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Los Alamos
NATIONAL LABORATORY

Design, Manufacture, and Calibration of Infrared Radiometric Blackbody Sources

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Introduction:

A Radiometric Calibration Station (RCS)[1,2,3] is being assembled at the Los Alamos National Laboratories (LANL) which will allow for calibration of sensors with detector arrays having spectral capability from about 0.4-15 μm. The configuration of the LANL RCS is shown in Figure 1. Two blackbody sources have been designed to cover the spectral range from about 3-15 μm, operating at temperatures ranging from about 180-350 K within a vacuum environment. The sources are designed to present a uniform spectral radiance over a large area to the sensor unit under test. The thermal uniformity requirement of the blackbody cavities has been one of the key factors of the design, requiring less than 50 mK variation over the entire blackbody surface to attain effective emissivity values of about 0.999.

Once the two units are built and verified to the level of about 100 mK at LANL, they will be sent to the National Institute of Standards and Technology (NIST), where at least a factor of two improvement will be calibrated into the blackbody control system. The physical size of these assemblies will require modifications of the existing NIST Low Background Infrared (LBIR) Facility[4,5,6,7]. LANL has constructed a bolt-on addition to the LBIR facility that will allow calibration of our large aperture sources.

Methodology for attaining the two blackbody sources at calibrated levels of performance equivalent to present state of the art will be explained in the following.

Blackbody design:

Two blackbody designs were required to satisfy two radiometric functions within the RCS list of capabilities. The smaller of the two units will be used as the absolute radiometric calibration standard. It has a 4.1 inch diameter opening with a length/diameter ratio of

3.17. The larger unit, which will be used to provide background radiances for contrast sensitivity measurements, initially had a length/diameter ratio of 4.92 with an aperture of 6 inches. The crimped cylinder capped with a cone (cylindro-conical), see Figure 2, was a design that was found to provide high effective emissivity with relative ease of control capability within the physical size constraints of the busy RCS source area. Calculations done at NIST with assumptions based on modeling at LANL, showed the effective emissivity values in the 1-14 μm wavelength range, when spectrally averaged over a 9.06° half-angle field-of-view (FOV), to be very near 0.999. The temperature uniformity required for this threshold was on the order of 30-50 mK. Several of the results of NIST analyses which predicted optimum cone angle, cylinder length, and aperture lip are shown in Figure 3. All aperture sizes can be scaled from this data. The cavity:aperture ratio defines the clear diameter of the aperture lip in relation to the cylindrical cavity inner diameter, nominally chosen for our systems to be 1.31. The internal coating, Enhanced Martin Black[8] (EMB) to be applied by Lockheed/Martin Astronautics (LMA), on the blackbody is also assumed to have diffusivity (the ratio of diffuse to total reflectance) near 0.90 and emissivity of 0.96 over the 1-14 μm spectral range for these analyses. LMA is presently reverifying these values over an even broader spectral range using their standard size test coupons. These two assumptions have been the center of broad attention during the design of these units. LMA has also extended the development the EMB process to allow for the coating of the large blackbody shells, partially due to a LANL-supplied custom tank for the last phase of the LMA EMB process. Final uniformity of the inner surface area of the shells was found to be free of cosmetic defects.

The thermal control of the blackbody shells between 180-350 K first involves a heat source. The method of supplying heat to the blackbody cavities is being furnished by Tayco Corp. in the form of a multilayer kapton heater/sensor assembly. The primary heater and sensor layers for the small blackbody are shown in Figure 4. Each heater zone is a 50 Ω resistor with control feedback provided by four equally spaced sensing elements imbedded into the aluminum shell. In the case of the small blackbody, there are three zones in the cylindrical portion of the heater, three in the conical, and one on the front face, totalling seven. The large blackbody heater design will have eleven zones. The leads for the heater traces are run within a kapton encapsulated layer to the front of the blackbody. These leads are in the outermost layer of the six-layer assembly, due to expected heat dissipation along their lengths.

Each of the sensors is a Lakeshore rhodium-iron resistance temperature device (RTD) with 100Ω resistance at ice point, nominal sensitivity of 0.34 Ω/K, and long term stability of about ±5 mK over a one year period. The sensors are constructed of a mounting block of berillium-oxide and a sapphire saphire block onto which the rhodium-iron traces are laid. The two blocks are bonded together using indium. The bottom berillium-oxide surface of these sensors is bonded into a small pocket machined into the outer surface of the blackbody shell using a thermally conductive epoxy. The ductile indium interface to the saphire sensor block allows for the strain due to the difference in the coefficients of expansion between the aluminum/berillium-oxide and sensor to be decoupled from the strain sensitive thermal detection occurring within the rhodium-iron sensor traces. The four leads from each of the detectors is run through a copper/kapton encapsulated trace to the front of the blackbody. The RTD sensors within each zone will be averaged to arrive at the temperature for the individual zone. The RTD resistance is monitored by a set of controller devices custom designed by Conductus. Using thermally controlled 100 ohm precision resistors, these units have demonstrated +/-1 mK precision and less than +/-4 mK drift, with 68% confidence, over a 48 hr period.

To stabilize the blackbody at temperatures below ambient, the cavity is housed in a liquid nitrogen (LN2)-filled jacket that serves as a heat sink. With the exception of the aperture, the cavity is completely enclosed within the cryo jacket. Because radiation is the only desired heat transfer mechanism between the cavity and the jacket, the two are separated by a space of 5.0 mm. About 1.0 mm of this vacuum space is occupied by the multilayer heater/sensor assembly, which is bonded to the outer surfaces of the cavity. Thus the two radiative surfaces of the cavity/jacket interface are the outer kapton foil of the heater/sensor assembly and the electro-polished inner surface of the jacket. The jacket and blackbody are individually isolated thermally from a common base plate by three kinematic ball mounts resting on tube columns. While the tube columns are configured to provide long thermal conduction paths, the primary thermal resistance is the kinematic ball interface itself. A simple 1-2-3 kinematic geometry results in only six points of contact between the base plate and the cold bodies. In this arrangement the aperture end of each body is supported by a ball on either side, and on the closed end by another ball in a counter-sink. On the aperture end, one ball rests in a groove while the other rests on a flat. Thus, both the blackbody and the cryo enclosure are well isolated thermally, yet free to expand and contract independently, in a stable strain-free manner.

subscript

The surrounding environment, which is viewed by the aperture of the blackbody, is also planned to be held to within +/- 1 degree Fahrenheit. The blackbody assemblies for the large and small blackbodies are shown in Figures 5 and 6, respectively.

The aperture of the cavity is surrounded by an electro-polished ring thermally grounded to the jacket on four pads. Heater and sensor leads from the cavity surfaces are routed through two of the four oblong spaces separating these pads. Because of their flexibility, thermal isolation of the leads in the space between the ring and the jacket is a concern. Foam insulation may be needed in this space to ensure isolation of the leads from the cold surfaces. Outside of the jacket assembly, the leads are supported between two plates adjacent to the jacket. A thin heat shield is placed between the plates and the jacket to improve thermal isolation of the leads. Joule heat generated in the power leads outside the jacket assembly is dissipated by clamping the leads to the base plate.

The LN_2 liquid level in the jacket is controlled by a level sensor coupled to a solenoid-operated cryogen valve by an oscillator/transmitter and controller. During normal operation the liquid level will fluctuate between two set points. At the maximum set point, or level, the vapor space above the liquid is about 10% of the total jacket capacity. Excess capacity, or the volume of the liquid allowed to boil off before refill, for both of the blackbodies is about 25% of the maximum liquid volume. At the minimum set point, the highest point on the inner shell of the jacket remains submerged about 5 mm in liquid. Cold vapor from the jacket is vented to the atmosphere.

The control of the blackbody within the vacuum environment is governed by the thermal surroundings to a large degree. During the NIST calibration of the small blackbody, a 40 K gaseous helium cooled aperture plate will be positioned near the front opening. During the actual use of the blackbodies in the RCS chamber, a 77 K LN_2 target plate will be placed at this position. These conditions, when compared to the situation where the full aperture is viewed by the sensor under test, will present radically different views to the internal surface of the blackbody. The determination of the effect of these changes will be closely monitored during calibration efforts. In the initial design, the quantity and widths of heating zones were determined roughly according to the view factor between the scene seen through the aperture and a number of circumferential strips along the inner wall of the cavity in the axial direction. A graph of the view factor, or fraction of radiant energy from the blackbody aperture that is intercepted by the inner wall, as a function of axial position for the cylindrical and conical sections is shown in Figure 7. The figure also shows, for a given uniform aperture temperature, the joule heating power distribution over the length of the cavity necessary to balance the radiant heat load from the aperture. The equations behind these plots are,

$$F = (1 - (R_{cyl}^2 + d_{axial}^2) / R_{ape}^2 - \sqrt{(1 + (R_{cyl}^2 + d_{axial}^2) / R_{ape}^2)^2 - 4\, R_{cyl}^2 / R_{ape}^2}) / 2$$

where VF is the view factor for each position d_{axial} down the length of the cavity, R_{cyl} is the radius of the cylinder/conical section, R_{ape} is the radius of the aperture opening, REF is the radiant energy fraction, α is the Stefan-Boltzmann constant, T_{ape} is the temperature of the aperture, and T_{cyl} is the temperature of the cavity. Although the model used to generate the data for these curves is rudimentary, the view factor data proved to be valuable when applied to a detailed finite element model used to determine a number of zone parameters. These included the quantity of zones, zone widths, and relative surface power densities for joule heating in order to achieve temperature uniformity within 20 mK. The finite element model also considered heat transfer by conduction between zones. Results of the analyses indicated that cavity temperature uniformity within 20 mK can be achieved with surface power density increments within the zones as coarse as 0.1 W/m^2. This corresponds to a current of about 2.7 ma in the smallest of the zones. The Conductus sensor/controller with resolution to much better than this is being assembled. The sensing channel is capable of detecting 10 mK changes at about 1 hz while the 16 bit heater controller is capable of controlling the zone voltages to a level on the order of 0.9 mv, which is equivalent to 17 na for these heaters. The largest error source for this controller system will be the heaters and sensors themselves.

When situations arise where nonuniform thermal views are presented to the blackbody aperture, rotationally symmetric sensing and control of the assembly may not suffice. Considerations for a type of design with further segregation of the zone pattern into peripheral quadrants will then be considered.

Calibration:

Calibration of the temperature sensors is being accomplished at LANL by encapsulating the blackbody shell, with the sensors and heater/sensor kapton layers attached, within a vacuum tank and then immersing this within a thermally controlled water or methanol bath. A representation of the calibration test setup is shown in Figure 8. The fluid control is being provided by a 44 liter Hart High Precision Bath

WENDY 5-5404

liquid. Cold vapor from the jacket is vented to the atmosphere.

The control of the blackbody within the vacuum environment is governed by the thermal surroundings to a large degree. During the NIST calibration of the small blackbody, a 40 K gaseous helium cooled aperture plate will be positioned near the front opening. During the actual use of the blackbodies in the RCS chamber, a 77 K LN_2 target plate will be placed at this position. These conditions, when compared to the situation where the full aperture is viewed by the sensor under test, will present radically different views to the internal surface of the blackbody. The determination of the effect of these changes will be closely monitored during calibration efforts. In the initial design, the quantity and widths of heating zones were determined roughly according to the view factor between the scene seen through the aperture and a number of circumferential strips along the inner wall of the cavity in the axial direction. A graph of the view factor, or fraction of radiant energy from the blackbody aperture that is intercepted by the inner wall, as a function of axial position for the cylindrical and conical sections is shown in Figure 7. The figure also shows, for a given uniform aperture temperature, the joule heating power distribution over the length of the cavity necessary to balance the radiant heat load from the aperture. The equations behind these plots are,

$$VF=\left(1-\left(R_{cyl}^2+d_{axial}^2\right)/R_{ape}^2+\sqrt{\left(\left(1+\left(R_{cyl}^2+d_{axial}^2\right)/R_{ape}^2\right)^2-4R_{cyl}^2/R_{ape}^2\right)}\right)/2$$

$$REF_i=VF_i-VF_{i-1},\ \Sigma REF_i=1$$

$$RE=\pi\alpha\,(REF)\,R_{ape}^2\left(T_{ape}^4-T_{cyl}^4\right)$$

where VF is the view factor for each position d_{axial} down the length of the cavity, R_{cyl} is the radius of the cylinder/conical section, R_{ape} is the radius of the aperture opening, REF is the radiant energy fraction, α is the Stefan-Boltzmann constant, T_{ape} is the temperature of the aperture, and T_{cyl} is the temperature of the cavity. Although the model used to generate the data for these curves is rudimentary, the view factor data proved to be valuable when applied to a detailed finite element model used to determine a number of zone parameters. These included the quantity of zones, zone widths, and relative surface power densities for joule heating in order to achieve temperature uniformity within 20 mK. The finite element model also considered heat transfer by conduction between zones. Results of the analyses indicated that cavity temperature uniformity within 20 mK can be achieved with surface power density increments within the zones as coarse as 0.1 W/m^2. This corresponds to a current of about 2.7 ma in the smallest of the zones. The Conductus sensor/controller with resolution to much better than this is being assembled. The sensing channel is capable of detecting 10 mK changes at about 1 hz while the 16 bit heater controller is capable of controlling the zone voltages to a level on the order of 0.9 mv, which is equivalent to 17 na for these heaters. The largest error source for this controller system with a maximum fluid interchange rate of 15 liters/min. This same Hart bath has been shown to provide thermal control to within 5 mK, but with the heat losses/additions expected through conductive transfer into our system, we seem to be limited to the 10-20 mK range. The system has be taken through several tests to determine all design modifications that were required to obtain a nominal 10 mK uniformity within the liquid bath which contains the blackbody unit. The transfer of the bath temperature to the blackbody shell is provided by conductive transfer at three points on the open end of the blackbody and at a single point on the apex of the cone, as well as randomly along the length of the outer surface of the blackbody by inducing matted steel wool to the vacuum chamber. It has been demonstrated the if a pressure is induced into the vacuum enclosure, for instance if a helium purge replaced the vacuum environment and steel wool, the sensors are distorted on the epoxy pads and give false readings. The fluid changeover from water/antifreeze to methanol will occur at about 240 K due to viscosity changes in the bath. A number of calibration temperatures between 240-350 K are being chosen to allow sufficient determination of the sensor characteristics throughout that temperature range. The temperature range below 240 will not initially be calibrated due to environmental considerations at the laboratories. Once the characteristics of each individual sensor are determined, the calibration coefficients will be written into the sensing software to allow for accurate determination of temperature when in actual use with the heater controller.

Once the sensors have been calibrated within the isothermal bath, the unit will be assembled within the cryogenic housing. Extra care must be taken in the thermal shielding of the heater/sensor leads that are routed outside of the cryogenic jacket. The 180° bend at the open end of the blackbody shell is the most critical with respect to thermal isolation. If the heater leads were to come in contact with the cryogenic jacket, the heat input into the front, conductively cooled, face would probably change the local temperature enough to cause the symmetry of the heat sink to be affected, thereby causing the nearest sensor to read slightly higher which would, in turn, affect the average control temperature for the front zone. The sensor leads, with their copper shielding, provide another excellent path for heat from the heater/sensor assembly. This would again cause an asymmetry in the blackbody thermal profile.

The assembly will be tested at LANL within a vacuum chamber that has been constructed for use in the NIST LBIR facility, as an extension to their existing chamber. This chamber will provide remote movement of a LANL blackbody about a stationary helium-cooled, 9 mm inside diameter, 40 K aperture. Figure 9 shows the chamber with the small blackbody assembly inside. The blackbody assembly will be placed into the chamber and taken through the required operational temperature range. This test will also provide an opportunity to check the motion control system, the cryogenic transfer system, as well as the outgassing properties of the assembly. The port that will attach to the NIST LBIR chamber will be made with an infrared window to allow viewing of the internal cavity at temperatures below room ambient with an existing camera that has sensitivity to about 100 mK. We also plan to attach a Cambridge unit to that port to allow sensitivities well below this. Testing outside of the chamber has already been performed at temperatures above room ambient, where no cryogen is involved, using the Conductus controllers as the feedback device. Once the system has been demonstrated and is fully understood, the blackbody assembly and calibration chamber extension for the NIST LBIR will be shipped to the NIST facility. The LANL testing schedule for the large blackbody will be largely determined by the results of the small blackbody calibration.

The active testing at NIST will, as mentioned earlier, be done over a 9 mm diameter aperture placed in front of the blackbody. This aperture plate will be controlled to 40 K using refrigerated helium at a mass flow rate of 5 grams/sec, which should allow no more than a 4 K temperature rise due to a 100 watt heat load. This heat load is probably somewhat conservative, although the 9 mm aperture is within a large 18 inch diameter invar disk within the room-temperature vacuum chamber. The plate is also in close proximity to a 350 K maximum temperature blackbody, with either a 4.1 or 6 inch aperture, with assorted other heat losses in the transfer lines.

The radial grating on the blackbody side of the aperture plate is meant to provide for minimal reflected signal back into the cavity. Raytrace shows that less than 0.08% of the emergent radiation returns back into the cavity if the reflectance of the plate groves is held to 7%. This same plate will be further utilized as an absolute cold reference for the sensor under test in the RCS by placement of the plate, with an additional machined plug for the 9 mm aperture, directly in front of the sensor entrance aperture. Design of this end of the RCS has not progressed very much beyond concept.

Further baffling, as shown in Figure 10, has been designed and fabricated with the exception that the small inserts will define the limiting apertures. The analysis of these are still under study at NIST due to large (3-5%) diffraction effects at the NIST LBIR detector when circular apertures are used[9]. Tentative results indicate that by rippling the inner edges of the apertures, the diffraction can be reduced significantly. The LBIR detector lies approximately 70 inches from the 9 mm cold aperture at the blackbody output. The room temperature chamber walls are hidden from the path in the space between the 9 mm aperture and the existing NIST LBIR tank, using cooled copper tubes. One of these is remotely mobilized through the gate valve area, when open. All of these copper tubes are thermally grounded to the 20-40 K cryogenic sources.

The blackbody will be moved in both axes behind the 9 mm aperture to allow spot coverage of the entire aperture of either of the cavities. Allowance has also been designed into the fixturing for tilting of the blackbodies, within the horizontal plane, $\pm 9^{\circ}$ to match the full FOV of the blackbodies as seen from the sensor under test in the RCS. This would require that the additional chamber be opened for the repositioning, but this should only have to occur once. The resultant calibration would therefore be over the full infrared spectral range at two field angles for each of the two blackbodies.

Summary:

The blackbody units have been completed through design phase and machining of all components is completed. The enhanced Martin Black coating had provided a challenge to LMA due to the size of the pieces, but they were successful in obtaining an as-advertized coating. The heater assemblies have pushed the multi-layering technology to a new level of sophistication, but did not pose an insurmountable hurdle for the assembly. The sensor/heater lead routing was found to be delicate up to the point that a transition is made to a more standard cable. The control of the device is still being tailored for our specific uses, but measurements indicate that these modified off-the-shelf components will perform nicely. The calibration efforts, both at LANL and NIST, have required many modifications to existing equipment, but the expectation is that the efforts will be successful. We anticipate that this first prototype will be controllable in temperature to within 30-50 mK and be absolutely traceable to NIST standards by the end of FY'96, to be followed by a second larger unit with the same traceability. It is worth noting that NIST has adopted the design of the small blackbody and plans to build a second unit during FY'96.

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Figure Captions:

Fig. 1: The LANL Radiometric Calibration Station will be used for absolute calibration of sensor packages within a vacuum environment. The satellite package shown is a multi-spectral thermal imaging device, one of the first to utilize the calibration station. The station includes blackbodies, an integrating sphere, a monochromator, and an interferometer with targets for

visible and infrared sources scanned across the sensor focal plane using a scanning fold flat.

Fig. 2: The LANL blackbody cavities. The smaller one will serve as an absolute radiometric reference. The larger one will serve as a source for contrast measurements. Both will be spectro-radiometrically calibrated at NIST. The blackbodies were modified, splitting the deep cavity into two separate pieces, in order to allow Lockheed/ Martin Astronautics to more easily blacken the inner surfaces.

Fig. 3: The results of the NIST analyses showed that the cone angle at the back end of the blackbody was tolerable over a fairly wide range. The lip defining the aperture in relation to the cylinder size was minimized to keep the packages small in diameter. The length of the units were also permitted to be only as long as the restricted space allowed.

Fig. 4: The heater/sensor layers to be utilized for the LANL small blackbody are composed of heaters (on the left), sensor leads (in the middle) and heater leads (on the right). The sensor leads will be sandwiched between copper sheets for shielding. Each layer will be kapton encapsulated. The entire 6-layer assembly is less than 1 mm in thickness.

Fig. 5: The LANL large blackbody inside of its cryogenic housing with heater/sensor leads routed to connectors. The cryogenic housing is mounted independently from the blackbody shell inside, providing for thermal isolation. Radiative cooling is accomplished over the 4-5 mm gap between the inner shell and the housing.

Fig. 6: The LANL small blackbody shell is shown inside of its cryogenic housing. The housing is cut away showing the inner shell. The basics of the design are basically the same as the large blackbody.

Fig. 7: The view factor, or fraction of the energy incident through the opening of the small blackbody, guides the heater power when a uniform scene is present outside of the blackbody opening. Shown here is the case where a

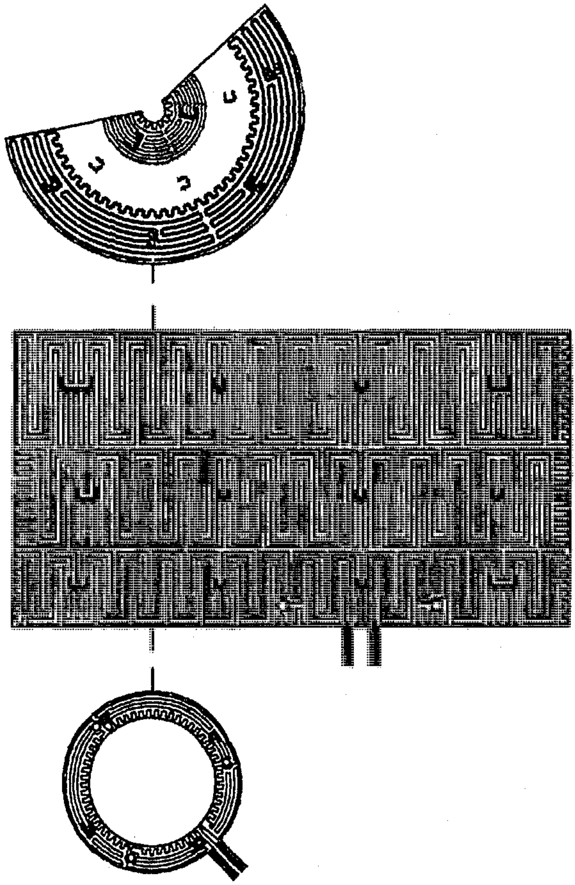
293 K scene is outside of the blackbody while the unit is being controlled to 250 K.

Fig. 8: The sensors will be calibrated within an isothermal bath for both blackbodies. The blackbody shell will reside within a vacuum tank submerged within a thermally controlled circulating bath. Several set points will be used to map the sensor responses.

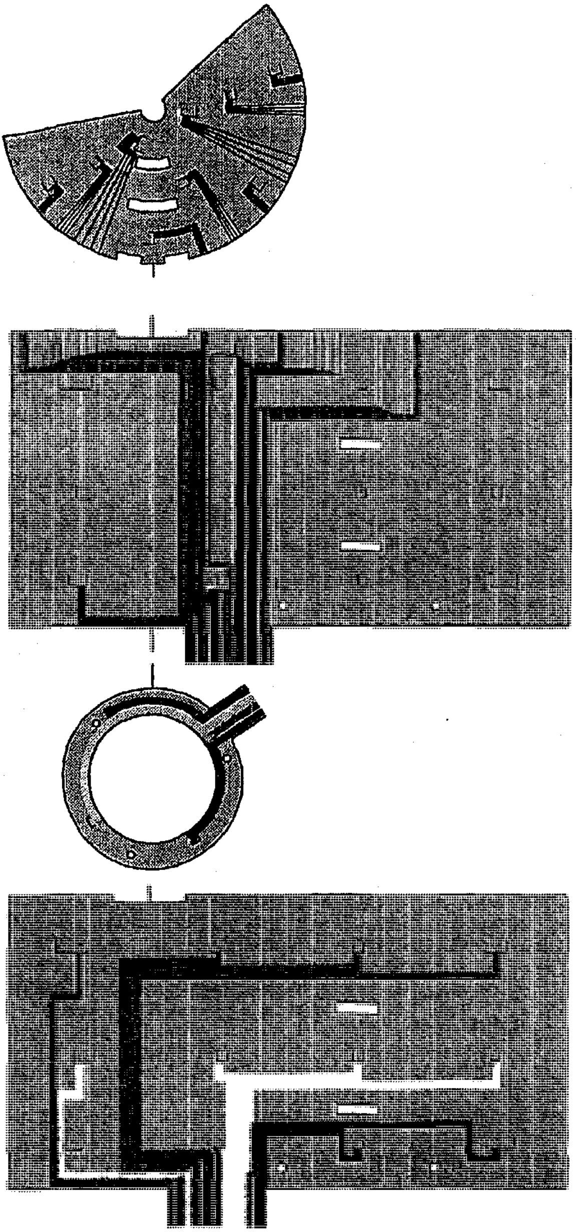
Fig. 9: A custom tank designed and built at LANL, will be sent to NIST to extend their LBIR testing capabilities. The tank, with the LANL small blackbody shown inside, will also house a 40 K, 18 inch diameter, aperture plate. The blackbodies will be moved remotely in two axes behind the 9 mm aperture to provide mapping of the radiometric uniformity across the blackbody aperture.

Fig. 10: The baffling inside of the tube that will connect the LANL manufactured tank and the present NIST LBIR tank is shown. The 9 mm, 40 K, aperture is on the right. Two different baffles are attached to this plate and should be at or near 40 K. All other baffles shown on the left are thermally grounded to the NIST LBIR inner shroud, which is kept near 20 K. The innermost knife-edge inserts within the baffles will probably need a special serrated shape to minimize diffraction.

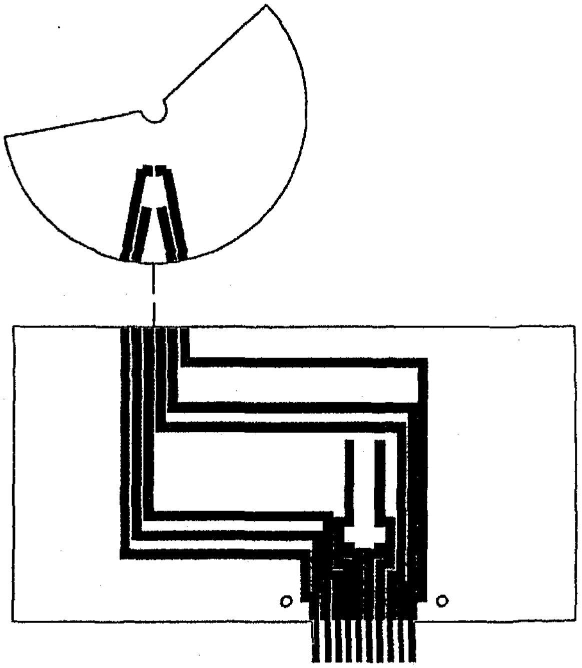
Heater Traces

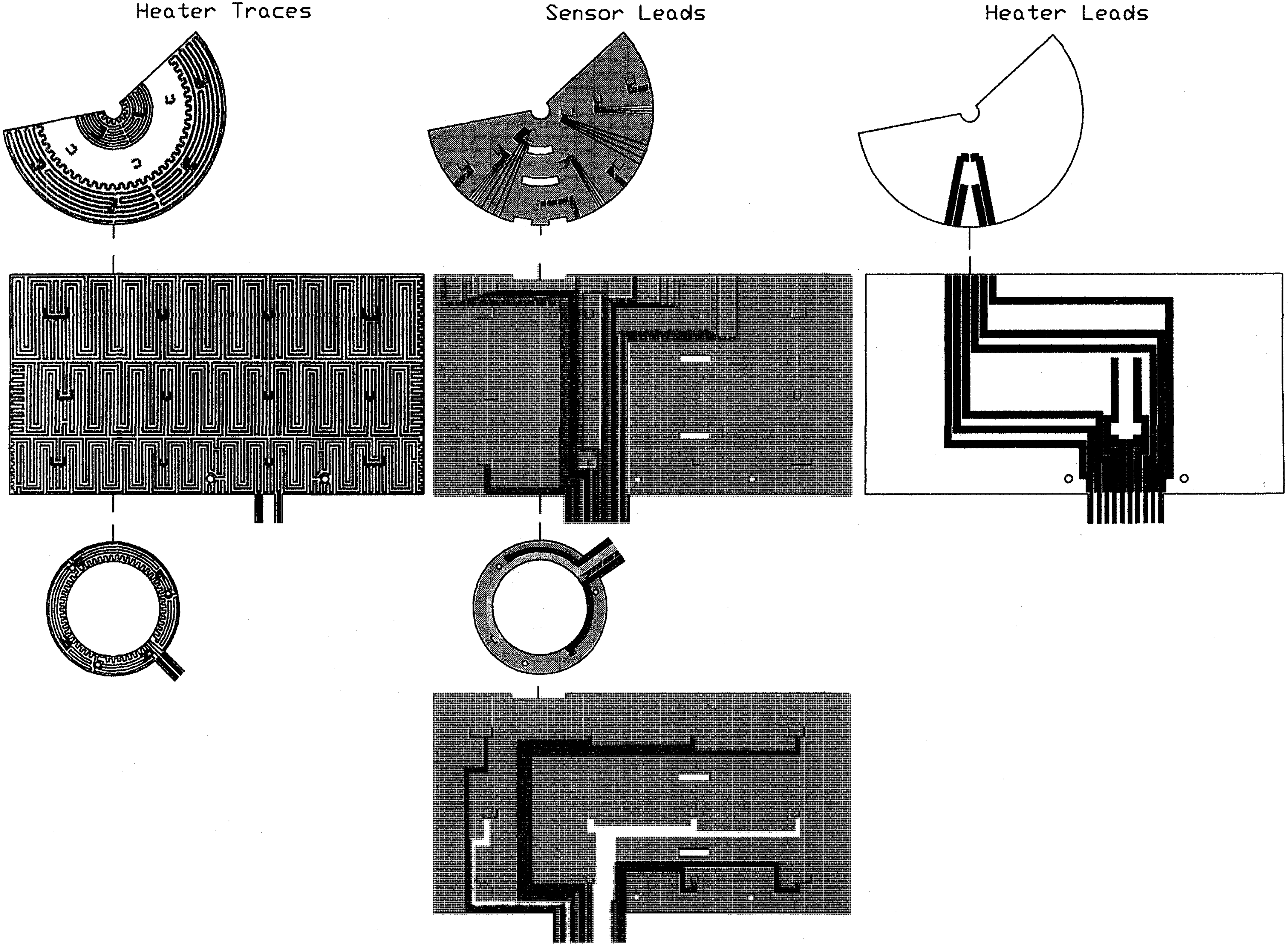


Sensor Leads



Heater Leads

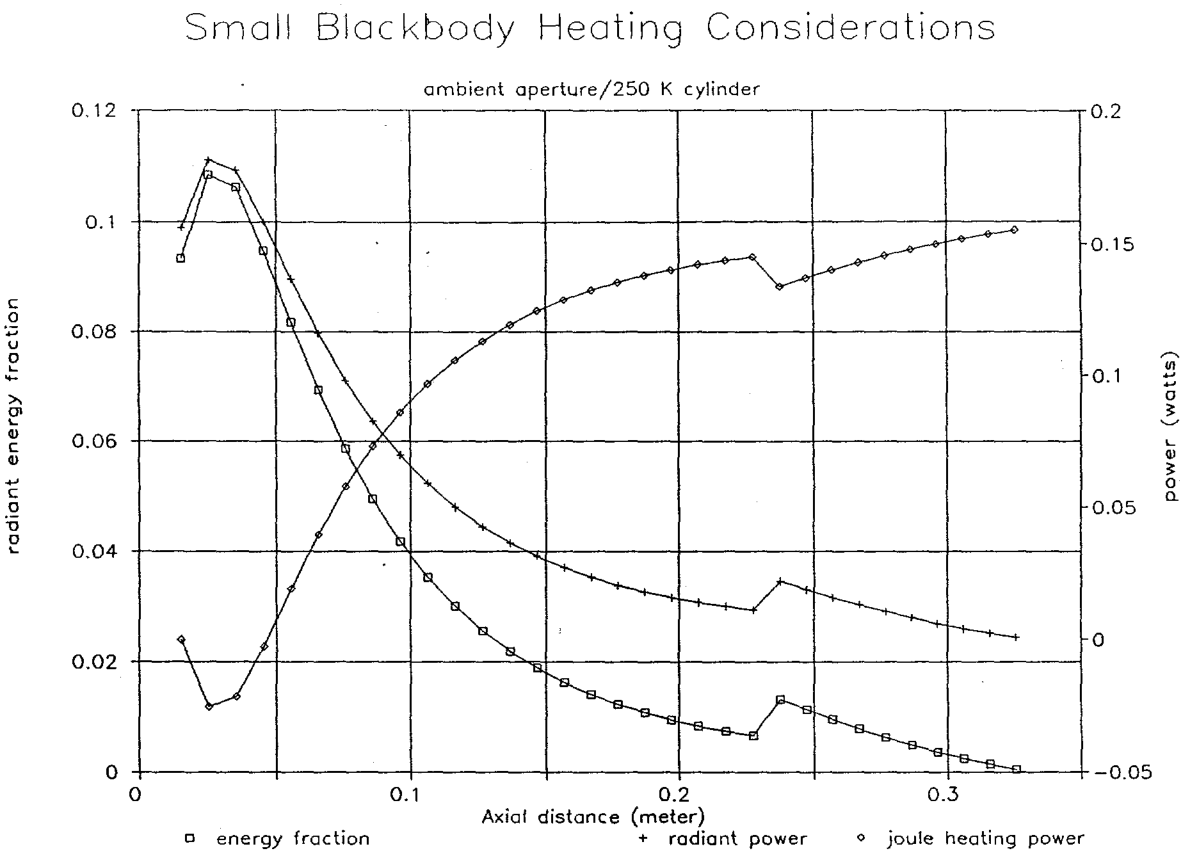


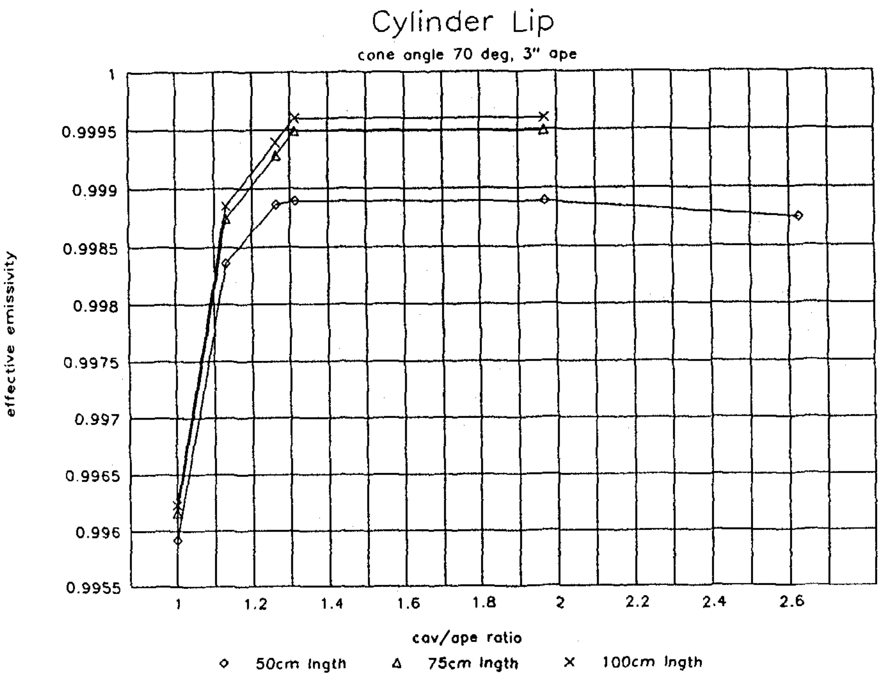


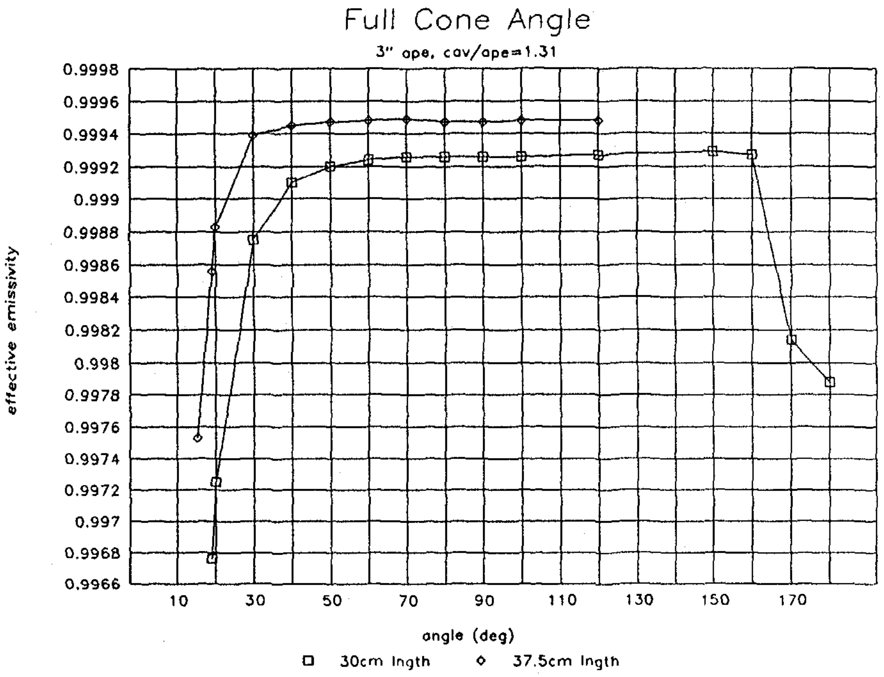
Heater Traces

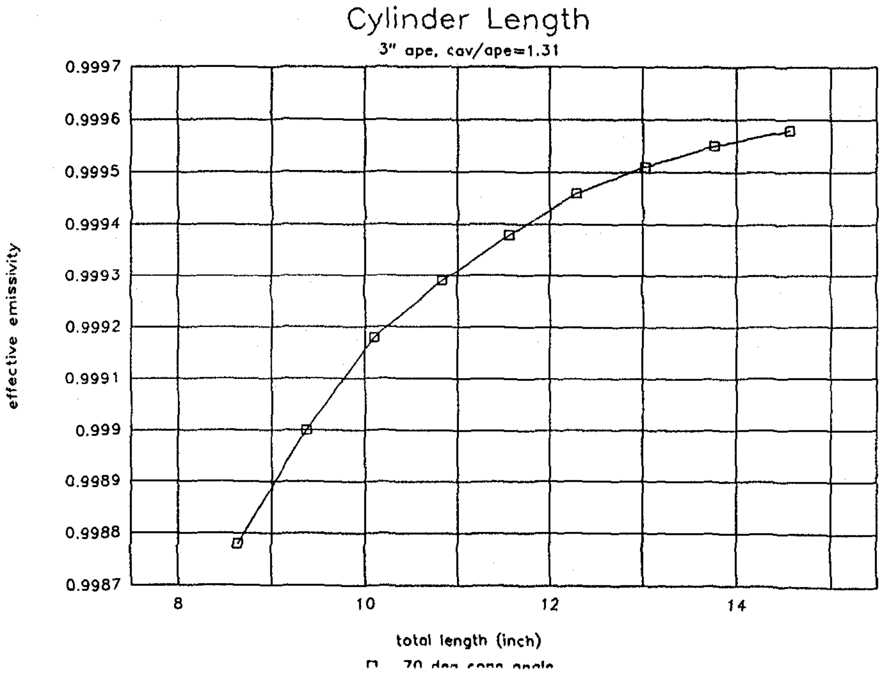
Sensor Leads

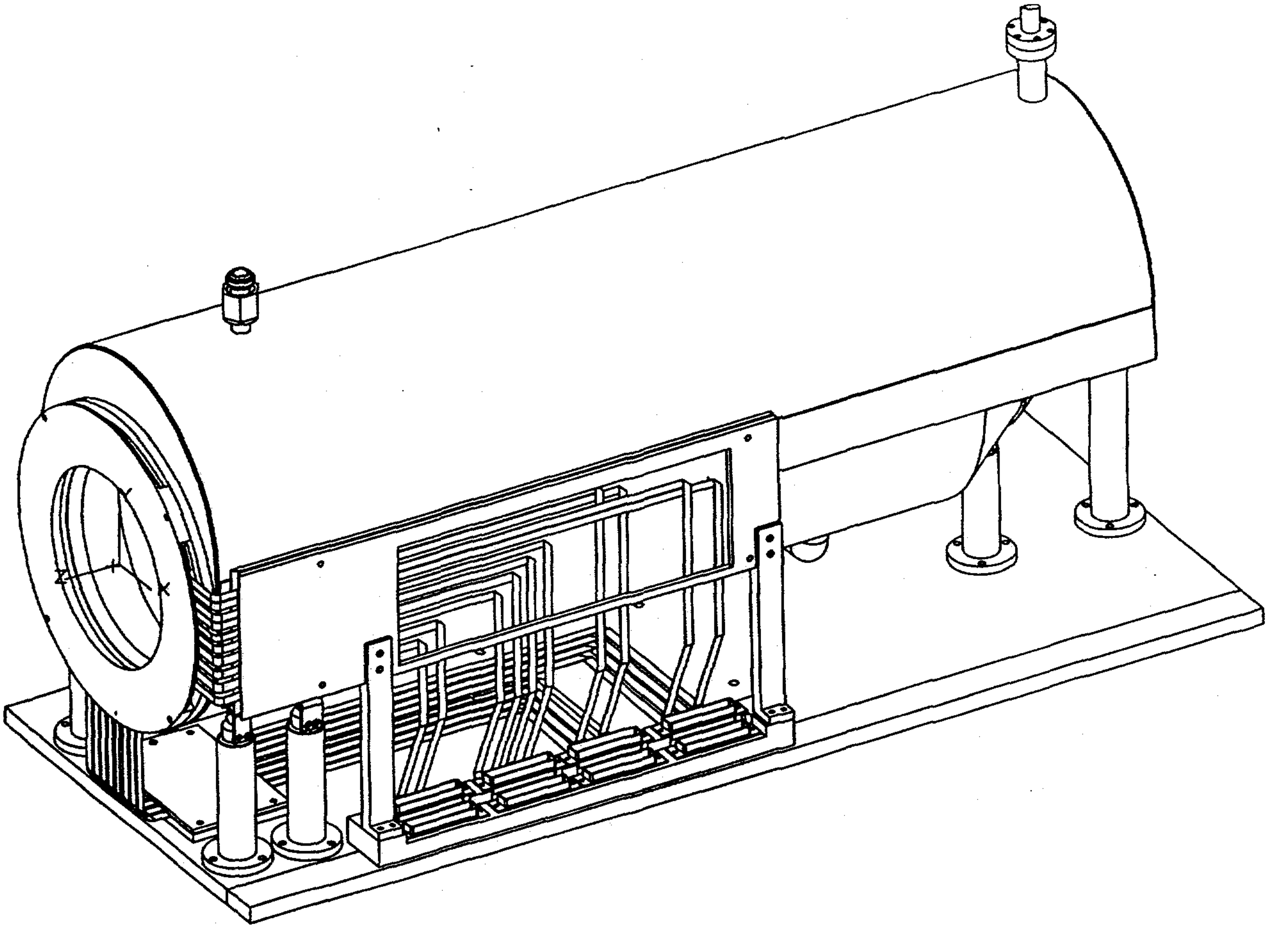
Heater Leads


Small Blackbody Heating Considerations
ambient aperture/250 K cylinder
radiant energy fraction
0.12
0.1
0.08
0.06
0.04
0.02
0
power (watts)
0.2
0.15
0.1
0.05
0
−0.05
0
0.1
0.2
0.3
Axial distance (meter)
□ energy fraction
+ radiant power
◇ joule heating power

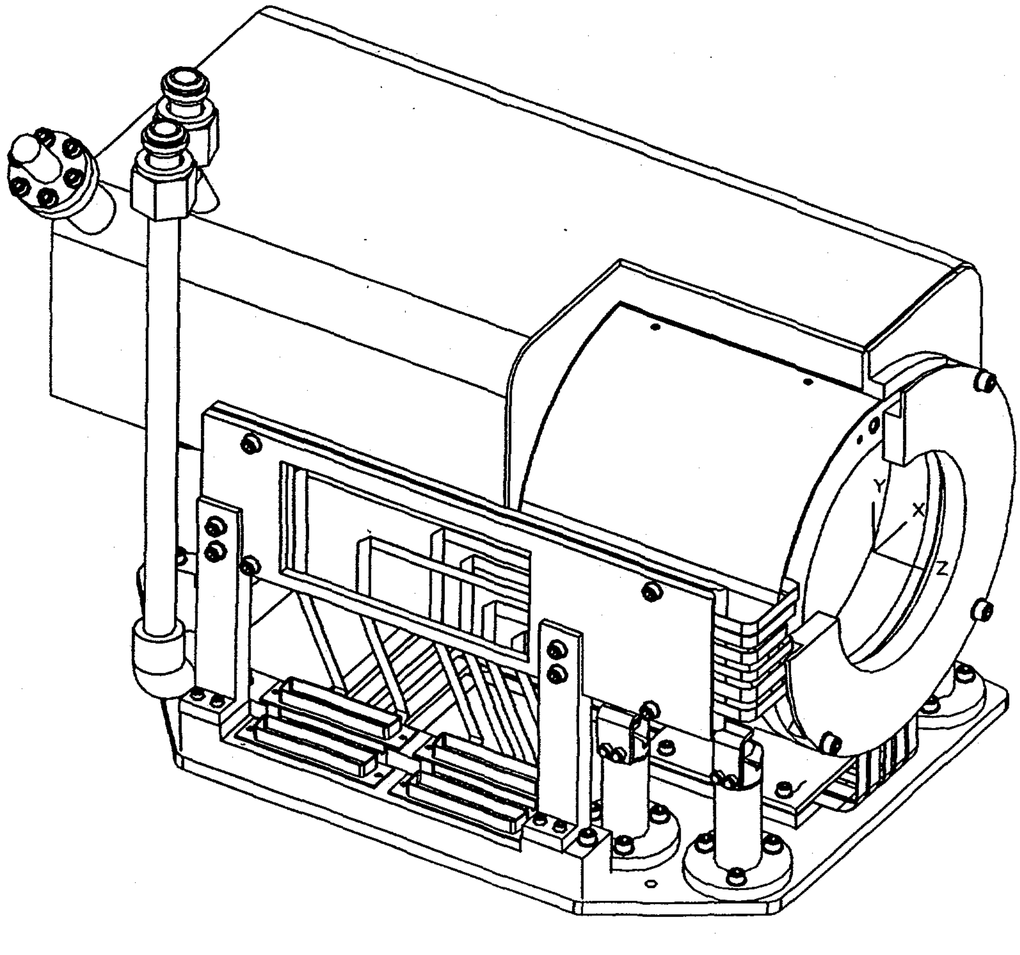

Cylinder Lip
cone angle 70 deg, 3" ape
effective emissivity
1
0.9995
0.999
0.9985
0.998
0.9975
0.997
0.9965
0.996
0.9955
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
cav/ape ratio
◇ 50cm lngth
△ 75cm lngth
× 100cm lngth


Full Cone Angle
3" ape, cav/ape=1.31
effective emissivity
0.9998
0.9996
0.9994
0.9992
0.999
0.9988
0.9986
0.9984
0.9982
0.998
0.9978
0.9976
0.9974
0.9972
0.997
0.9968
0.9966
10
30
50
70
90
110
130
150
170
angle (deg)
□ 30cm lngth
◇ 37.5cm lngth

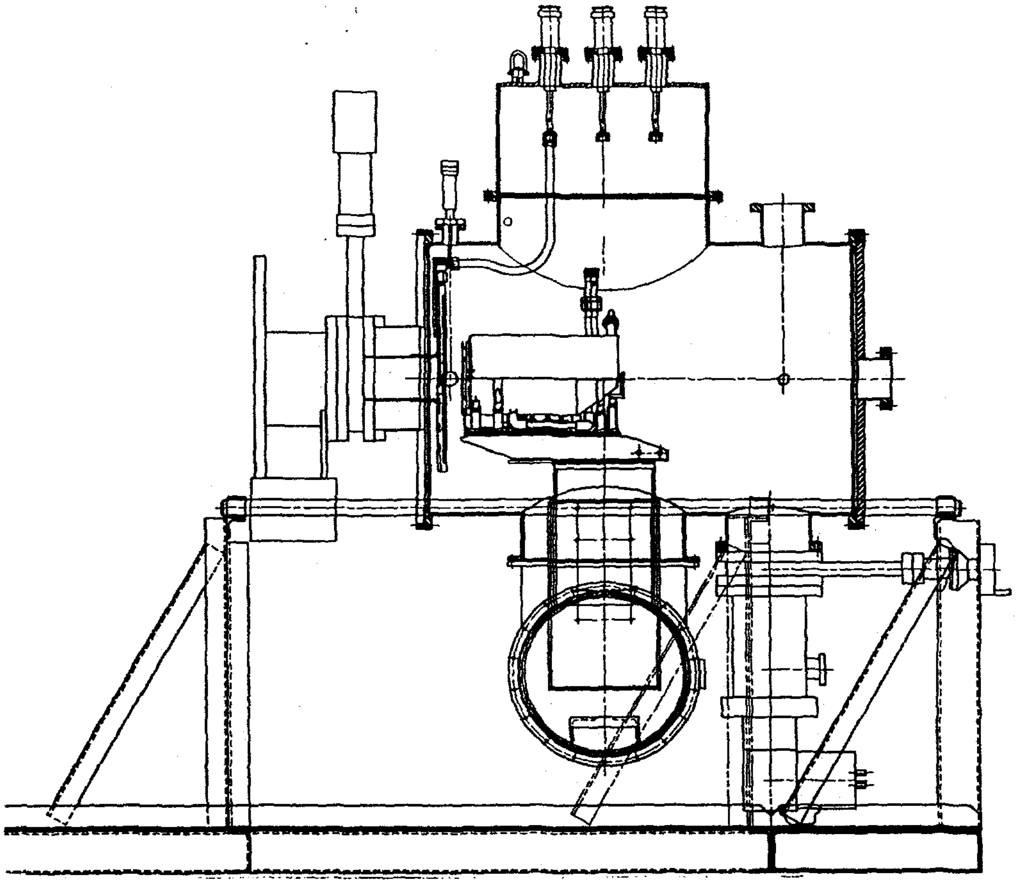

Cylinder Length
3" ape, cav/ape=1.31
effective emissivity
0.9997
0.9996
0.9995
0.9994
0.9993
0.9992
0.9991
0.999
0.9989
0.9988
0.9987
8
10
12
14
total length (inch)
□ 70 deg cone angle



Z
Y
X



Y
X
Z



DISCLAIMER