Accurately Calibrated Airborne and Ground-based Fourier Transform Spectrometers II: HIS and AERI Calibration Techniques, Traceability, and Testing

F. Best, H. Revercomb, D. LaPorte, R. Knuteson, and W. Smith

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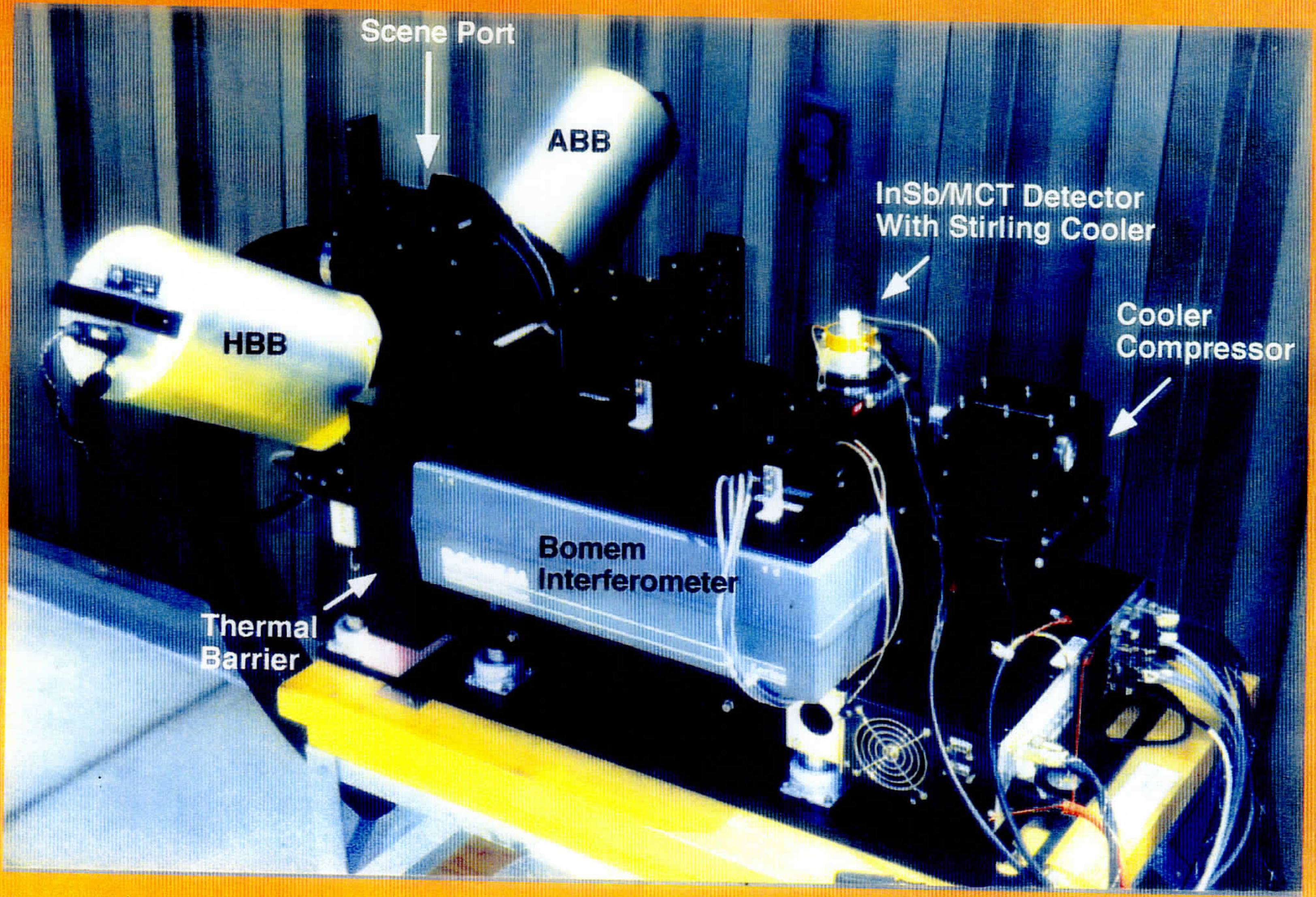
Space Science and Engineering Center

Topics

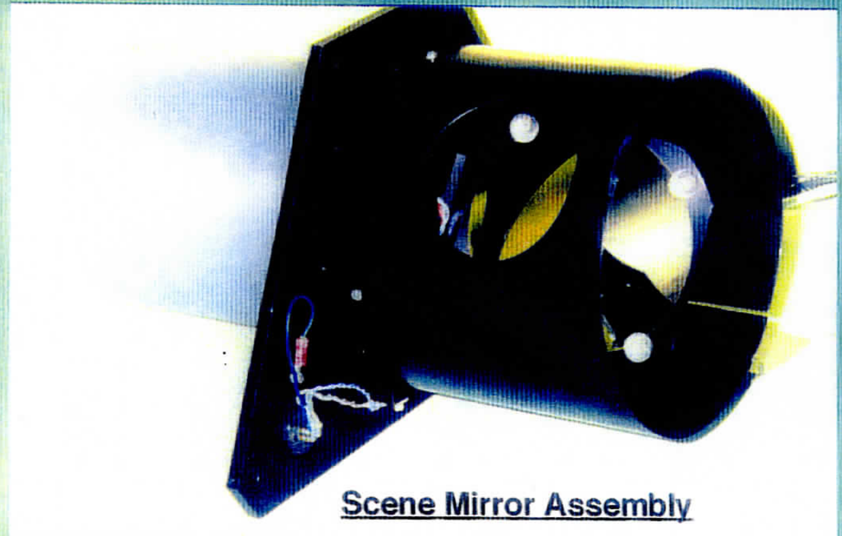
- AERI Instrument Hardware Overview
- AERI Instrument Calibration Errors Due to Blackbody Uncertainties
  - Temperature Knowledge of HBB, ABB, and Ambient Temperature
  - Emissivity Knowledge of HBB and ABB
- AERI Blackbody Design
- Summary of Blackbody Error Contributions
- Blackbody Calibration Traceability and Error Assessment
  - Combined Calibration System Errors
  - AERI Blackbody Thermistor Calibration
  - Temperature Non-uniformity Uncertainty
  - Paint / Cavity Emissivity
- AERI End-to-end Instrument Calibration Verification

AERI Interferometer Assembly



AERI Front End Hardware

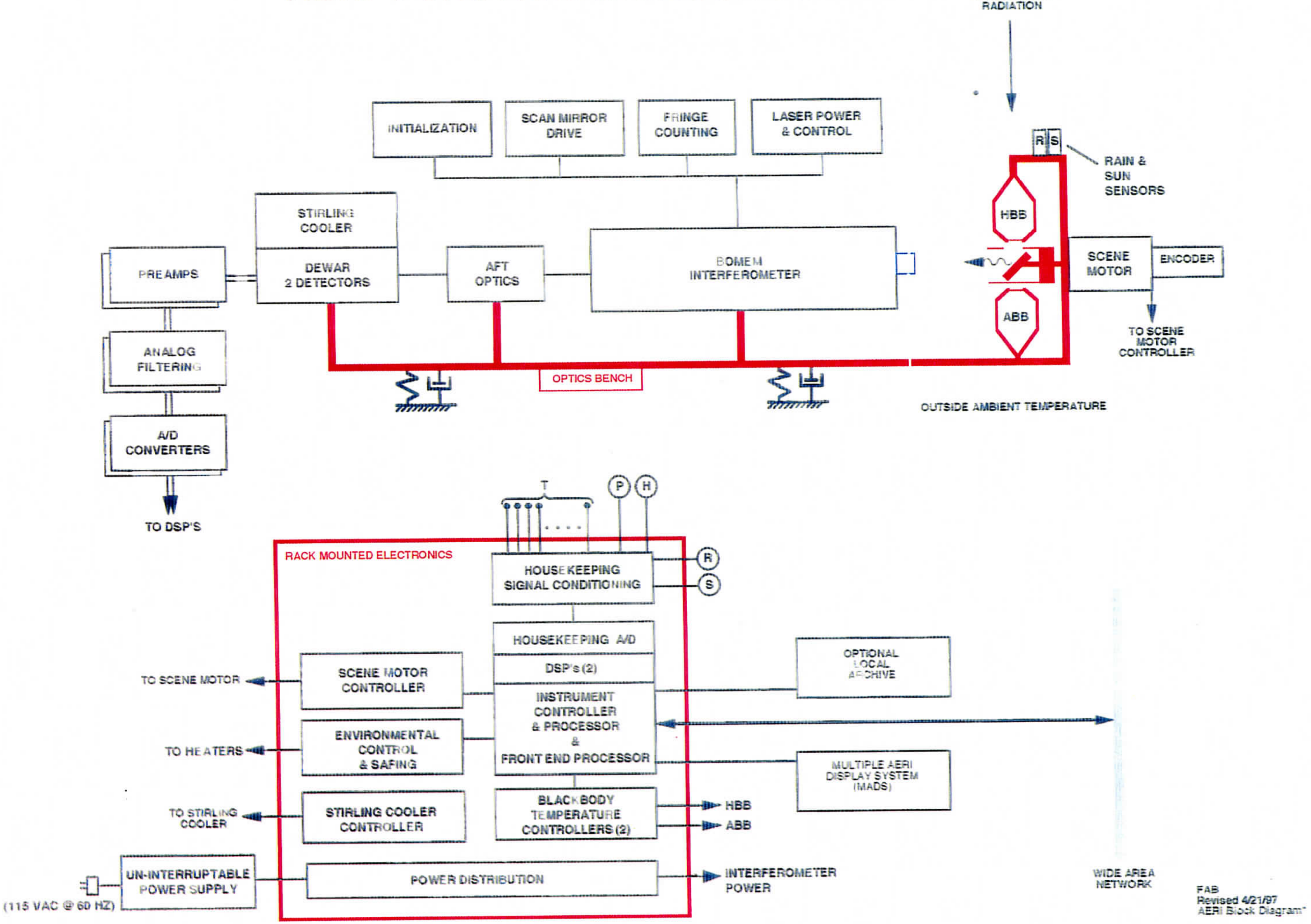
Interferometer Assembly



Scene Mirror Assembly

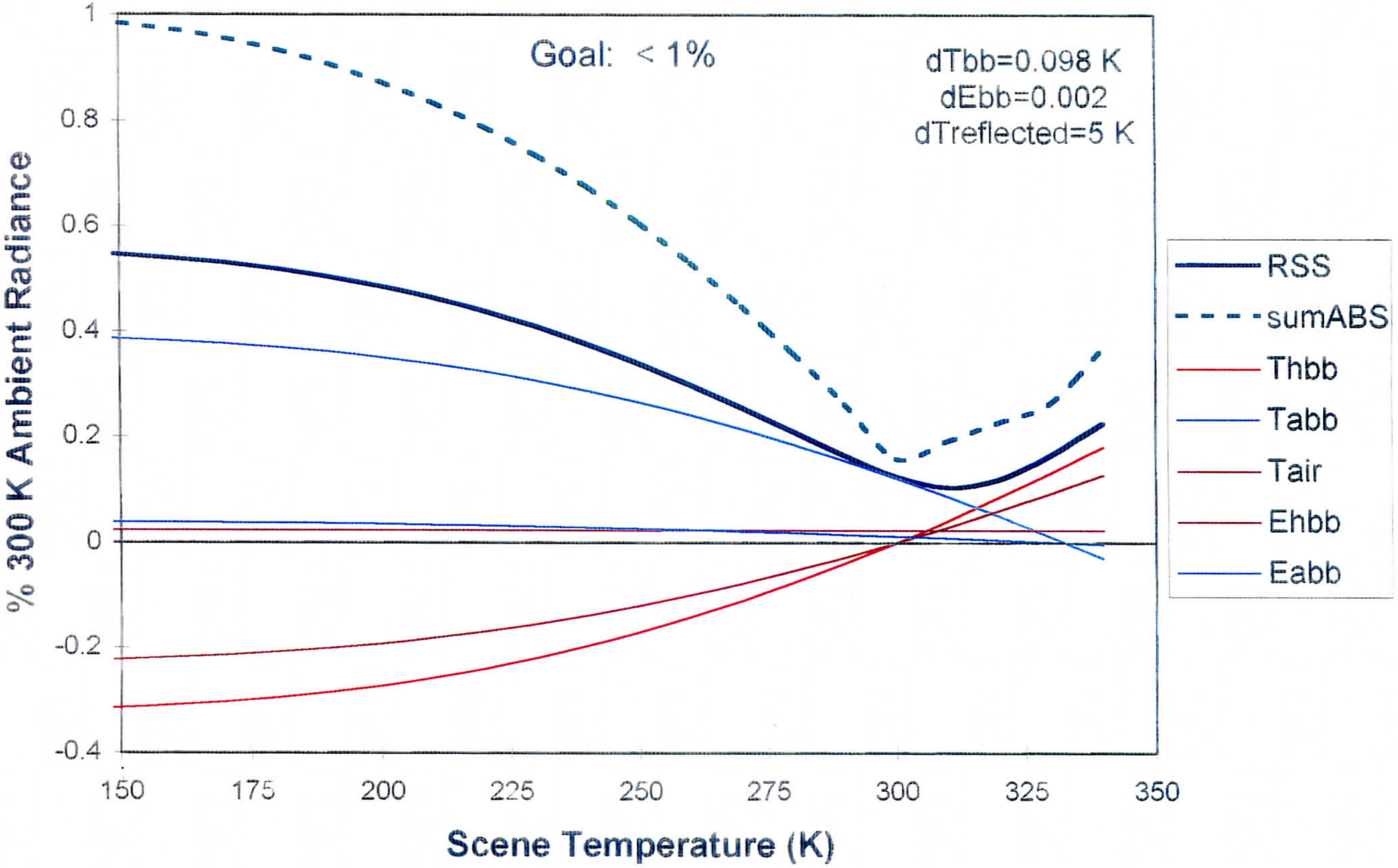
Interferometer Assembly Scene Mirror Removed

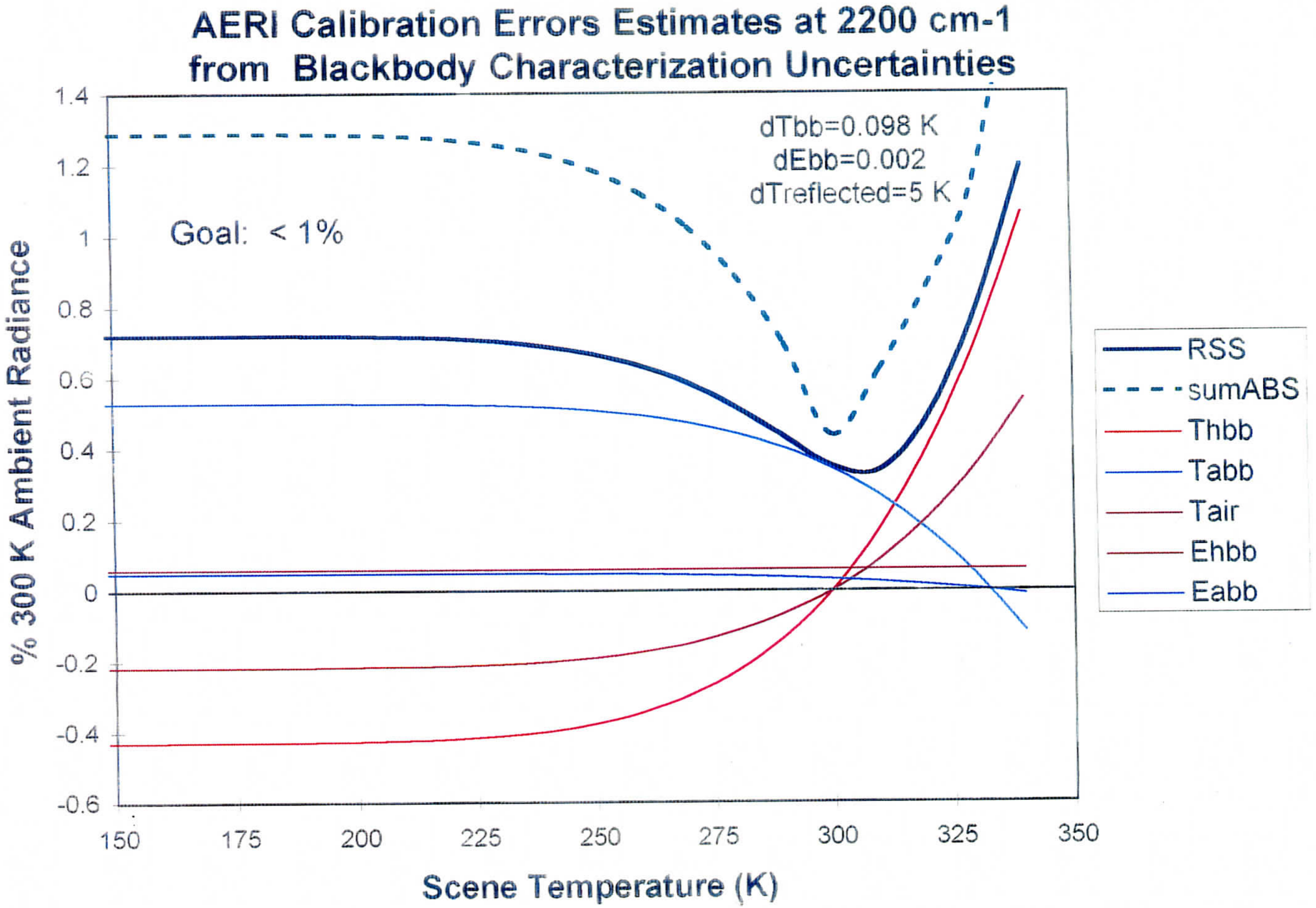
AERI FUNCTIONAL BLOCK DIAGRAM



FAB
Revised 4/21/97
AERI Block Diagram"

AERI Calibration Errors Estimates at 770 cm-1 from Blackbody Characterization Uncertainties





AERI Calibration Errors Estimates at 2200 cm-1 from Blackbody Characterization Uncertainties

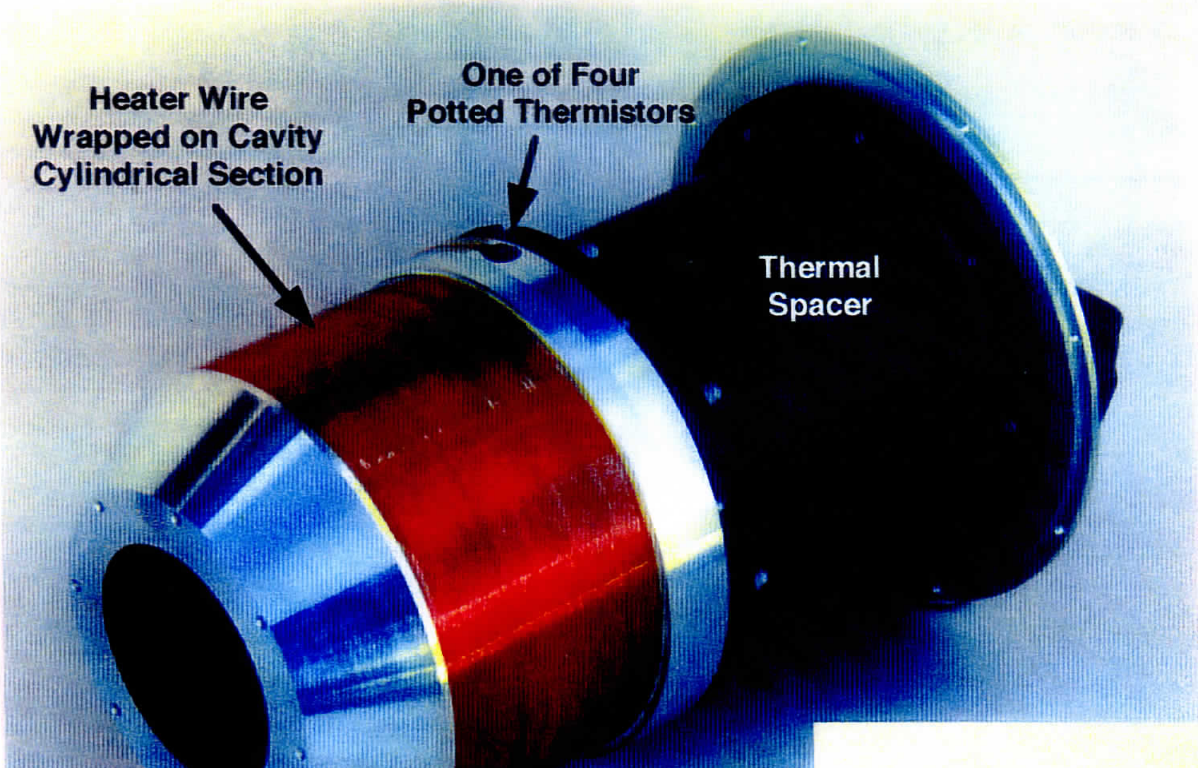
Top Level Design Choices for the AERI Blackbody

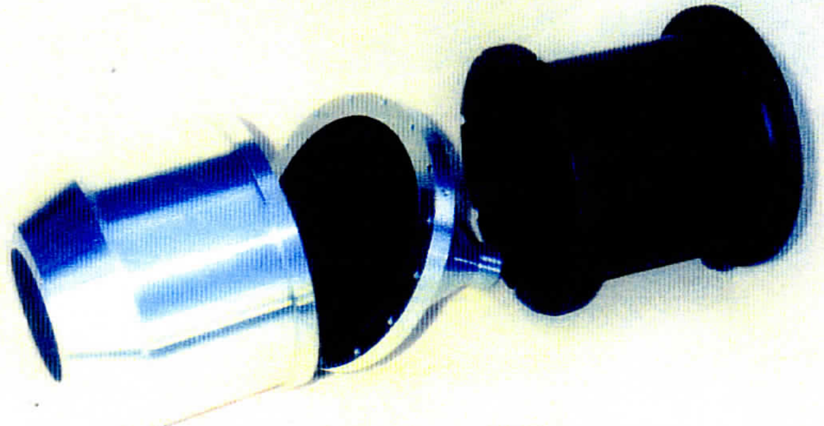
- **Cavity Approach**
  - Provides High Emissivity
  - Emissivity Enhancement Due to Cavity is Well Characterized
  - Cavity Walls Provide Good Thermal Conduction (Low Gradients)
  - Easy to Manufacture

- **Chemglaze Z-306 Paint**
  - Provides High Emissivity That is Well Characterized and Stable
  - Provides a Hardy Surface
  - Because the Paint is Diffuse, It's Emissivity is Less Sensitive to Slight Contamination than Specular Paint Would Be

- **Thermistor Temperature Sensors**
  - Very Stable
  - Easy to Couple Thermally to Blackbody Cavity
  - Reasonably Rugged

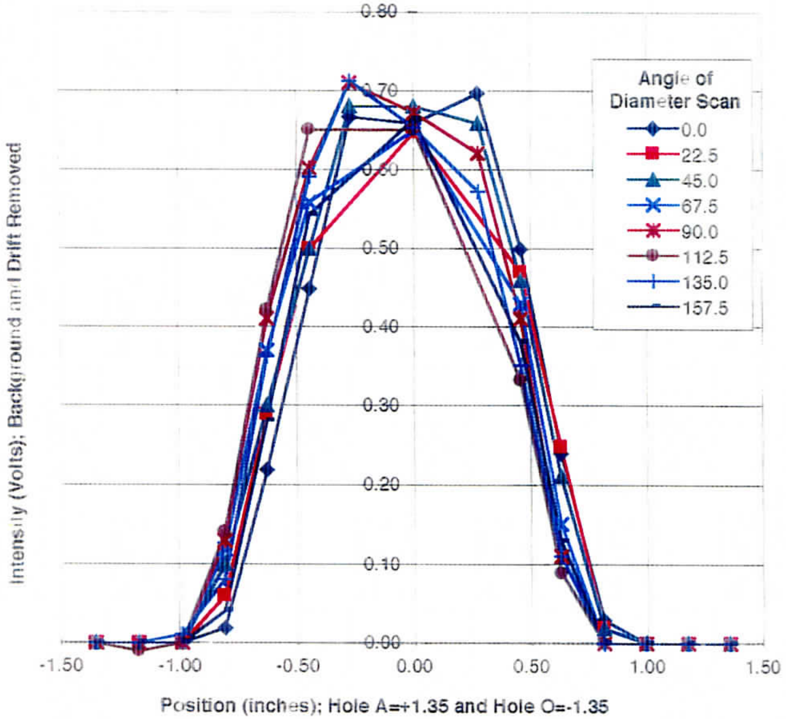
AERI 2.7 Inch Aperture Blackbody

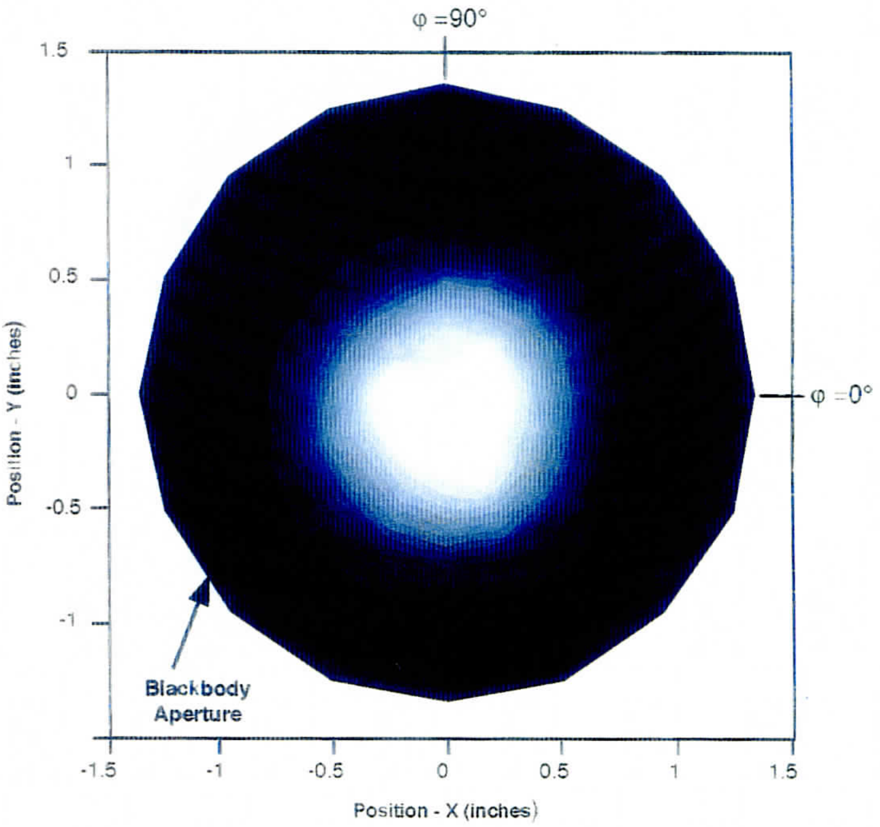



Barrrel, Cone, and Thermal Spacer

TYPICAL AERI FOV MAPPED AT A BLACKBODY POSITION

(Purpose of test: Insure the AERI Field-of-View is looking totally inside the blackbody)





Mapping of the AERI Field of View (FOV) at a blackbody position:

- A plate with a radially symetric array of 105 small apertures is positioned by alignment pins to the blackbody position.
- A small source is inserted into each aperture (in turn) and the amplitude at a given wavenumber is recorded.
- The source drift and background signal are removed and the data are plotted as shown above.

Summary of Blackbody Error Contributions

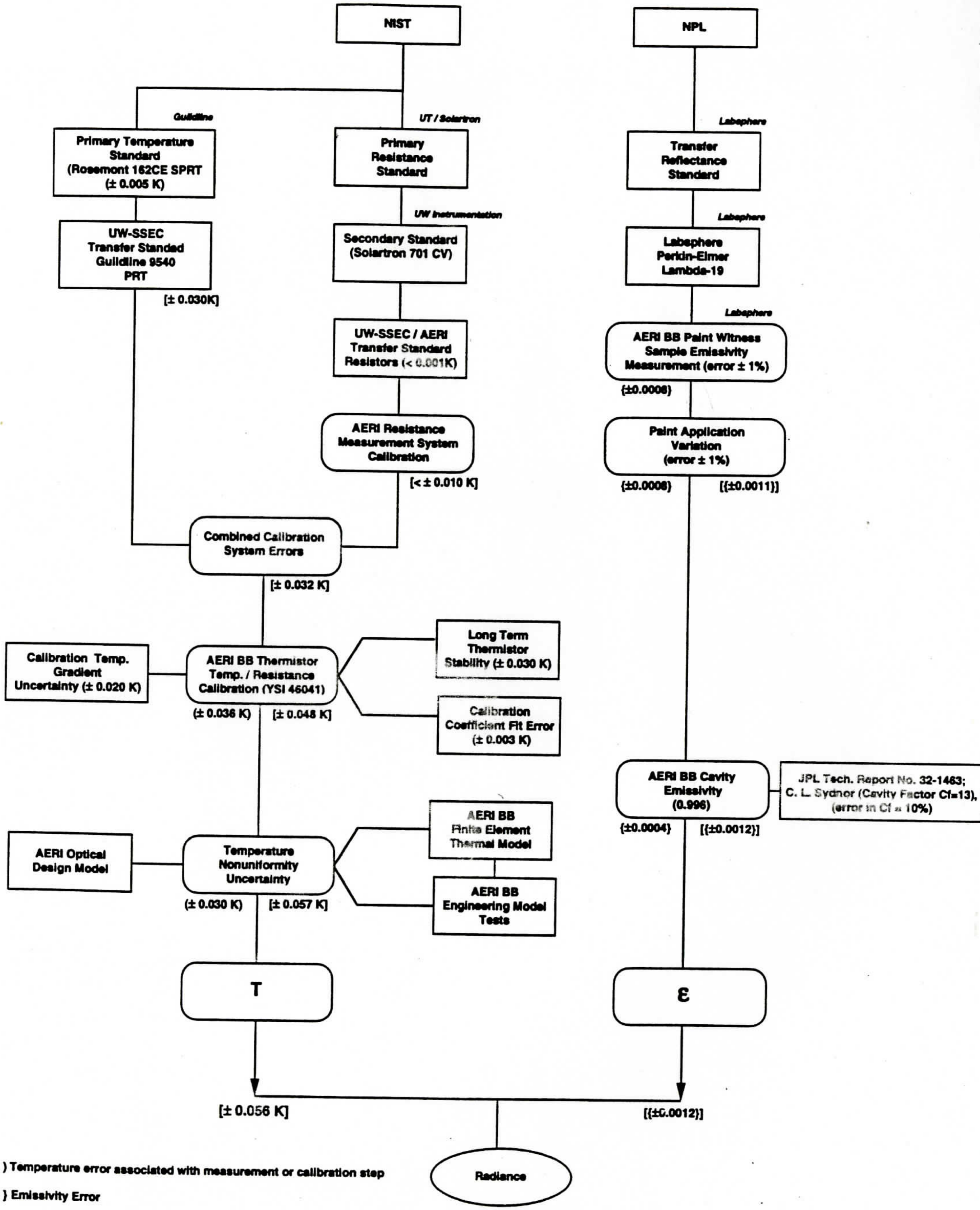
TEMPERATURE (errors in degrees K)

	± peak error	(RSS)	(Additive)
Calibration System Errors			
Temperature Transfer Standard (Guildline)	0.030		
Resistance Measurement System Calibration	0.010		
RSS ±	0.032	± 0.032	± 0.032
Thermistor Temperature Calibration			
Calibration Temperature Gradient Uncertainty	0.020		
Calibration Coefficient Fit Error	0.003		
Long-Term Stability	0.030		
RSS ±	0.036	± 0.036	± 0.036
Cavity Wall Temp. Non-uniformity Correction Uncertainty			
Azumuthal Gradients Due to Free Convection			
Longitudinal Gradients Due Primarily to Conduction			
Radial Gradients Due to Conduction, Convection, and Radiation			
RSS ±	0.030	± 0.030	± 0.030
		Total Error ± (RSS) 0.057	Total Error ± (Additive) 0.098

EMISSIVITY (errors in cavity emissivity)

	± peak error	(RSS)	(Additive)
Paint Witness Sample Measurement	± 0.0008	± 0.0008	± 0.0008
Paint Application Variation	± 0.0008	± 0.0008	± 0.0008
Cavity Factor Uncertainty	± 0.0004	± 0.0004	± 0.0004
		Total Error ± (RSS) 0.0012	Total Error ± (Additive) 0.0020

AERI BLACKBODY CALIBRATION TRACEABILITY AND ERROR ASSESSMEN

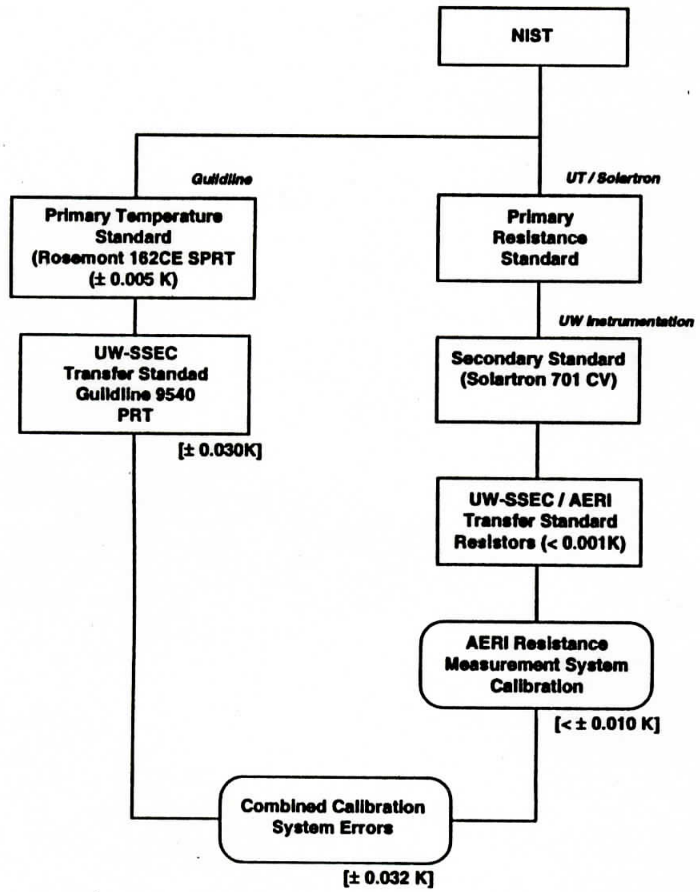


( ) Temperature error associated with measurement or calibration step

{ } Emissivity Error

[ ] Accumulated (RSS) quantity

AERI BLACKBODY CALIBRATION - TEMPERATURE AND RESISTANCE STANDARDS



NIST

Guildline

Primary Temperature Standard (Rosemont 162CE SPRT (± 0.005 K)

UW-SSEC Transfer Standad Guildline 9540 PRT

[± 0.030K]

UT / Solartron

Primary Resistance Standard

UW Instrumentation

Secondary Standard (Solartron 701 CV)

UW-SSEC / AERI Transfer Standard Resistors (< 0.001K)

AERI Resistance Measurement System Calibration

[< ± 0.010 K]

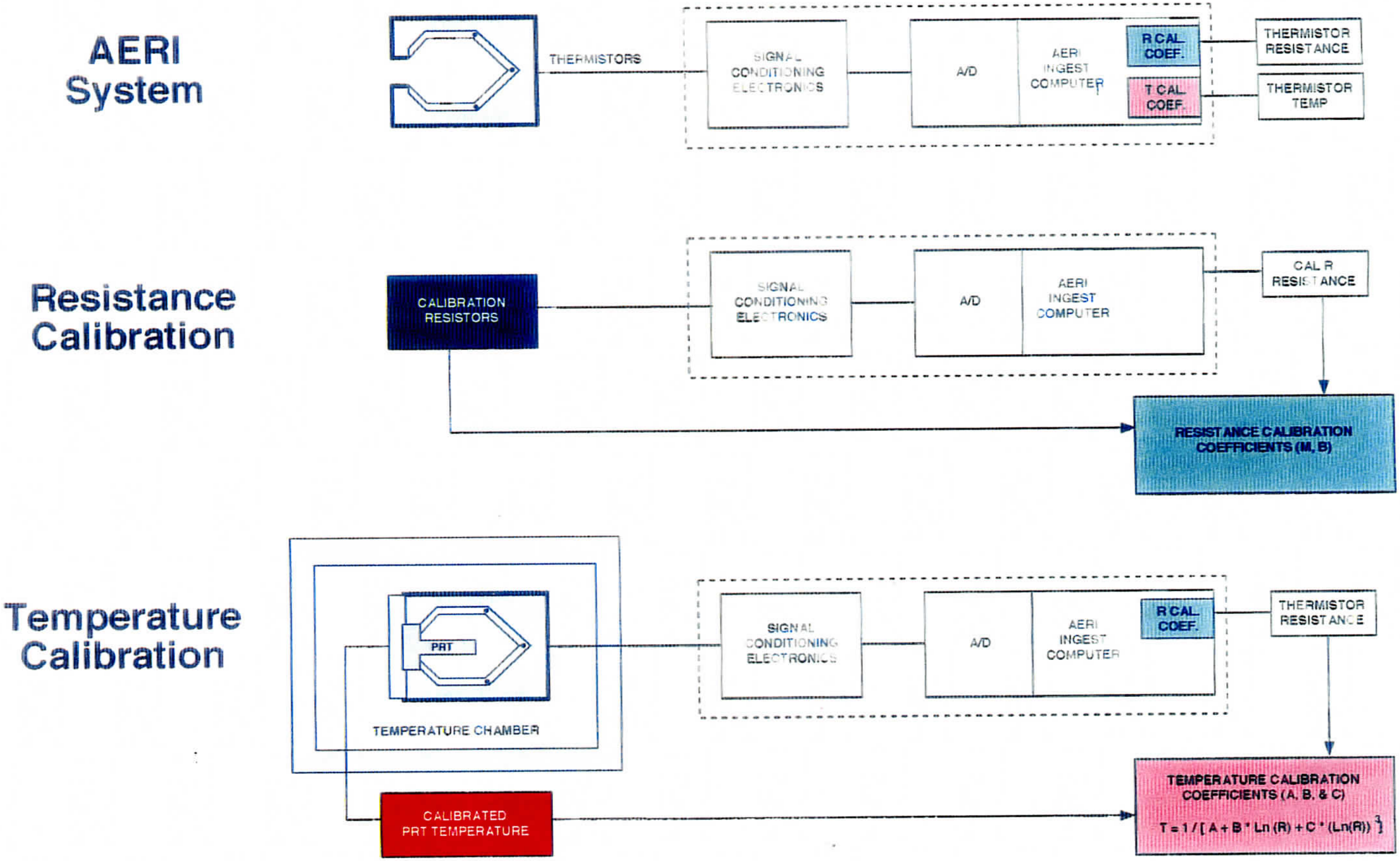
Combined Calibration System Errors

[± 0.032 K]

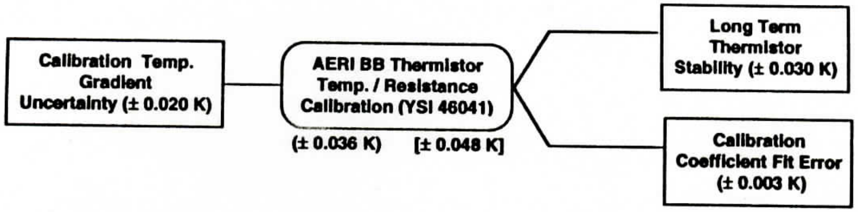
- The Calibration System involves both temperature and resistance measurements.
- UW SSEC maintains a calibrated Guildline 9540 PRT for use as a Transfer Standard.
- This PRT instrument is used as a Transfer Standard between the Rosemont 162CE SPRT (Maintained at Guildline) and the AERI Blackbody thermistors.
- UW SSEC maintains a set of calibrated resistors with values corresponding to the expected range of thermistors.
- These calibrated resistors are used in the end to end calibration of the AERI thermistor resistance reading electronics.
- This end-to-end calibration involves all the hardware and software that make up the AERI thermistor reading electronics.
- The calibration of each resistance measurement channel results in a linear regression fit over the resistance measurement range.

- The AERI blackbody thermistors could be calibrated using the Transfer Standard PRT and an uncalibrated resistance measurement electronics. However, this scheme would not allow blackbodies to be interchangeable between different sets of electronics - the blackbodies would have to be used only with the resistance measurement system that they were calibrated with. This constraint is very undesirable if there are several instruments in various locations in the field, without access to calibration facilities (temperature chambers).

AERI BLACKBODY CALIBRATION



AERI BLACKBODY CALIBRATION - THERMISTOR CALIBRATION



- The Guildline PRT is conductively coupled to the AERI Blackbody cavity . The PRT / Blackbody assembly is heavily insulated and placed inside a temperature chamber.

- The AERI Blackbody is connected to the calibrated AERI Resistance Measurement Electronics in the same way as for normal use.

- Thus, during calibration the AERI Blackbody thermistors are powered and sampled the same way as they are during normal use (using the same hardware and software).

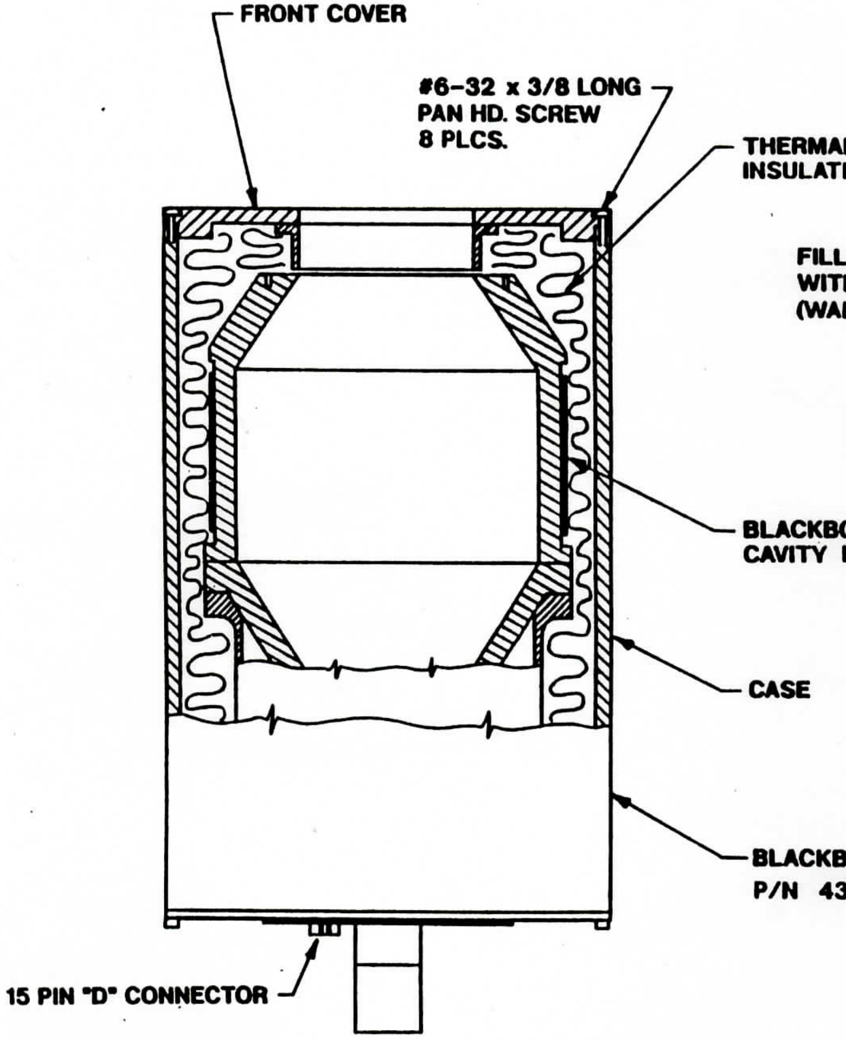
- This scheme eliminates thermistor self heating differences between calibration and normal use. In general, these self heating differences can be a problem if thermistor resistances are measured using a DVM.

- Typically there are five temperatures used for AERI Blackbody thermistor calibration. A regression fit of these five (temperature, resistance) points is used to determine the three traditional Steinhart and Hart coefficients: A, B, and C. The fit relationship represents test results to with an error of less than ± 0.003 K.

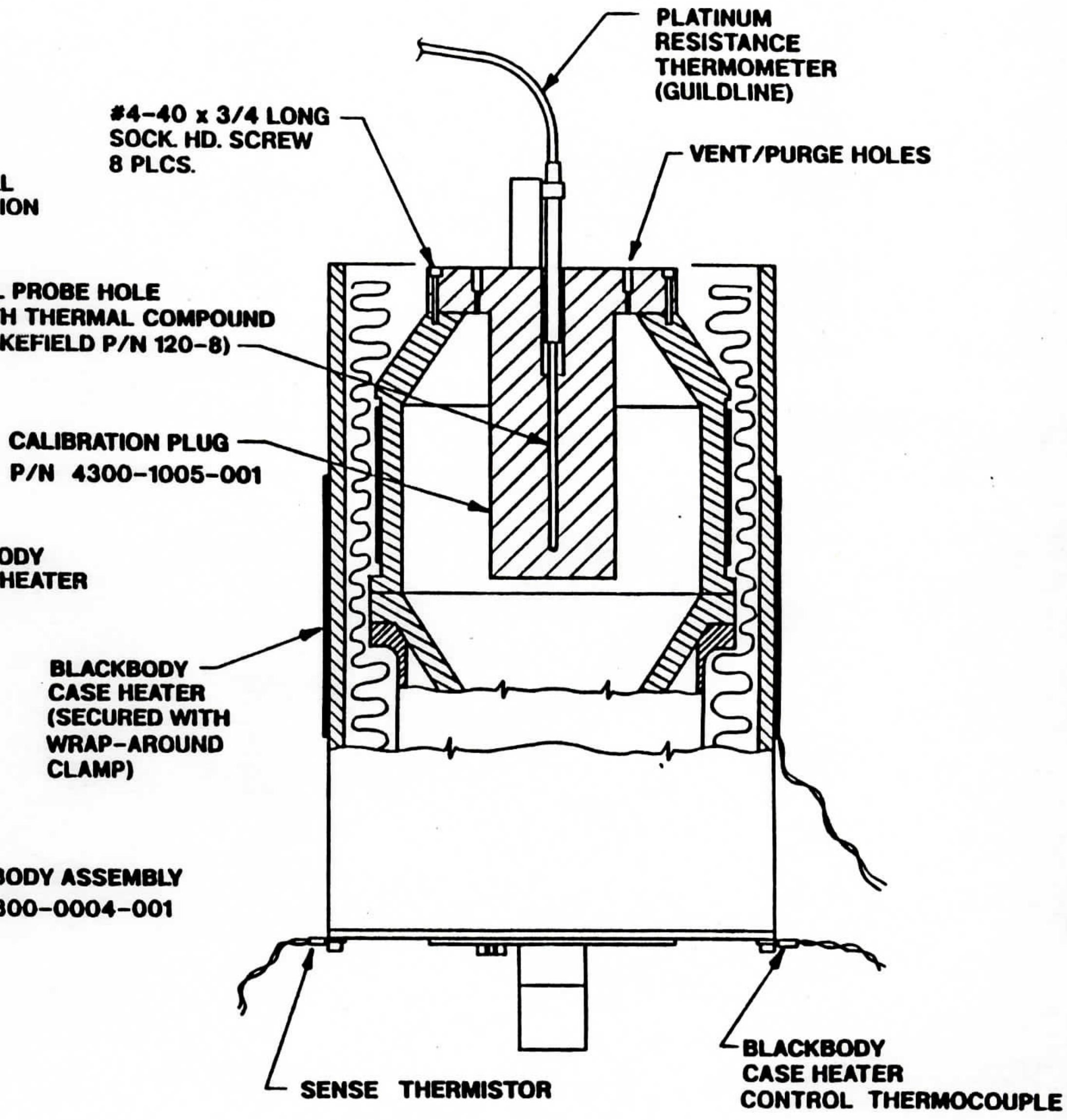
- The thermistors used in the AERI Blackbodies are YSI 46041 Super-Stable Precision Themistors. The thermal drift of these thermistors at 70°C after 100 months is specified to be less than 0.01°C.

- The thermistors are mounted in holes drilled into the cavity wall using thermally conductive (non-creeping) paste, which provides a stress free thermal coupling.

- Although the test set-up and procedure facilitate a very high degree of isothermality at each temperature calibration point, there is an uncertainty of ±0.02 allocated for the gradient between the Guildline probe and the thermistors that are imbeded in the cavity.



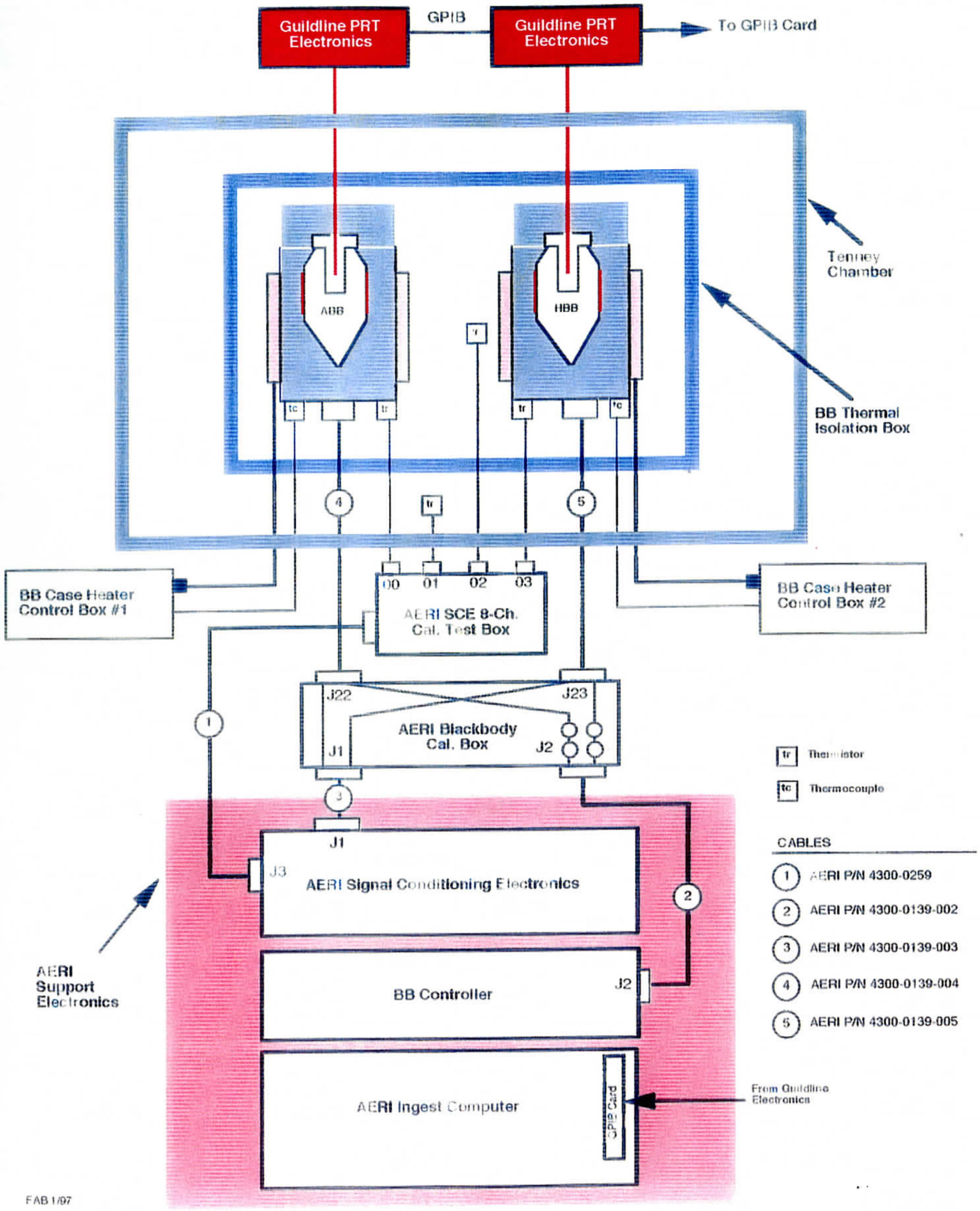
BLACKBODY ASSEMBLY



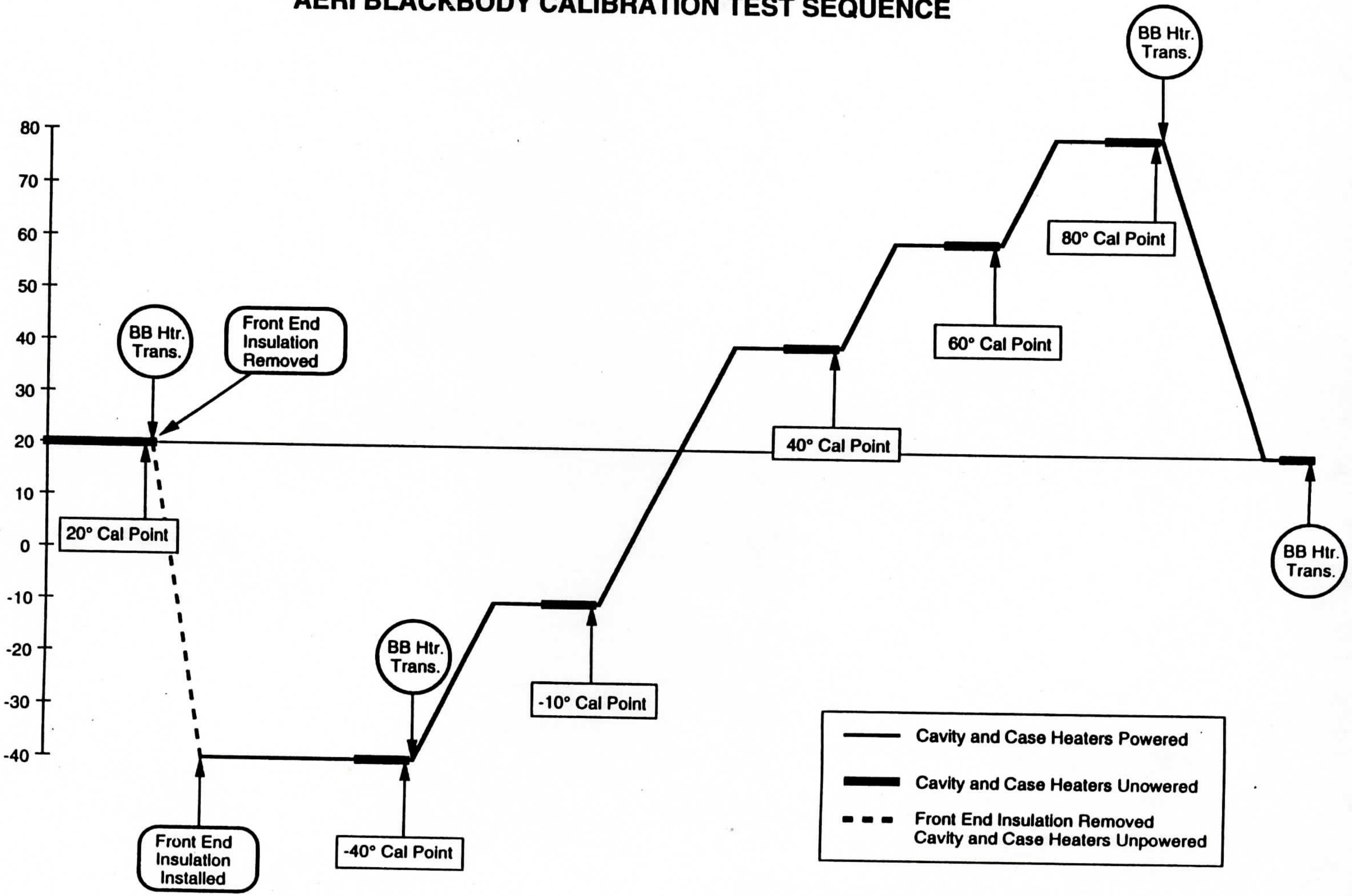
BLACKBODY ASSEMBLY

WITH CALIBRATION PLUG, CASE HEATER,

AERI BLACKBODY CAIBRATION TEST CONFIGURATION



AERI BLACKBODY CALIBRATION TEST SEQUENCE



AERI Thermistor Calibration Coefficients Using Regression Fit of Steinhart and Hart Relationship

$$1/T = A + B^*(\ln(R)) + C^*(\ln(R))^3$$

If n (absolute) temperature-resistance points (R_1, T_1), (R_2, T_2), ...(R_n, T_n), are determined by test, the least square best fit Steingart and Hart Coefficients can be determined by assembling and solving the matricies as shown below:

$$|R| \quad * \quad |S| \quad = \quad |Z|$$

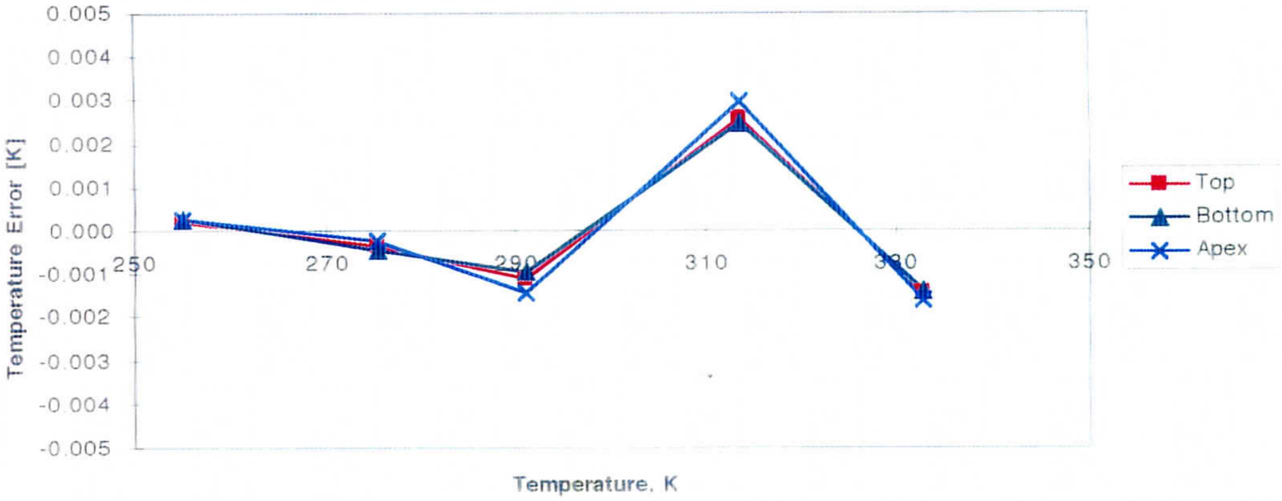
$$\begin{vmatrix} n & \sum(\ln(R_i)) & \sum(\ln(R_i))^3 \\ \sum(\ln(R_i)) & \sum(\ln(R_i))^2 & \sum(\ln(R_i))^4 \\ \sum(\ln(R_i))^3 & \sum(\ln(R_i))^4 & \sum(\ln(R_i))^6 \end{vmatrix} * \begin{vmatrix} A \\ B \\ C \end{vmatrix} = \begin{vmatrix} \sum(1/T_i) \\ \sum(1/T_i)^*(\ln(R_i)) \\ \sum(1/T_i)^*(\ln(R_i))^3 \end{vmatrix}$$

Where the sumations sum over the number of data points n, which is the number of data points. The coefficient matrix [S] can be solved for by premultiplying the [Z] matrix with the inverse of the [R] matrix:

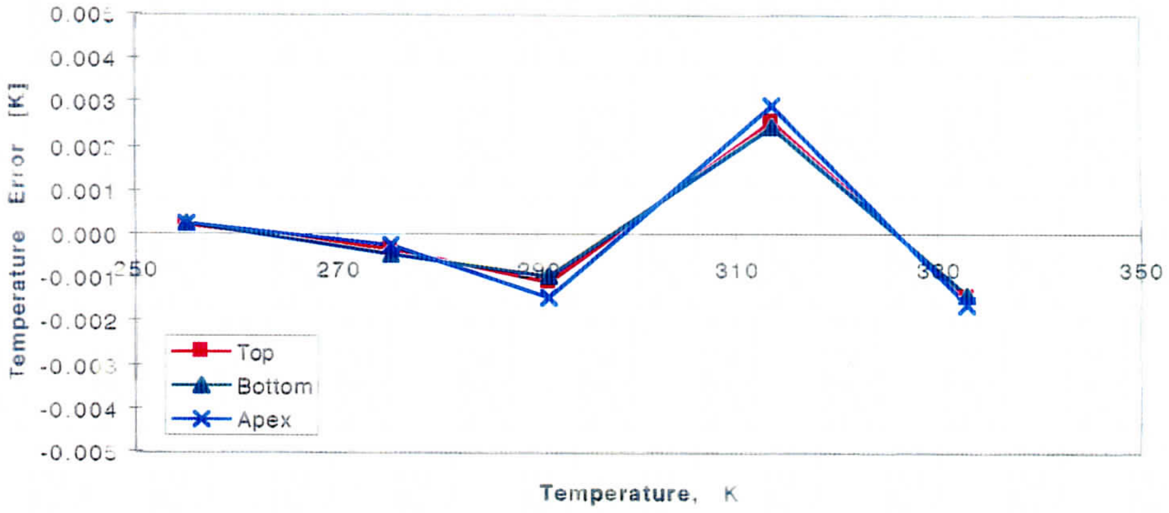
$$|S| = |R|^{-1} * |Z| = \begin{vmatrix} A \\ B \\ C \end{vmatrix}$$

Typical Errors Due to Regression Coefficient Fit

(for the three thermistors of one blackbody)

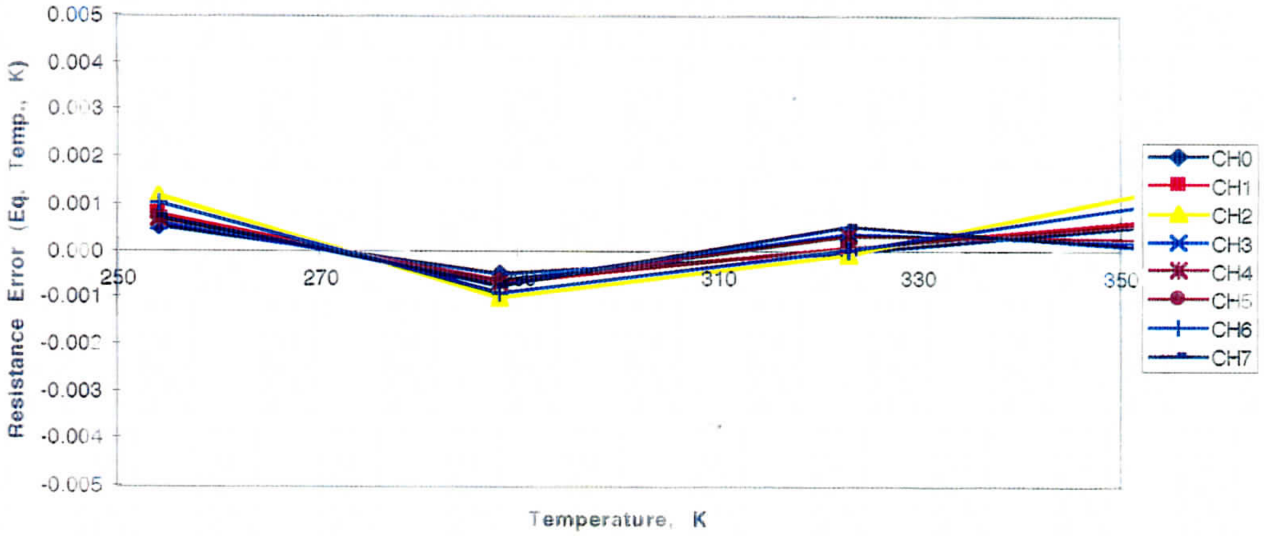


AERI Regression Fit and Resistance Measurement Errors Compared



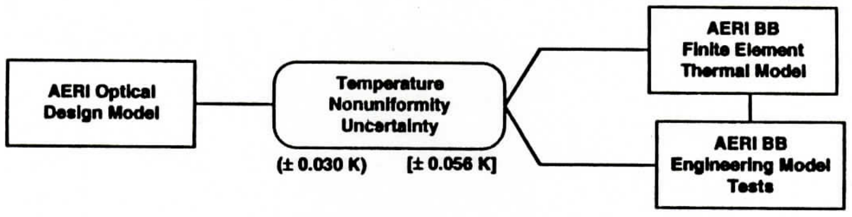
Errors Due to Regression Coefficient Fit

(for the three thermistors of one blackbody)



Typical AERI Resistance Measurement Errors

AERI BLACKBODY CALIBRATION - TEMPERATURE NON-UNIFORMITY UNCERTAINTY



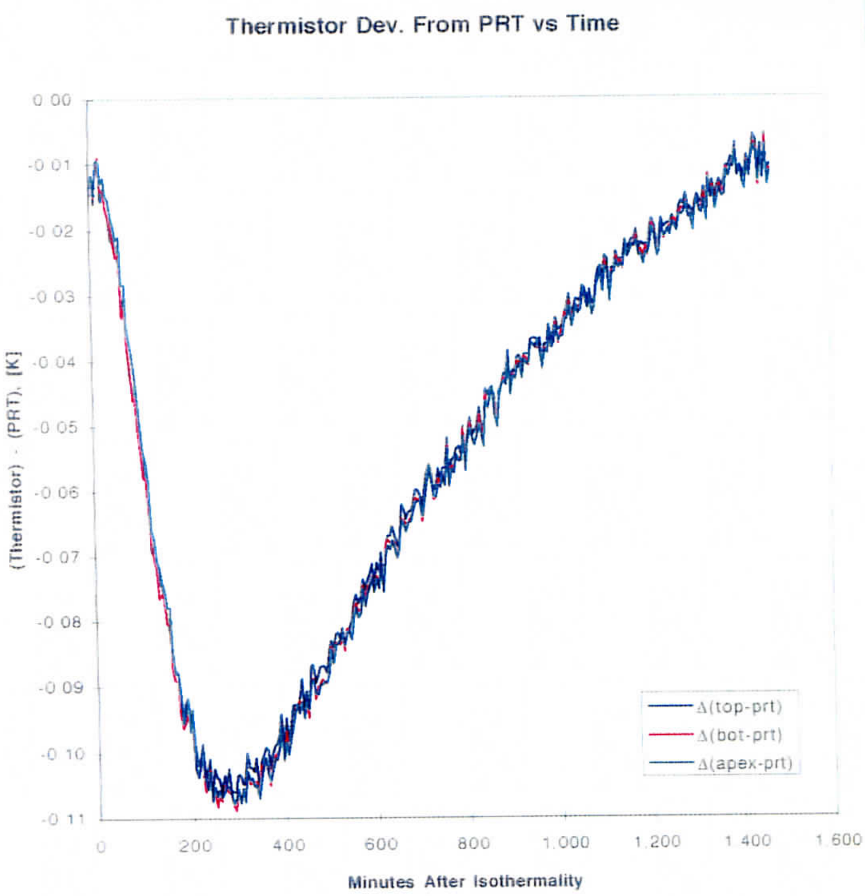
- When the AERI Blackbody is not operated at ambient temperature, thermal gradients will develop in the cavity wall that are proportional to the temperature difference between blackbody set point and ambient . Typically, the AERI Hot BB is run at 60°C at with an ambient temp. of 20°C; gradient numbers presented below assume this typical Blackbody operation point.

- Three types of gradient are accounted for in the AERI Blackbodies:

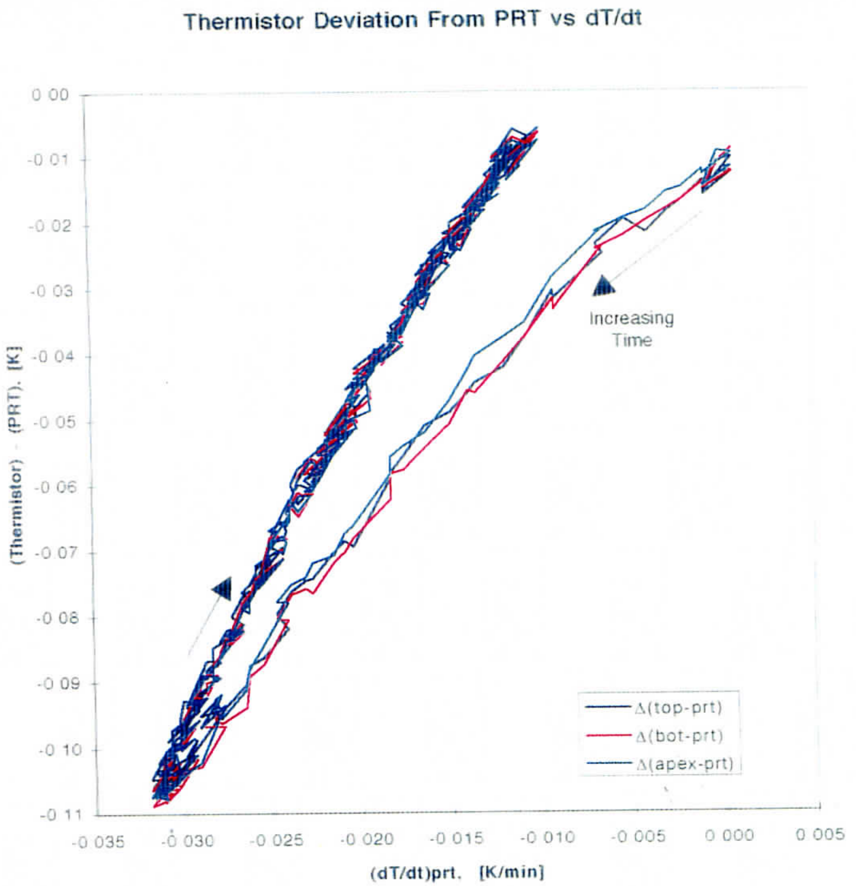
  (1) Thermistor to cavity inner wall temperature gradient. This gradient in the aluminum is calculated using the AERI Blackbody thermal model and is found 0.01 C for the apex thermistor and 0.02 C for the thermistors on the cylinder diameter. The gradient in the paint due to free convection and radiation must be added to these values. Results of testing indicate that these values are less than 0.01C.

  (2) Longitudinal gradients along cavity inner wall. With the AERI Blackbody thermal model and the AERI Optical Design model, Temperature Weighting Functions are calculated using the available thermistors located in the cavity apex (1) and on the cylinder diameter (3).

  (3) Azumuthal variations around the cavity inner wall due to convection. When the Blackbody is tipped toward one side, these gradients tend to be symmetric about the "top" side and "bottom" side. The top and bottom cylinder diameter thermistors are averaged to account for this gradient which is on the order of (0.07 C).



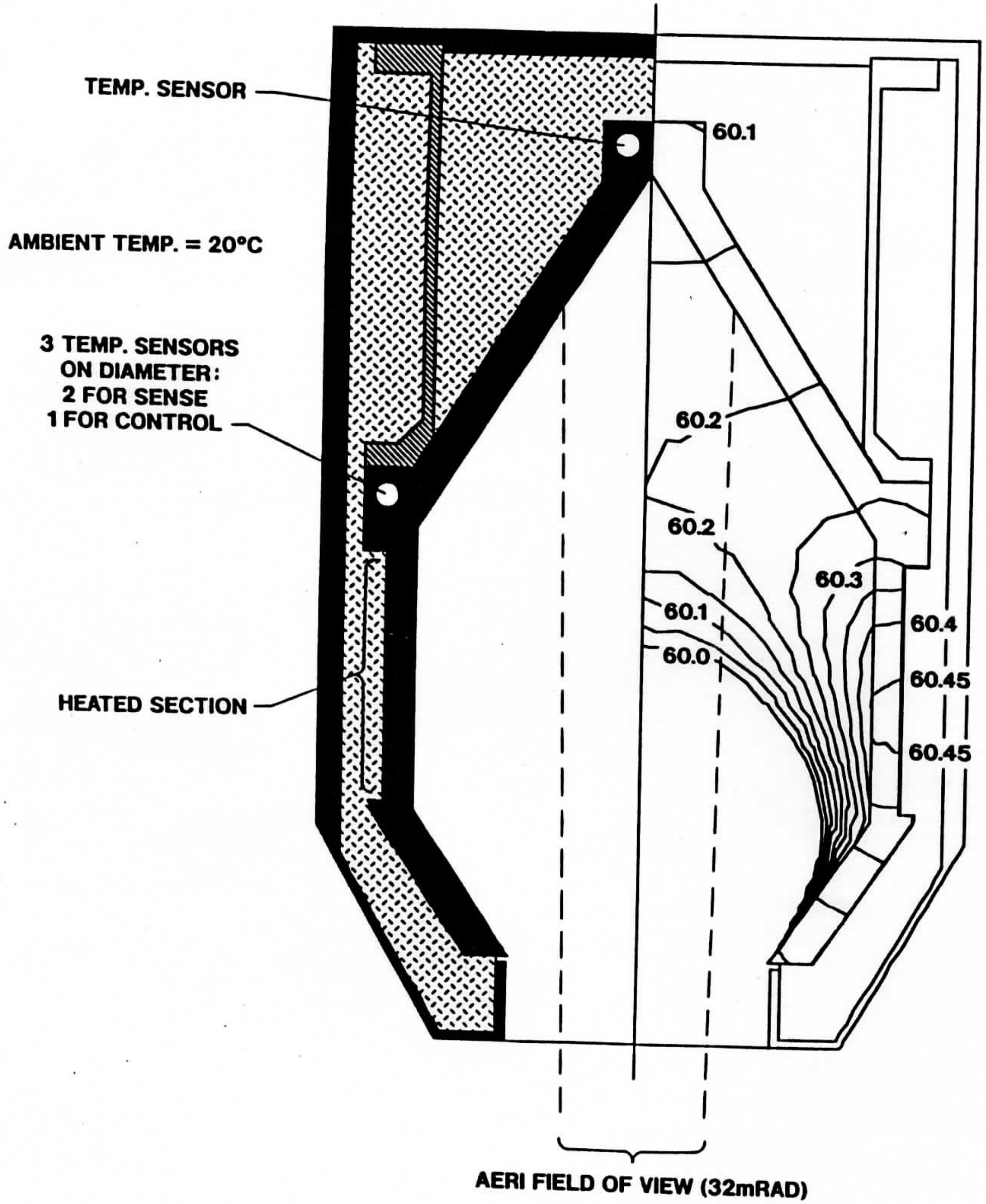
Thermistor Dev. From PRT vs Time

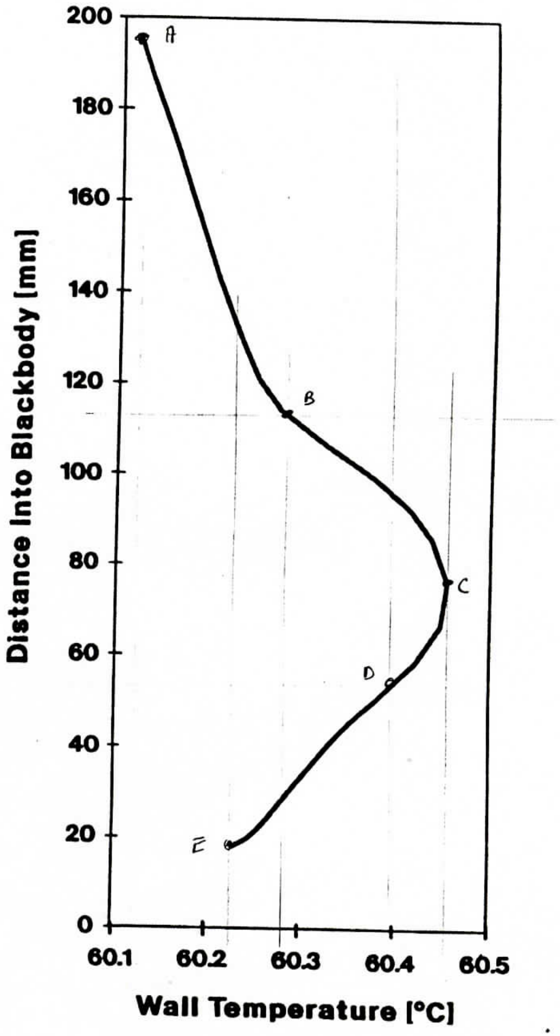


Thermistor Deviation From PRT vs dT/dt

Difference between each of the three AERI blackbody thermistors and the Calibration PRT during cooldown from 60 °C to 20 °C. Before the start of the test, Isothermality of the blackbody was achieved inside its calibration thermal isolation box at 60 °C. At time = zero, the temperature chamber door was opened to allow free convection between the isolation box and the room ambient air (20 °C). The left curve shows the difference between the (calibrated) blackbody thermistors and the calibration PRT vs time after chamber door opening. The right curve shows these same differences vs the time rate of change of the calibration PRT. The purpose of the test was to determine the allowable blackbody time rate of change during calibration that would keep the gradients between the thermistors and the PRT within acceptable limits. At the start of the test the thermistor / PRT gradient is shown as somewhat larger that 0.01; this is the thermistor calibration coefficient regression error. For the purposes of calibration, a gradient magnitude of 0.01 K is acceptable between a thermistor and the calibration PRT. The curve at right indicates that PRT temperature rates of change less than 0.003 K/min would keep the thermistor / PRT gradients less than -0.01 K (read off the Y-axis at -0.02 K because of the added -0.01 K offset due to the thermistor coefficient regression fit error.)

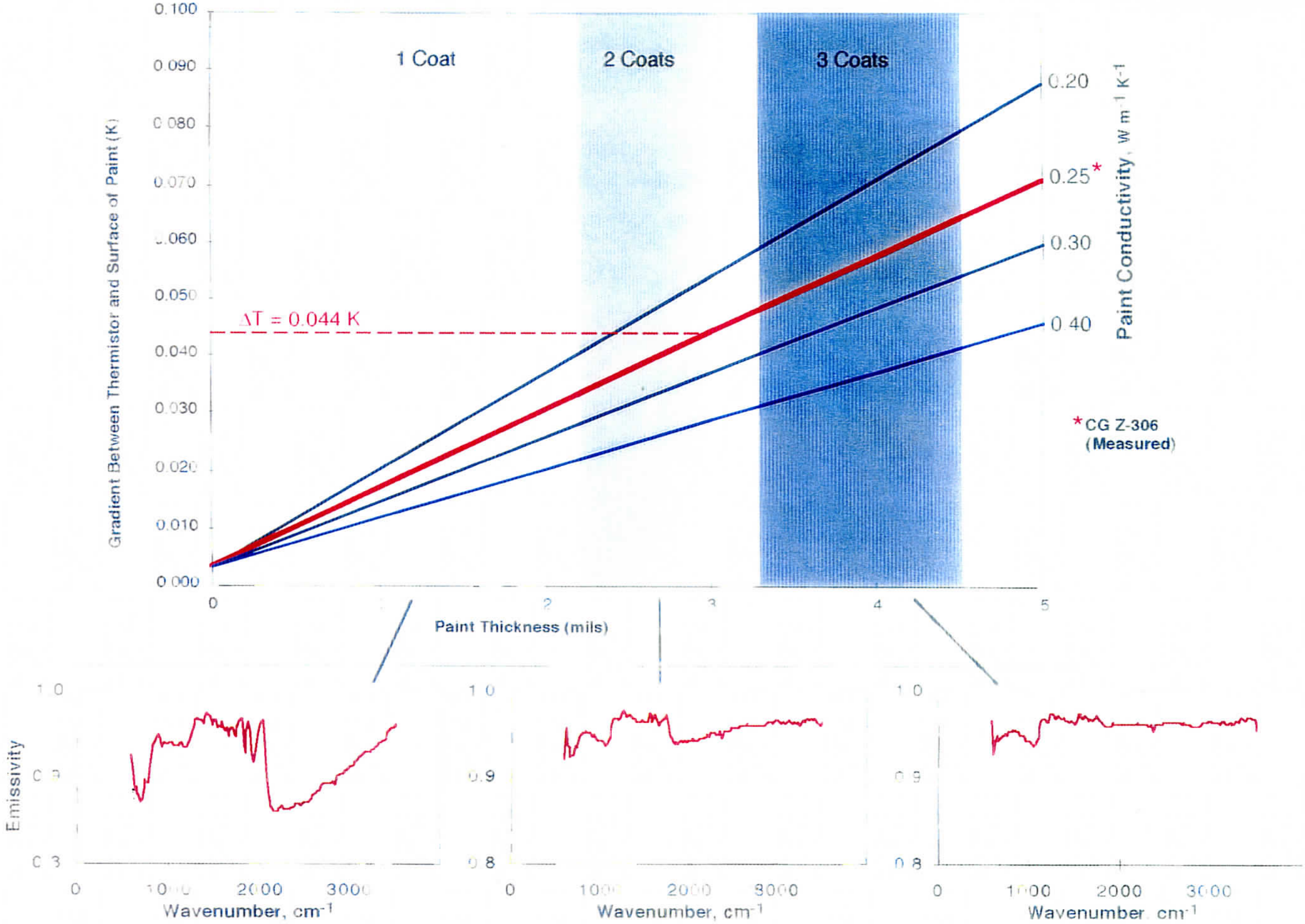
AERI BLACKBODY THERMAL MODEL RESULTS



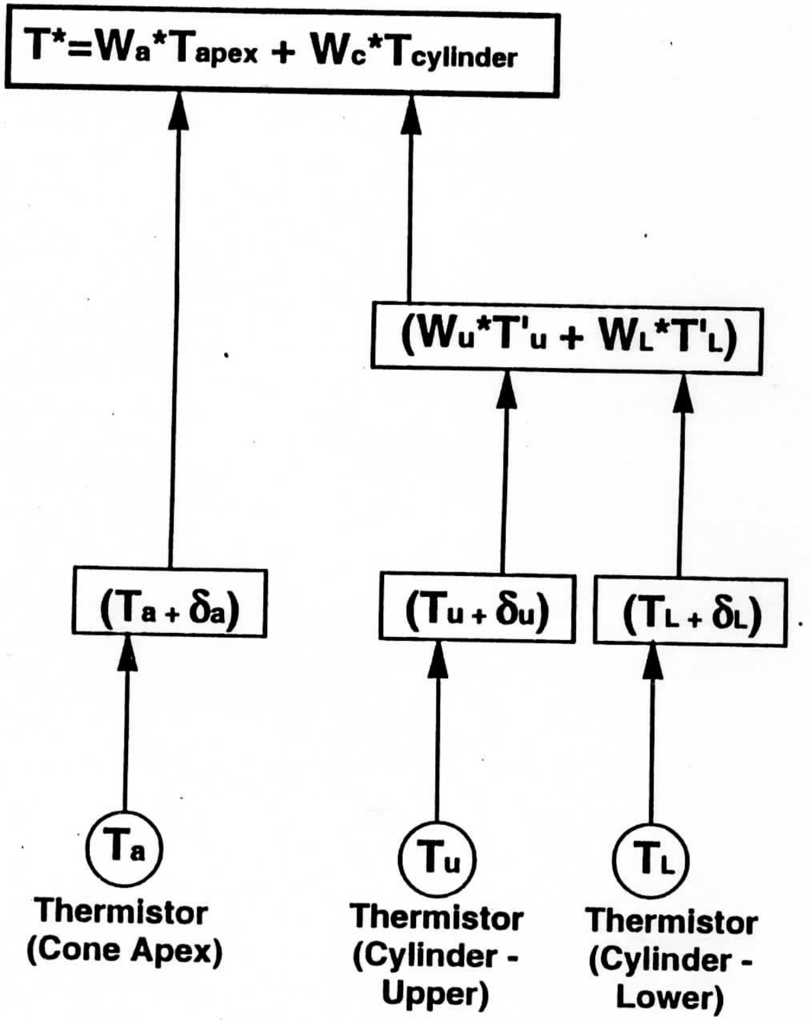


Temperature Gradient Estimates Between Thermistor and Paint Surface

(Estimated Maximum Heat Flux Between BB Aperture Open and Closed is 133 W/m^2)



AERI Blackbody Temperature Non-Uniformity Weighting Factors



$T^{*}=W_a{*}T_{apex} + W_c{*}T_{cylinder}$

$(W_u{*}T'_u + W_L{*}T'_L)$

$(T_a + \delta_a)$

$(T_u + \delta_u)$

$(T_L + \delta_L)$

T_a Thermistor (Cone Apex)

T_u Thermistor (Cylinder - Upper)

T_L Thermistor (Cylinder - Lower)

T* is the Radiometeric Blackbody Temperature Used in the AERI Calibration Algorithm.
Wa and Wc Account for Longitudinal Gradients by Weighting BB Thermistor Temperatures Based on AERI Viewing Geometry and Thermal Model and Thermal Test Results.

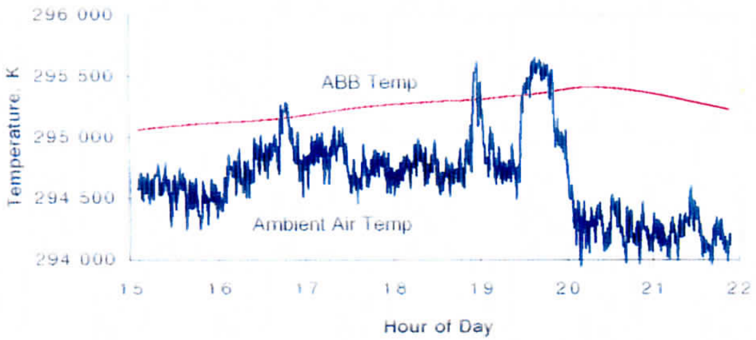
W_u and W_L are Azimuthal Weighting Factors For the Upper and Lower Thermistors That are Located in the Cavity Cylindrical Section.
These Weighting Factors Account for Convection Asymmetries.

$$\delta_i = (\delta_i)_{\Delta=40} * \frac{(T_{HBB}-T_{ABB})}{(40)} \quad \text{(where i = a, u, L)}$$

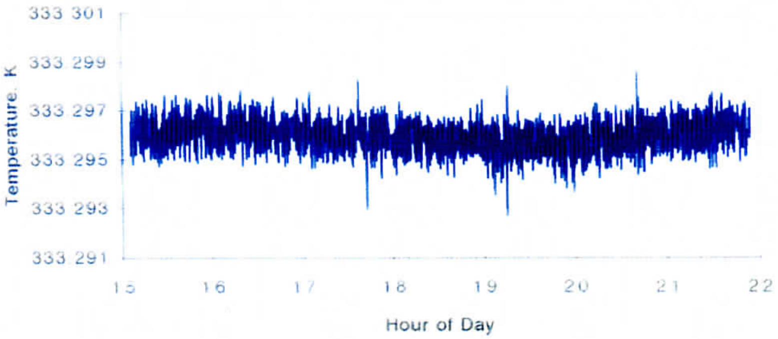
(δ's represent gradient between thermistor location and cavity inner wall. δ's at $\Delta=40$ determined by thermal model.)

AERI Hot Blackbody Temperature Stability

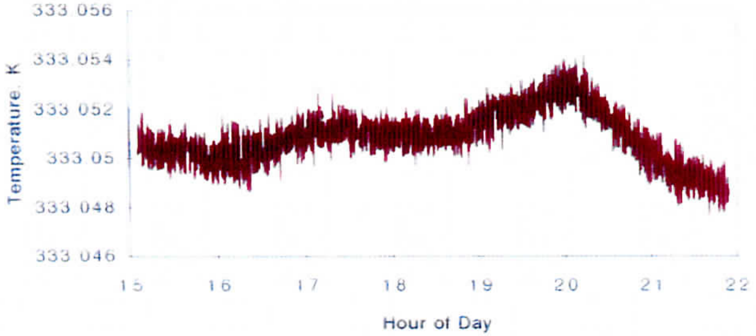
ABB Apex Thermistor



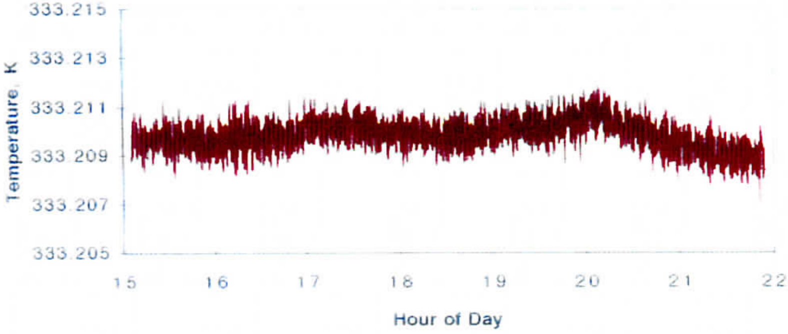
HBB Top Thermistor



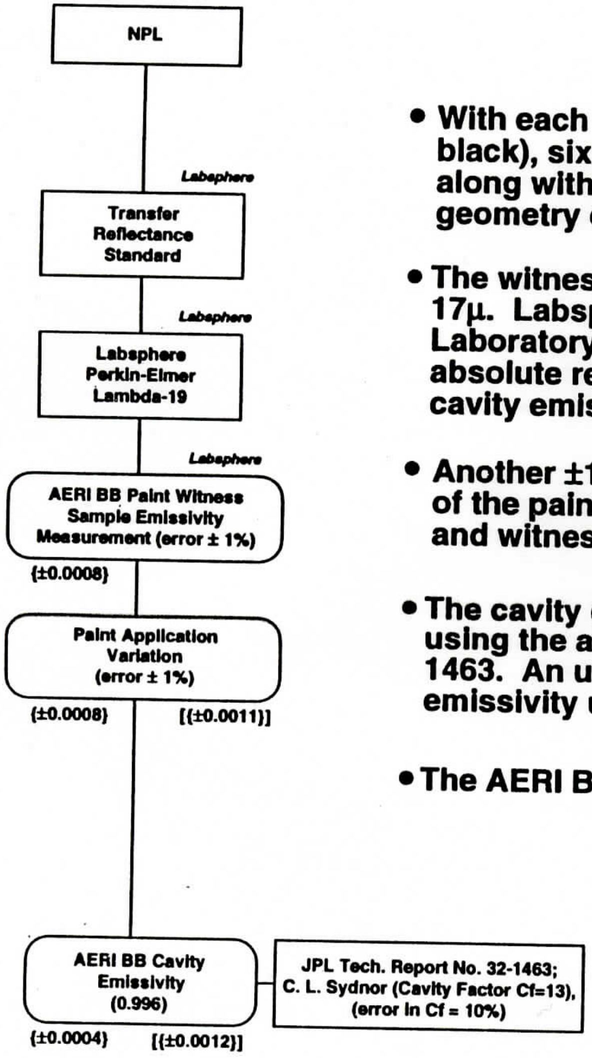
HBB Apex Thermistor



HBB Bottom Thermistor



AERI BLACKBODY CALIBRATION - DETERMINATION OF EMISSIVITY



- With each lot of AERI Blackbody cavities that are painted (with Chemglaze Z306 flat black), six witness samples are coated at the same time. These samples are cured along with the cavities. The witness samples are painted in a fixture that mimics the geometry of the blackbody cone.

- The witness samples are sent to Labsphere for reflectance measurements, from 2 to 17μ. Labsphere maintains reflectance traceability back to the National Physical Laboratory in England. Emissivity is (1-Reflectance). Labsphere measures the absolute reflectance of the witness samples to better than ±1%. This translates to a cavity emissivy uncertainty of ±0.0008.

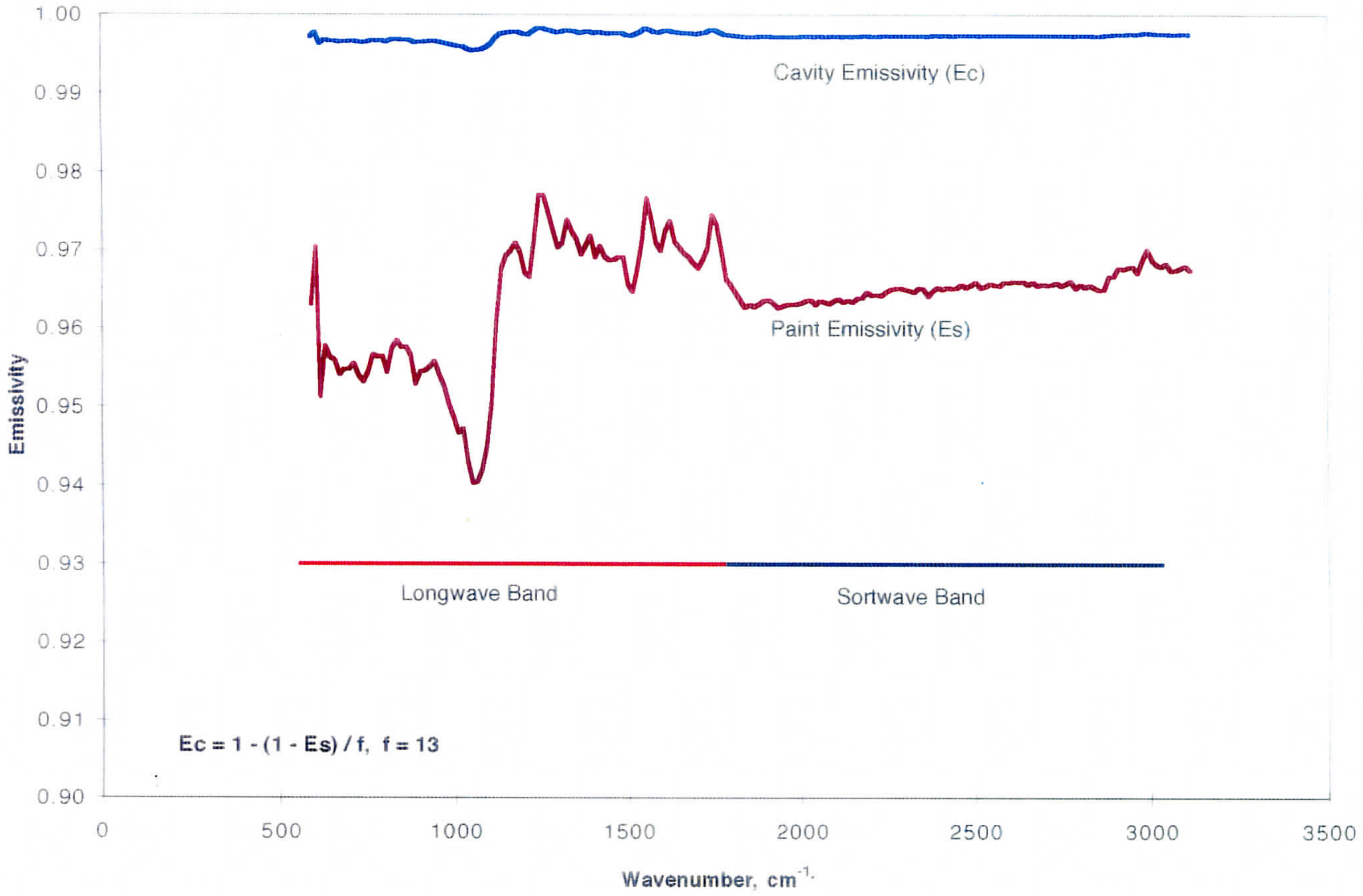
- Another ±1% uncertainty has been added to account for the variation in the application of the paint. This accounts for variations within a blackbody and between blackbody and witness samples. This value was chosen based on experience.

- The cavity enhancement factor for the AERI Blackbodies is calculated to be 12.76, using the analysis of C. L. Sydnor which is presented in JPL Technical Report No. 32-1463. An uncertainty of 10% has been added to this factor. This translates to a cavity emissivity uncertainty of ±0.0004.

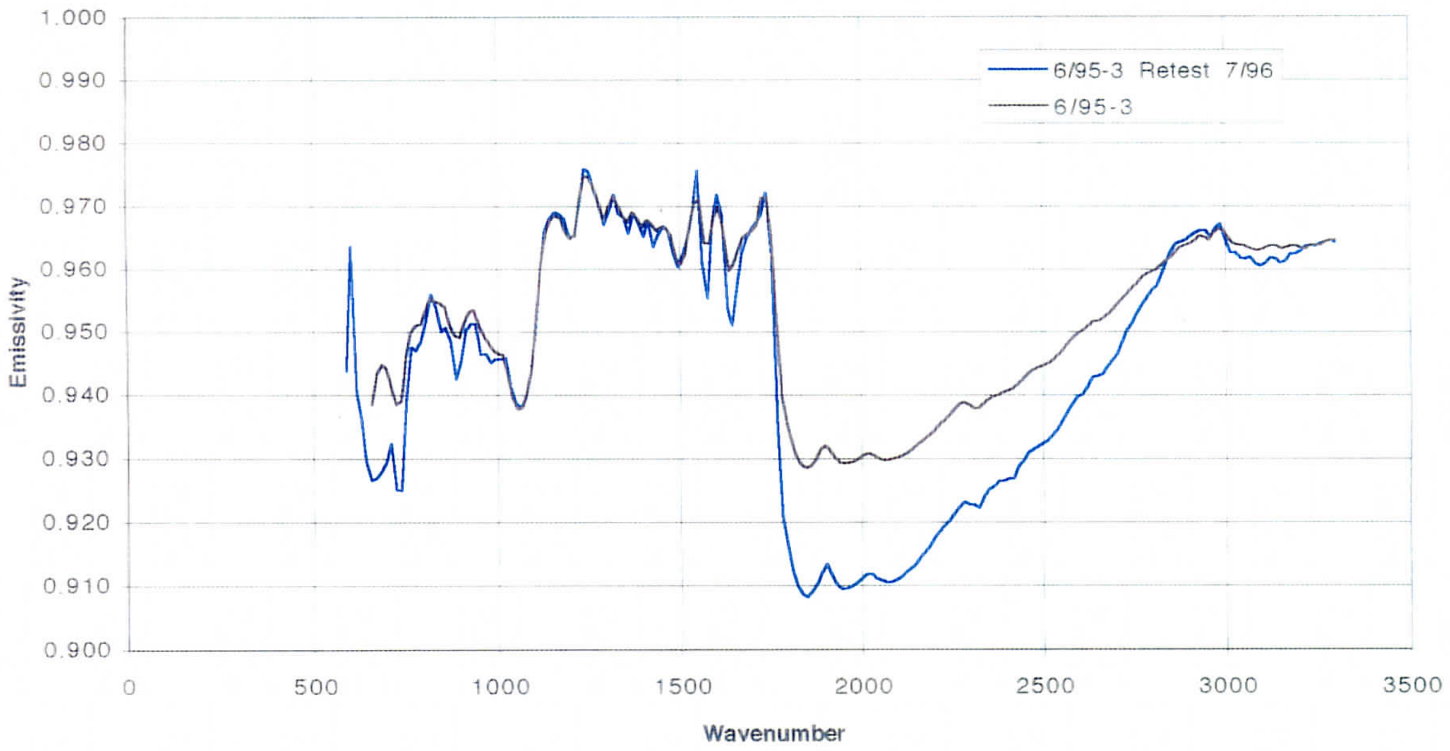
- The AERI Blackbody Cavity emissivity is determined to be 0.996.

AERI BLACKBODY PAINT AND CAVITY EMISSIVITY

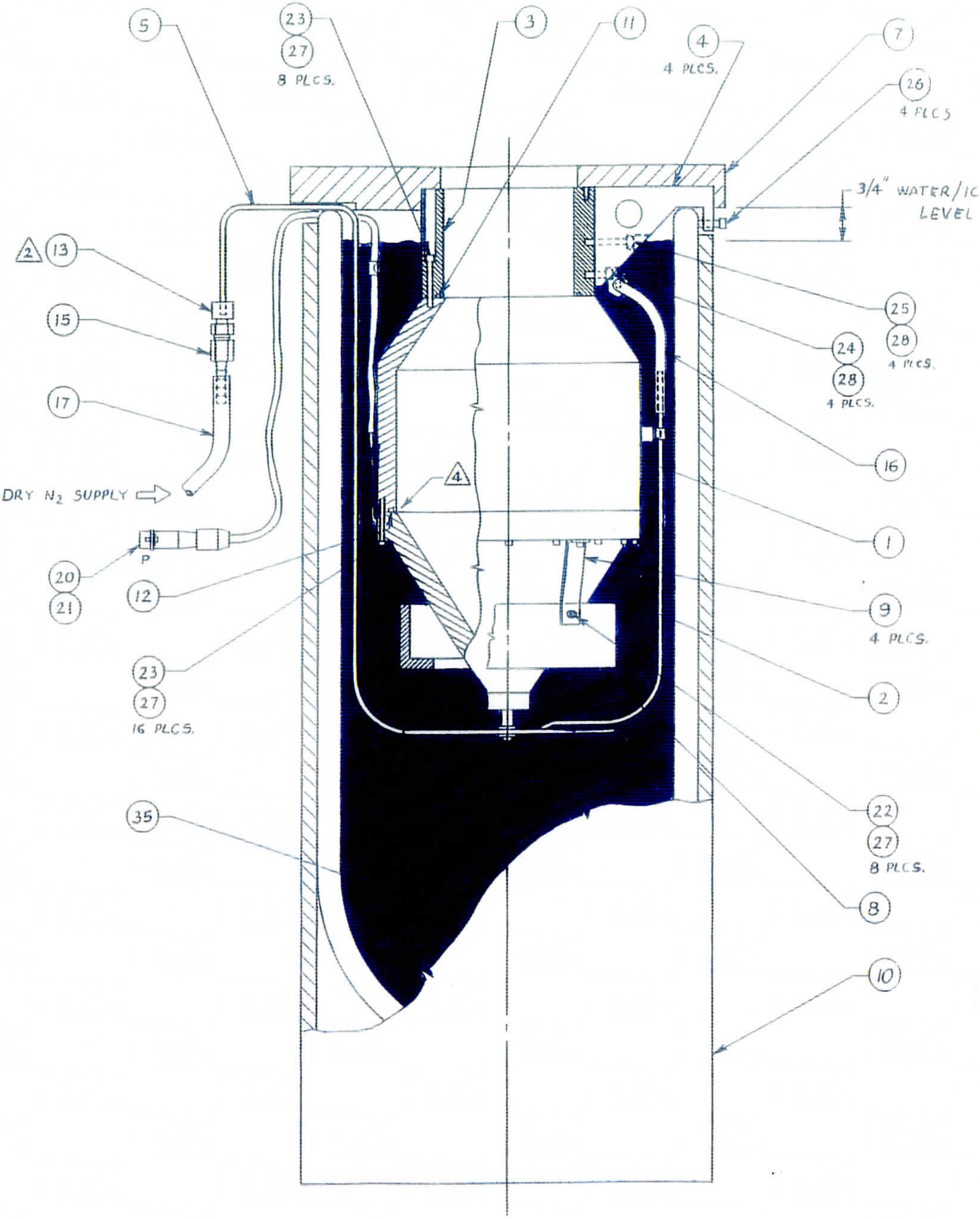
(Paint Sample 7/96 #5, 2 coats of Chemglaze Z306; Tested at Labsphere)



Retest of Same Sample



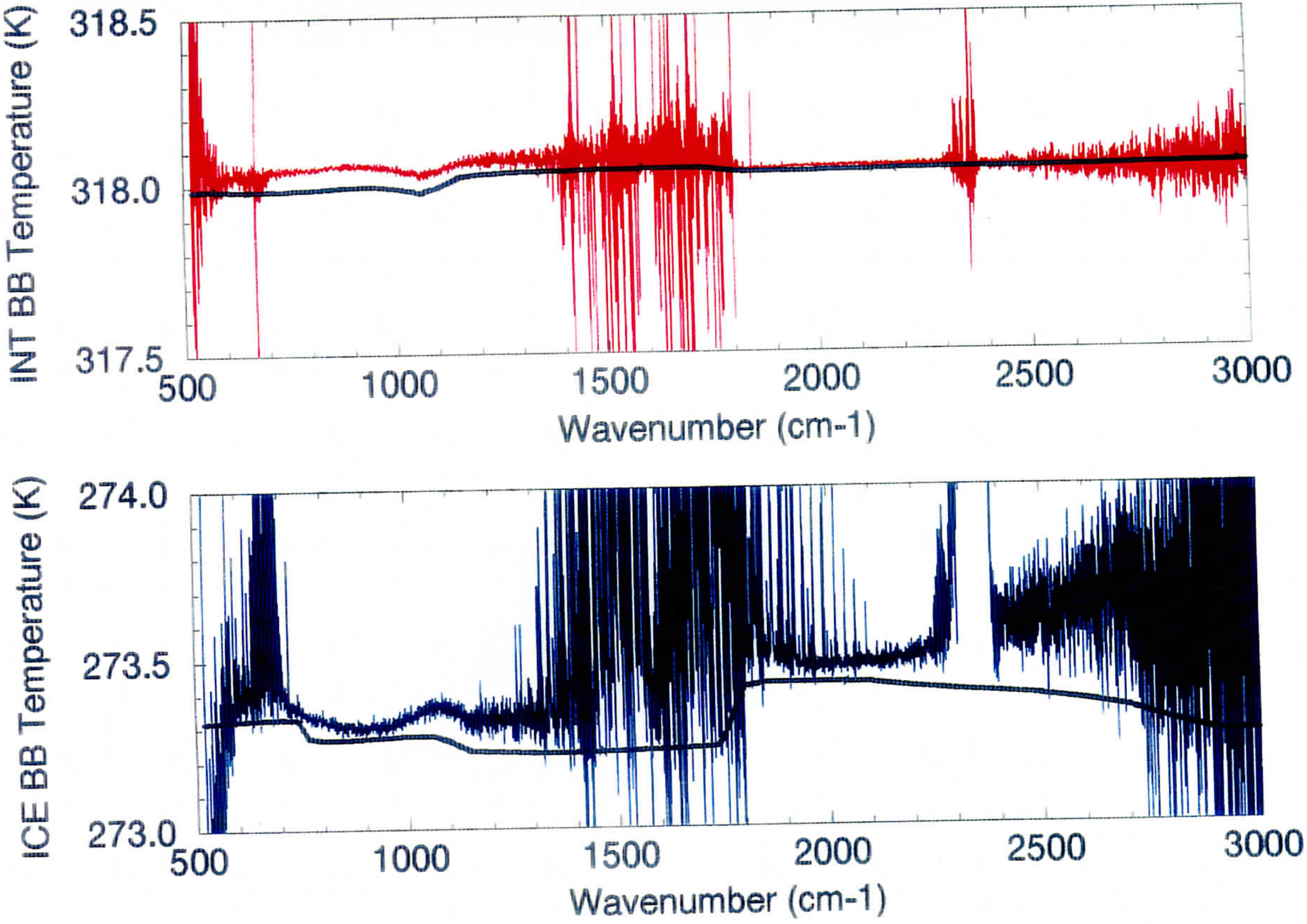
This graph shows the agreement between two tests done at Labshpere of the same sample, one year apart. The stated accuracy of the Labsphere reference NPL #2393 standard is +/-(0.04r + 0.4)%, where r is the reported reflectance, with reflectance in percent ([100-r]/100=emissivity). This leads to emissivity errors of +/- 0.52% at emissivities of 0.97 and +/- 0.68% at emissivities of 0.93. The spectral features seen in the discrepancies between these samples have the same signiture as two samples with different paint thicknesses. A likely explanation of the differences in emissivity between these two measurements of the same sample is that the surface was slightly damaged between the original test and the retest.



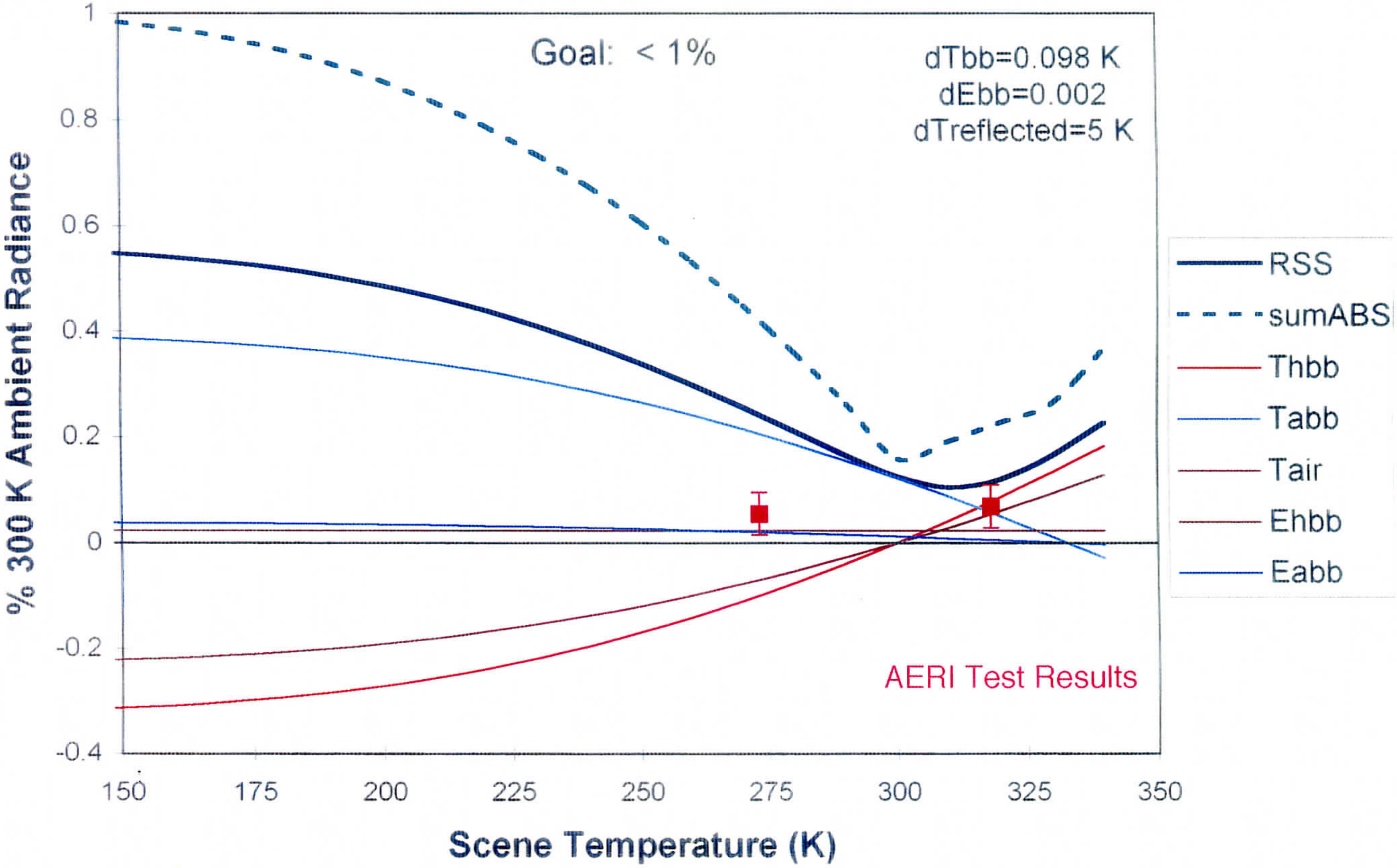
AERI ICE BODY ASSEMBLY

Intermediate / Ice BB Test

MAERI01 970331



AERI Calibration Errors Estimates at 770 cm-1 from Blackbody Characterization Uncertainties



AERI Calibration Errors Estimates at 2200 cm-1 from Blackbody Characterization Uncertainties