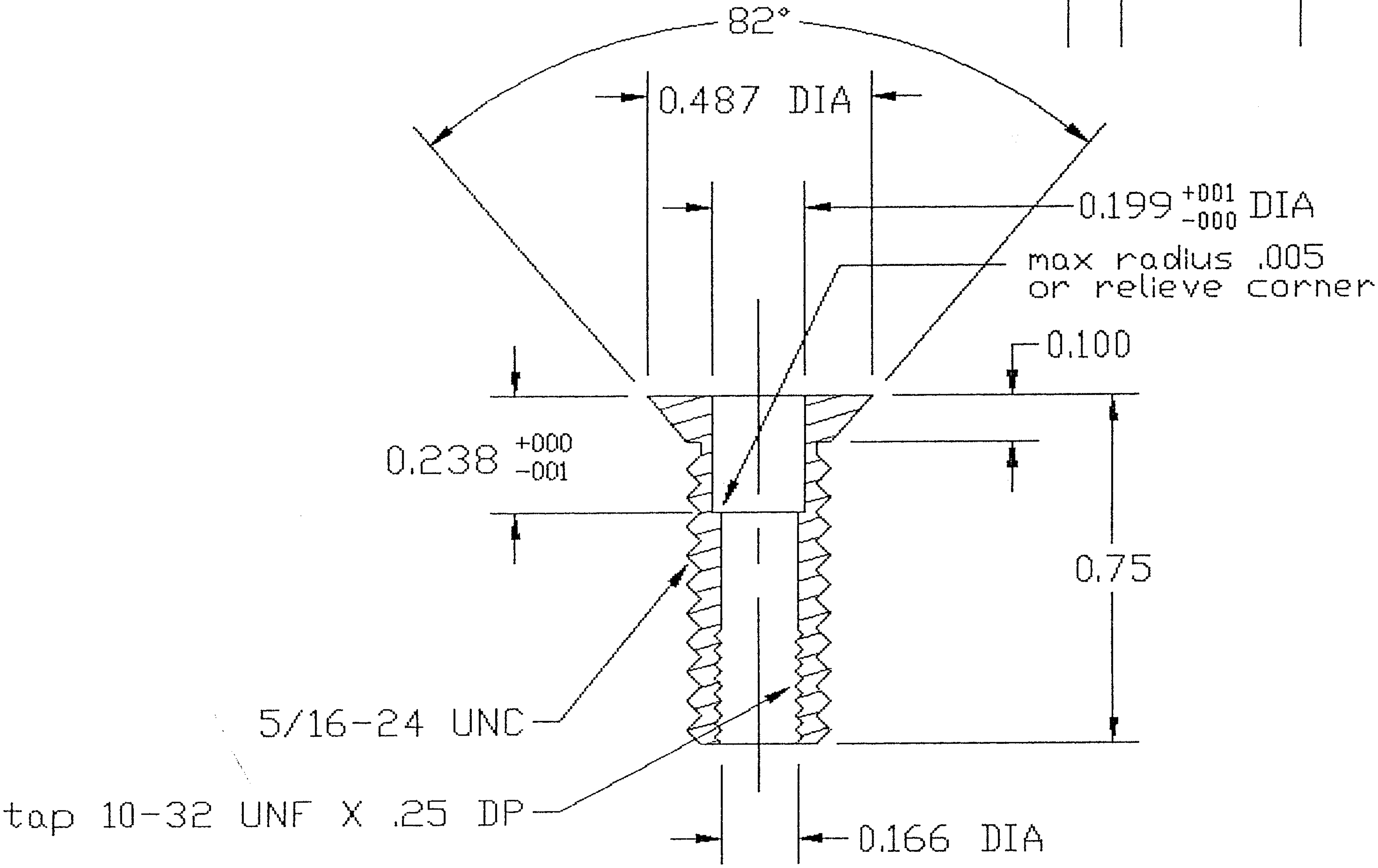
MTL.	TEMP.
Aluminum Nitride	1500° C
Aluminum Copper St. Steel	500°C 700°C 1000°C
Epoxy based Ceramic based	200°C 800-1700°C
Heat Shrink Teflon sleeving Fiberglass Braided ceramic	135°C 260°C 480°C 1200°C
LEMO	260°C



Standard 6"
Special ____

HFM6ISO.DWG

NO.	REVISION	DATE	CK.



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2001 S. MAIN ST.
BLACKSBURG, VA
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DIMENSION TOLERANCES
(except as noted)
.XX ± .010 inch
.XXX ± .002 inch

APP. BY:

MATERIAL: NARLOY Z

DRAWN BY: RH

TITLE: VPI-NASA housing
(for HFM6 sensor)

DATE: 11/30/94

DRAWING NO.: A94087

VATFORMA