Test and qualification results on the MOPITT flight calibration sources

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Abstract. The measurements of pollution in the troposphere (MOPITT) instrument is an IR radiometer that uses gas correlation spectroscopy to detect carbon monoxide and methane in the earth's troposphere. The instrument concept was developed by the Department of Physics of the University of Toronto and it was designed, manufactured and tested by COM DEV Ltd., Canada, the prime contractor, for the Canadian Space Agency. MOPITT will be flown on the National Aeronautics and Space Administration (NASA) earth observing system (EOS) AM1 platform in mid 1998. The MOPITT instrument has eight optical channels that operate in the spectral band 2130 to 4510 cm^{-1} (2.2 to 4.6 μm). The radiometric calibration of the instrument is achieved by using four onboard compact high-emissivity calibration sources working in the range 285 to 500 K that were designed, manufactured and tested at Bomem, Inc., Canada. A description of these calibration sources and the results of the qualification and acceptance testing performed are presented. [S0091-3286(97)00111-6]

Subject terms: infrared radiometric sensor calibration; blackbody; source; space; calibration; radiometry; Martin Black; high emissivity.

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1 Introduction

Spaceborne IR radiometers are used extensively to monitor the earth's environment and climate. Of key issue is the calibration of those instruments throughout their lifetime. Various techniques have been used to achieve this goal (blackbody, diffuser plate, lightbulb, etc.). The use of blackbodies on spaceborne equipment is not new. They are used as reference IR sources that follow closely the Planck equation in a given spectral domain. Their temperature of operation is normally close to the temperature range of the scene to be observed (e.g., the earth).

The measurements of pollution in the troposphere (MOPITT) instrument is an IR radiometer that uses gas correlation spectroscopy to detect carbon monoxide and methane in the earth's troposphere.[1] It is a nadir type sounder with eight optical channels.[2] Four of the channels observe the CO thermal emission from the atmosphere in the band 2130 to 2202 cm^{-1} (4.7 μm) with the earth as a background. The other channels observe the CO and CH_4 bands between 4255 and 4510 cm^{-1} (2.2 to 2.4 μm) that are visible through the solar reflection from the surface. A solar diffuser plate would normally be a good choice for the calibration of those channels, but this option was not retained because of practical design considerations. A lightbulb was not an alternative either because it could not adequately fill the instrument's optical beam shape (about 5×7 cm). Another alternative was to custom design a blackbody with the correct aperture, capable of reaching 500 K and adequate for flight use.

Originally, it was planned to use eight blackbodies on the MOPITT instrument: four high-emissivity calibration sources around 300 K (not heated) and four sources operated at 500 K. However, a review of the instrument's calibration needs showed that if the thermal channels needed to be calibrated regularly during operation, in the case of the solar channels, a monthly calibration would be sufficient. This conclusion along with space, size and weight limitations led to the consideration of the design of four blackbodies with dual functions.

This design approach was finally selected. A breadboard and an engineering model were produced to address the preliminary requirements set forward for the instrument. In late 1995 the flight production phase started. The units were manufactured in 1996 and acceptance testing resumed in January 1997.

2 Calibration Source Design Concept

The MOPITT calibration sources are cylindrical cavities that are insulated thermally to minimize the power required to heat them up to 500 K (227°C) and to reduce thermal gradients. The cavities use a black diffuse coating (Enhanced Martin Black) and a cavity length to aperture diameter ratio of $\sim 2:1$ to achieve the desired high emissivity (Fig. 1).

The cavity is ended by a cone shape. The cone's angle is chosen to prevent specular reflection from the environment signal back into the MOPITT instrument, which would otherwise add radiometric uncertainties during calibration. The cone is made thicker than the sidewalls to increase the thermal uniformity and stability of this surface that is viewed directly by the instrument.

There are two different models of calibration sources. The first three sources are identical. The fourth source has

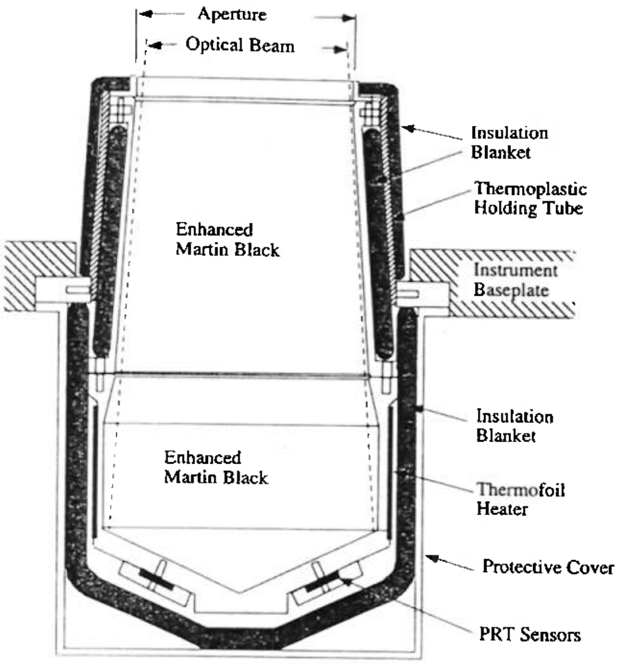


Fig. 1 Calibration source cross section.

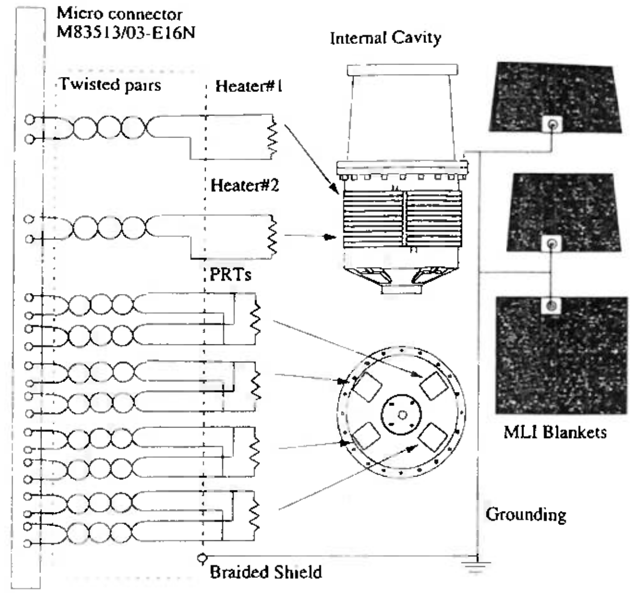


Fig. 2 Calibration source electrical outline.

the same geometry but is slightly enlarged in diameter to accommodate a larger beam footprint for two of the optical channels of the instrument.

A truncated conical thermoplastic holding tube is used to mechanically fix the internal cavity to the remaining blackbody structure while insulating it thermally. In addition, three multi-layer insulation (MLI) high-temperature blankets made with metallized Kapton films are used to further insulate the cavity. Both the internal cavity and the blankets are grounded electrically (Fig. 2) to prevent static charge buildup caused by high-energy particle bombardment.

The calibration sources can be heated up to 500 K using a polyimide thermofoil heater mounted on the cavity's side walls with high-temperature room temperature vulcanizing (RTV) silicone rubber. Outgassing problems associated with the use of RTV at high temperatures are eliminated by performing a baking of the blackbody in vacuum with the internal cavity set at 500 K. Two heating elements are integrated in the thermofoil heater design for redundancy and improved reliability. The heaters are driven by programmable power supplies located on the MOPITT instrument.

The calibration source temperature is monitored by four high-precision 2000 Ω platinum resistance thermometers (PRTs) located on the cone of the cavity. Under normal operations, two PRTs are used for temperature monitoring and the other two are redundant. Each PRT is connected to a resistance bridge via a four-wire lead configuration and is monitored through a differential amplifier and an analog-to-digital (A/D) converter onboard the MOPITT instrument.

3 Optical Design/Performance

The optical requirements for the calibration sources are given in Table 1. The cavity surface finish is selected based on previous flight experience, low outgassing, good optical properties and capability to endure a temperature up to 500 K without significant degradation. The Enhanced Martin Black (made by Lockheed Martin) complies with these requirements. The combination of etching, anodizing and dying processes provides a high-emissivity diffuse black coating especially for wavelengths greater than 2.8 μm.

In the thermal spectral range (2130 to 2202 cm^{-1}), the surface emissivity is above 0.98, which is more than acceptable to meet the cavity emissivity (Fig. 3). In the solar channels (4255 to 4510 cm^{-1}), the emissivity is about 0.76, which is also adequate to achieve the required cavity emissivity.

3.1 *Cavity Emissivity Evaluation*

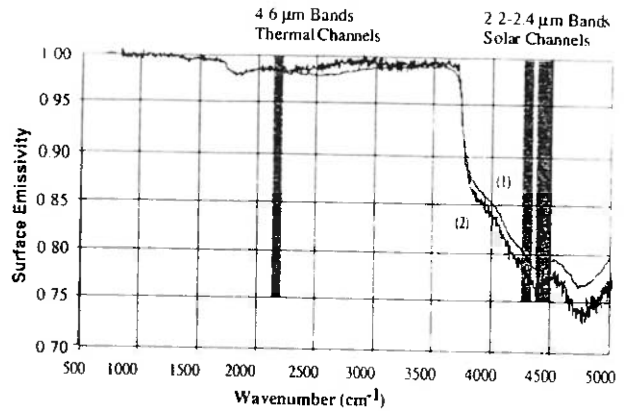
A software package has been developed to evaluate the emissivity of a cavity versus its surface emissivity. The coating is assumed to perfectly diffuse IR light and the cavity to be isothermal. The cavity is divided into small elements. Each element receives and emits an IR signal to all the other elements. The software accounts for the multiple reflections occurring in the cavity.

The software uses a 3D mesh model of the cavity generated on AutoCAD. The output data is a file of all cavity elements with their calculated emissivity.

The cavity emissivity is derived from an average of emissivity of the cone elements in the cavity, which are

Table 1 Calibration source optical requirement

Instrument Channels	Spectral Range (cm^{-1})	Cavity Emissivity (EOL)	Cavity Temp (K)
Thermal channel	2130–2202	0.99 min	285–350
Solar channel 1	4255–4315	0.95 min	500 max
Solar channel 2	4351–4510	0.95 min	500 max



(1) Measurement done on a Bomem DA8 Interferometer & integrating sphere by NRC, Ottawa in 1996
(2) Measurement done with similar equipment by System Research Lab, Dayton, Ohio in 1991

Fig. 3 Enhanced Martin Black spectral emissivity.

viewed directly by the MOPITT instrument. A polynomial fit has been made over the calculated data for each cavity to define the cavity effective emissivity versus the surface emissivity.

$$\varepsilon_{\text{small cavity}}=0.8236+0.4300\varepsilon-0.3670\varepsilon^2+0.1130\varepsilon^3, \quad (1)$$

$$\varepsilon_{\text{large cavity}}=0.7781+0.5329\varepsilon-0.4510\varepsilon^2+0.1400\varepsilon^3. \quad (2)$$

Figure 4 shows a plot of the effective emissivity of both calibration sources as a function of the surface emissivity based on Eqs. (1) and (2). The polynomial fits of Eqs. (1) and (2) can also be used to calculate the effective cavity spectral emissivity (Fig. 5) based on the surface emissivity of the Enhanced Martin Black.

3.2 *Emissivity Variation in the Cavity Cone*

Each channel of the MOPITT instrument is composed of four detector pixels that may view different sections of the calibration source cone. Therefore, an emissivity variation in the cone will introduce a change of radiance from pixel to pixel. The surface viewed by each detector element is a circular spot of about 4 cm diameter on the cavity cone (Fig. 6). The worst case signal spatial variation is found when one detector sees the cavity cone edge while another one sees the center.

The average emissivity on a given spot is evaluated using the relationship:

$$\varepsilon_{\text{average spot } i}=\frac{1}{S_{\text{spot } i}}\int_{S_{\text{spot } i}}\varepsilon \ ds, \quad (3)$$

where ε is the emissivity in the spot viewed by the detector and $S_{\text{spot } i}$ is the spot surface observed by the detector. Based on calculations using the emissivity software and Eqs. (1), (2) and (3), an emissivity variation of ± 0.0012 is expected for a surface emissivity of 0.7 (for the solar channels), and a variation of ± 0.0002 for a surface emissivity of 0.95 (for the thermal channels).

3.3 *Thermal Gradients Effects on Emissivity*

The emissivity calculations made so far assume that the cavity is isothermal. Based on thermal analyses, the cavities may have along their sidewalls an internal thermal gradient up to 2 K for the thermal channels and up to 12 K for the solar channels (when at 500 K). A cavity with a tempera-

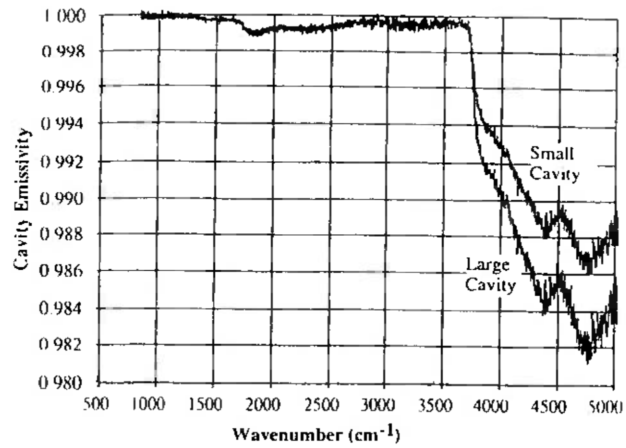


Fig. 5 Cavity spectral emissivity.

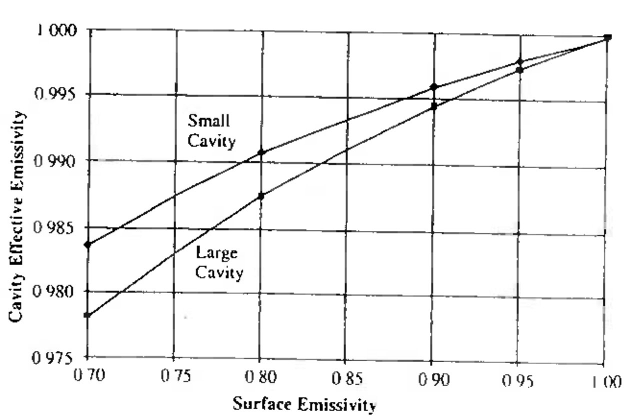


Fig. 4 Cavity emissivity versus surface emissivity.

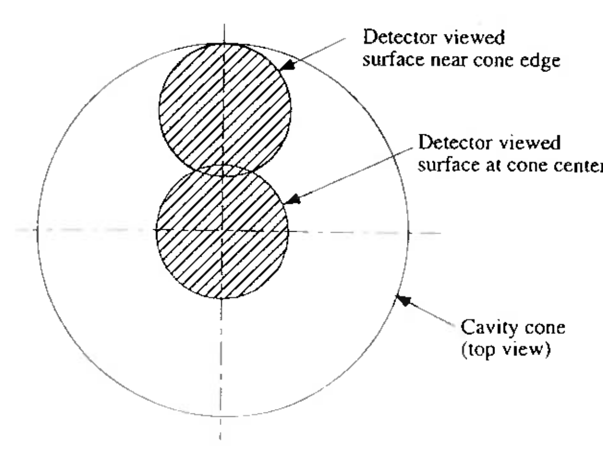


Fig. 6 Detector beam footprint on cavity cone.

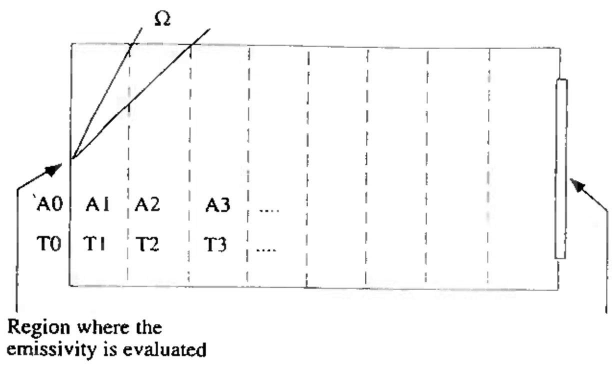


Fig. 7 Cavity thermal model approximation.

ture decrease on its sidewall between the bottom cone and the aperture can be approximated as a cavity with a lower emissivity (within a limited spectral range).

A simple radiometric model of the cavity (Fig. 7) was made to provide a first-order evaluation of the emissivity degradation caused by the thermal gradient in the cavity. The model approximates the cavity as a cylinder and the aperture as a circular surface. A thermal gradient is imposed on surface elements along the cylinder. The overall radiance at the bottom of the cavity is evaluated by summing all the radiance contribution from all the surface elements (multiple reflections are not included). This value is compared to a perfect blackbody at temperature $T0$ and an emissivity value is derived.

The model was first validated by comparing the emissivity results to an isothermal cavity. Figure 8 shows the cavity emissivity versus the surface emissivity as a function of different thermal gradients along the cavity sidewall and for different cavity temperature.

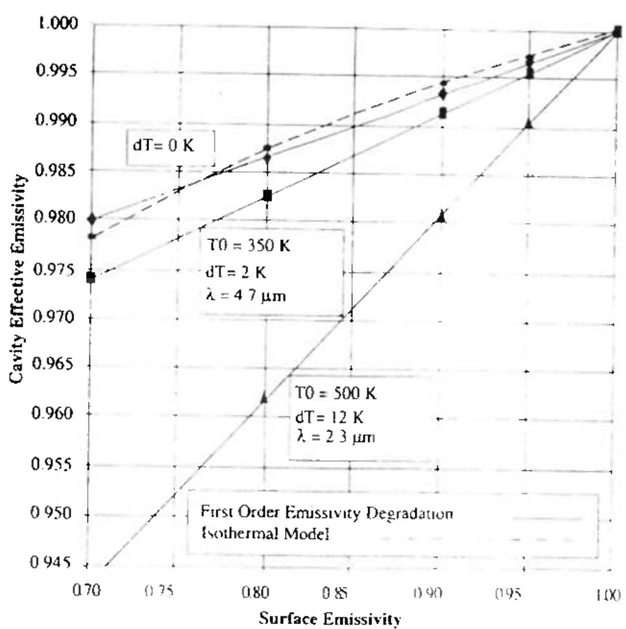


Fig. 8 Cavity equivalent emissivity degradation versus thermal gradient, temperature and wavelength

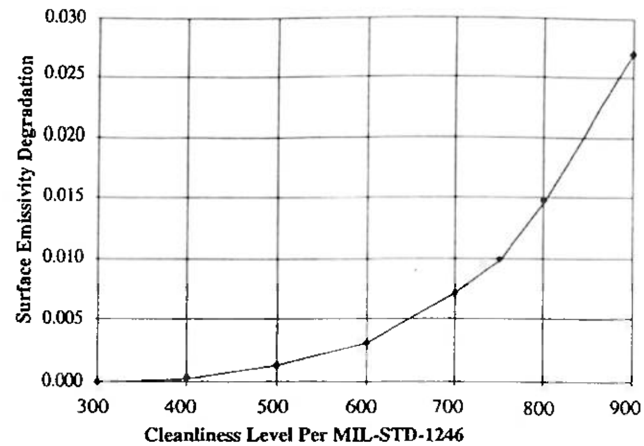


Fig. 9 Surface emissivity degradation versus cleanliness levels.

Based on the radiometric model of the cavity, the effective emissivity is reduced by <0.001 for a cavity temperature at 350 K with a thermal gradient of 2 K along the cavity sidewall (thermal channels). The effective emissivity is reduced by 0.02 for a cavity temperature at 500 K with a thermal gradient of 12 K along the cavity sidewall (solar channels).

3.4 *Contamination Effects on Emissivity*

The emissivity performance of the Enhanced Martin Black coating is sensitive to contamination and handling. Unfortunately, it cannot be cleaned easily once the assembly process has started. It is therefore necessary to assess the tolerance of the calibration sources to contamination.

There are two types of contamination to consider: molecular and particulate. Molecular contaminants come from lubricants left by the machining processes, volatile materials deposited from the environment, material outgassing and human handling. Molecular contamination is reduced by screening out undesired lubricants or volatile materials from manufacturing processes and also by using proper cleaning procedures. A baking in vacuum is also done at 80 °C on materials subject to outgasss (MLI blankets, harnesses, etc.) to eliminate those contaminants. Finally, at the beginning of the acceptance tests, the blackbody cavity is maintained in vacuum near 227°C for 48 h to complete the baking process. Molecular contamination can therefore be prevented from affecting the cavity emissivity.

Particulate contaminants are difficult to remove from the cavity and are cumulative. An obscuration factor can be associated to the cleanliness levels found in MIL-STD-1246.[3–4] A surface with high emissivity is subject to be more sensitive to particulate contamination. Figure 9 shows a surface emissivity degradation calculation that assumes an average emissivity of 0.5 for the particulate contaminants.

It can be observed that the cavity can tolerate a contamination up to level 900 with a surface emissivity degradation of only 0.027. Using Eqs. (1) and (2), this translates into a cavity effective emissivity degradation of only 0.0015. Practically, the blackbody cleanliness is maintained below level 600 as per MIL-STD-1246 during integration and testing of the instrument. During launch, the blackbodies

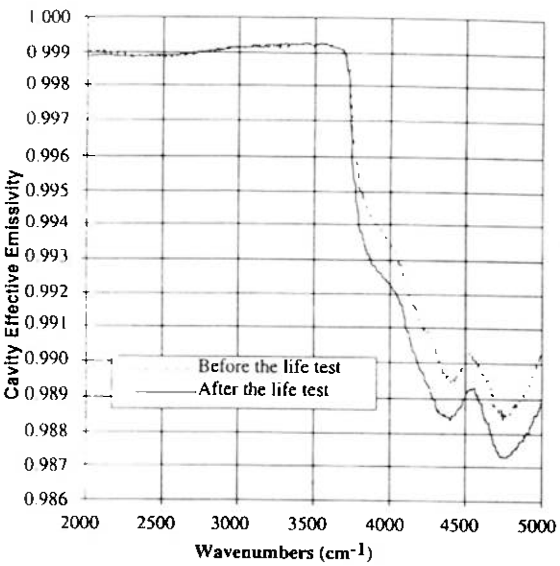


Fig. 10 Enhanced Martin Black spectral emissivity changes after 67 cycles from ambient to 227°C.

will not be subjected to significant contamination because the MOPITT instrument will somehow be sealed (although venting will take place). Therefore, the cavity emissivity degradation caused by contamination is considered small enough to be neglected.

3.5 *Enhanced Martin Black Emissivity Variation Caused by Aging*

A sample of Enhanced Martin Black was subjected to 67 thermal cycles from ambient to 227°C in vacuum to simulate the calibration source life operation onboard the instrument (the MOPITT solar channels will be calibrated once a month) as part of the qualification process.

The total reflectance of the sample was first measured before the life test by the National Research Council of Canada (NRC) in the range 2000 to 5000 cm^{-1} using a Bomem DA8 interferometer with an integrating sphere in an ambient pressure environment. The sample was then mounted in a vacuum chamber and cycled in temperature. The reflectance measurement was repeated on the sample after completion of the thermal cycles by NRC. The cavity effective emissivity versus wave numbers was derived from both measurements and plotted for comparison (Fig. 10).

The results show no measurable degradation of the emissivity in the range 2000 to 3700 cm^{-1} and an emissivity degradation of about 0.1% in the range 3700 to 5000 cm^{-1}. This indicates that the cavity effective emissivity for the thermal channels is not likely to change during the lifetime of the instrument and a degradation of 0.001 is likely to occur for the solar channel.

3.6 *Other Types of Emissivity Degradation*

3.6.1 *Space radiation, UV radiation, atomic oxygen*

Some Martin Black samples were flown on the National Aeronautics and Space Administration (NASA) Long Duration Exposure Facility (LDEF) to investigate the property changes occurring through long exposure in space.[5–7]

Table 2 Calibration source emissivity uncertainties for the thermal channels.

Degradation Effects Thermal Channels	Cavity Emissivity Uncertainties	Resulting Cavity Emissivity
Initial emissivity BOL	—	0.999
Thermal effects		
Emissivity changes due to thermal gradient	< 0.001	
Emissivity variation on cavity cone	Negligible	0.999
Life releated degradations		
Molecular contamination	Eliminated	
Particulate contamination	Negligible	
Space and UV radiation, atomic oxygen	None	
Surface aging	Negligible	0.999

Based on measurements made after recovery of the samples, a small decrease in the reflectance was noted in the spectral range of interest for the MOPITT calibration sources. It is believed to be caused by a decrease of the volatile components in the coating binder induced by the UV radiation. No data could be found specifically addressing other radiation effects on Martin Black coatings but such effects are considered small. Since the calibration sources are not in the line of impact of atomic oxygen, no degradation is expected.

3.6.2 *Space particulate damage*

Contamination can result from micrometeorid and space debris making impact to the surface of the MOPITT instrument. Since the calibration sources are located inside the instrument, it will not affect emissivity.

3.7 *End of Life Predicted Cavity Emissivity*

We can predict the end of life (EOL) effective emissivity of the cavities (assuming 7 y in space) for the thermal channels based on the emissivity degradation mechanisms identified so far. Table 2 assesses the EOL effective emissivity for both blackbody designs in the thermal channels starting from the emissivity at beginning of life (BOL). Tables 3 and 4 make a similar emissivity calculation in the solar channels for the small and large calibration sources.

Table 3 Small calibration source emissivity uncertainties for the solar channels.

Degradation Effects Thermal Channels	Cavity Emissivity Uncertainties	Resulting Cavity Emissivity
Initial emissivity BOL	—	0.990
Thermal effects		
Emissivity changes due to thermal gradient	0.02	
Emissivity variation on cavity cone	< 0.0012	0.969
Life releated degradations		
Molecular contamination	Eliminated	
Particulate contamination	Negligible	
Space and UV radiation, atomic oxygen	None	
Surface aging	0.001	0.968

Table 4 Large calibration source emissivity uncertainties for the solar channels.

Degradation Effects Thermal Channels	Cavity Emissivity Uncertainties	Resulting Cavity Emissivity
Initial emissivity BOL	—	0.986
Thermal effects		
Emissivity changes due to thermal gradient	0.02	
Emissivity variation on cavity cone	<0.0012	0.965
Life releated degradations		
Molecular contamination	Eliminated	
Particulate contamination	Negligible	
Space and UV radiation, atomic oxygen	None	
Surface aging	0.001	0.964

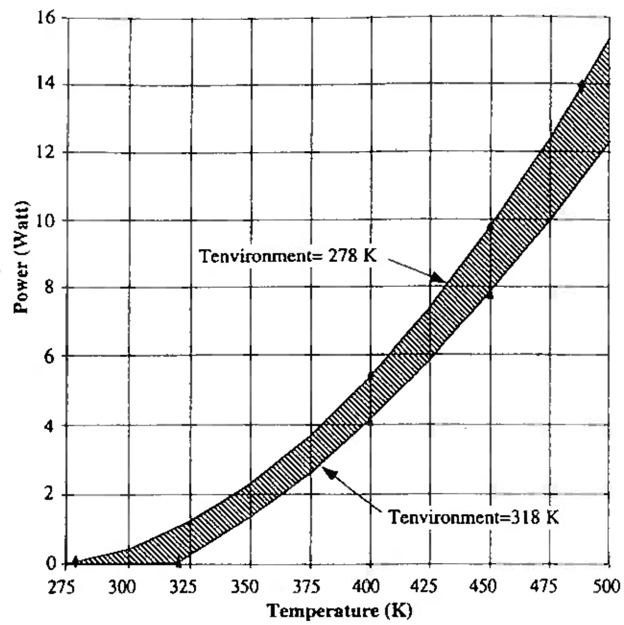


Fig. 11 Input power versus internal achieved temperature for a small calibration source.

4 Thermal Design/Performance

A thermal finite element model (FEM) analysis was done on the calibration sources to determine the thermal gradients in the cavity. Table 5 summarizes the results obtained. The power required to bring the internal cavity to a given temperature from an environment temperature ranging from 278 to 318 K has been estimated based on a limited set of measurements. A typical curve is for a small calibration source, as shown in Fig. 11.

The warm-up time to 500 K and cool-down time to ambient temperature were also measured. A typical graph is shown in Fig. 12 for the small calibration sources. The time required to warm up and stabilize the source near 500 K to within ±60 mK/min is measured to be 5.2 h maximum for both sources. The time required to cool down and stabilize the unit back to ambient temperature to within ±60 mK/min is about 8±0.5 h for the small sources and 8.5 ±0.5 h for the large source

5 Evaluation of Temperature Uncertainties Related to the PRTs

In addition to optical and thermal considerations, the selection of the PRTs, their mounting on the cavity and their calibration are important issues to address to achieve low temperature uncertainties for the calibration sources.

5.1 *PRT Monitoring Method*

Because of weight and design simplicity consideration, it was decided to monitor a high-impedance PRT in a resistance bridge with dc supplies rather than use a low-impedance PRT with an ac modulation technique. In both methods, the thermocouple effects caused by dissimilar metal junctions can be neglected or eliminated. The uncertainties associated with the electronics used to monitor the PRT was estimated not to exceed 0.07 K over the design life of the instrument.

Table 5 Calibration source thermal evaluation based on FEM.

Thermal Gradients Type	Small Cavity	Large Cavity
Along the wall of the cavity		
Thermal channels (285–350 K)	2 K	2 K
Solar channels (350–500 K)	11 K	11 K
On the cavity cone		
Thermal channels (285–350 K)	0.02 K	0.02 K
Solar channels (350–500 K)	0.10 K	0.10 K
Between PRT and cavity internal surface	<0.005 K	<0.005 K

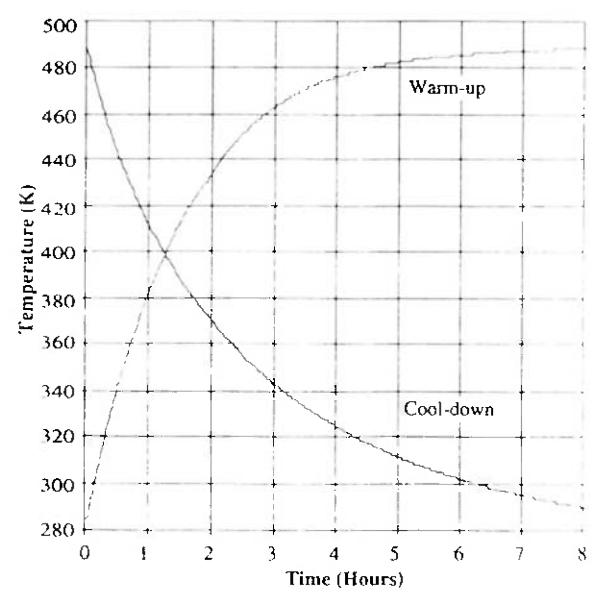


Fig. 12 Small calibration source warm-up and cool-down times

5.2 *Selection of PRT*

The 2000 Ω PRT was specifically selected for low thermal hysteresis and resistance stability for a given temperature versus time. The low voltage applied on the PRT ensured the self-heating effects to be very small. Based on manufacturer data, an hysteresis of 0.03 K is predicted in the thermal channels and 0.046 K for the solar channels. The hysteresis was assumed to be the largest in the middle of the expected thermal range of the cavity (around 115°C, range from 0 to 227°C) and to reduce linearly to zero at the thermal band edges based on the manufacturer available model. The resistance EOL changes were estimated from the manufacturer available data based on the expected design life and the PRT worst case temperature of operation.

5.3 *Mounting of PRTs to the Cavity*

The PRTs were mounted in grooves at the bottom cone of the cavity. A PRT metal cap was manually adjusted for each PRT to reduce the adhesive thickness on the PRT sides around 0.005 in. A high-temperature silicone rubber RTV was used to bond the PRT to the cone groove and the metal cap. The cap was then screwed and torqued in place. The cavity assembly was put temporarily in a reduced pressure compartment to eliminate air gaps that would be present around the PRT. The assembly was then left to cure and dry. The approach ensured that the PRTs were not stressed mechanically and were fully in contact with the cavity cone thus minimizing uncertainties associated with contact thermal resistance that can be significant when operating in a vacuum environment.

5.4 *Calibration of PRTs*

A reference PRT traceable to National Institute of Standards and Technology (NIST) standards was mounted on the cavity cone. The assembly was put in an isothermal chamber. The temperature was stabilized at five different temperature plateaus (0, 25, 75, 15, and 227°C) and the resistance of the 2000 Ω PRTs were monitored against the reference PRT temperature over a period of about 20 min. A fifth order polynomial fit was then performed over the data of each PRT to define the resistance versus temperature relationship. Based on previous experiments with other calibration sources a temperature uncertainty of 0.04 K is expected because of the test setup (imperfect isothermal chamber etc.) and 0.025 K for polynomial fit errors.

6 Evaluation of Blackbody Equivalent Temperature Uncertainty

The blackbody temperature uncertainty is an equivalent temperature value derived from all the uncertainties associated with the blackbody inherent design (parts, emissivity, etc.), calibration and operation (includes PRT electronic monitoring).

Table 6 gives the predicted blackbody temperature uncertainty for the thermal and solar channels. The equivalent temperature uncertainty derived from the cavity emissivity uncertainties is calculated taking into account the wavelength and temperature associated with the specific channel. The thermal channel value includes uncertainties associated with the predicted blackbody environment thermal variation. The uncertainty values for the solar channel neglect the blackbody environmental thermal variations but assumes a knowledge of the blackbody emissivity at beginning of life (during instrument alignment, the onboard blackbody is compared to an external reference high-emissivity source and the cavity equivalent emissivity at BOL is derived). In the uncertainty calculations for two PRTs, the hysteresis is considered correlated.

Table 6 Calibration source predicted EOL temperature uncertainty.

Uncertainty Type	Thermal Channel (285–350 K)	Solar Channel (500 K)
Blackbody emissivity changes up to EOL	±0.030 K	±0.173 K
Thermal gradients in cavity cone surface	±0.010 K	±0.060 K
Thermal gradients between PRT and surface	±0.005 K	±0.005 K
PRT uncertainties		
Self-heating	±0.005 K	±0.005 K
Thermal hysteresis	±0.030 K	±0.046 K
EOL resistance change	±0.030 K	±0.030 K
Calibration uncertainties		
Ref. PRT and monitor	±0.012 K	±0.012 K
Test setup (estimated)	±0.040 K	±0.050 K
Polynomial fit	±0.025 K	±0.025 K
Electronic uncertainties	±0.070 K	±0.070 K
Total root sum square (rss) uncertainties		
For 1 PRT	±0.10 K	±0.21 K
Coaddition 2 PRTs	±0.08 K	±0.20 K

7 Qualification/Acceptance Test Summary

The calibration sources were successfully subjected to the burn-in and environmental tests listed in Table 7. Various qualification tests were also performed to ensure that the parts, materials and manufacturing processes would not degrade during the lifetime of the calibration sources.

Table 7 Calibration source acceptance test summary.

Test Description	Test Specifications
Burn-in	Duration of 168 h with internal cavity in temp. range 450 to 500 K
Thermal vacuum	Five cycles from − 30 to + 60°C
Vibration test (launch limit loads)	Sine 20 Hz, five cycles at 12 g
Vibration test (random vibration)	Overall g_{rms} = 15 G
	20 Hz at 0.02 g^2/Hz
	20–50 Hz at 4.6 dB/oct.
	50–800 Hz at 0.08 g^2/Hz
	800–2000 Hz at − 4.6 dB/oct.
	2000 Hz at 0.02 g^2/Hz
Vibration test (sine vibrations)	5–9 Hz at 1.3 cm DA
	9–100 Hz at 2 g 4 oct./min

Table 8 MOPITT calibration source performance summary.

Specification	Small Source	Large Source
EOL effective emissivity		
From 275 to 350 K and in band		
800 to 3600 cm^{-1} (2.8 to >12 μm)	≥0.999	≥0.999
Up to 500 K and in band		
3600 to 5000 cm^{-1} (2 to 2.8 μm)	0.98	0.96
Internal cavity operating temperature	275–500 K	275–500 K
Power requirement at 500 K	~14.5 W	~19 W
Warm-up time to 500 K	~5 h	~5 h
Cool-down time from 500 K to ambient	~8.0±0.5 h	~8.5±0.5 h
Blackbody internal FOV uniformity		
From 275 to 350 K	<0.02 K	<0.02 K
Up to 500 K	<0.10 K	<0.12 K
Blackbody EOL equivalent uncertainty		
From 275 to 350 K (thermal channels)	<±0.07 K max. EOL	<±0.07 K max. EOL
Up to 500 K (solar channels)	<±0.20 K max. EOL	<±0.20 K max. EOL
Aperture size	~5 × 6.5 cm	~5.4 × 8.1 cm
Overall dimension	Cylinder about 11.5 cm dia.×18 cm deep	Cylinder about 12.5 cm dia.×18 cm deep
Mechanical resonant frequency	None observed below 2000 Hz	None observed below 1600 Hz
Weight	~1.15 kg	~1.25 kg

The polyimide thermofoil heaters were subjected successfully to a 1000 h burn-in test. Except for a minor delamination problem observed between the adhesive securing the wire junction to the heater foil (caused by human manipulation), no failures were reported. To further test those heaters, a sample was mounted on a plate fixture and was then brought by steps at high temperature to identify the first failure mechanism. Some heater delamination between the polyimide films started to occur around 260°C, which is outside our maximum operating temperature of 500 K (227°C).

A heater sample was mounted on a cavity using high-temperature RTV. Four PRTs were also mounted and calibrated using the described methods. Finally an Enhanced Martin Black sample was also included for test. This assembly was then subjected to 67 warm-up cycles to ~227°C by applying the maximum power to the heater and then cooling down to ambient. These cycles were performed in a rough vacuum environment. The temperature sensor calibration was repeated on the four PRTs after the life test and showed variations to be within the calibration setup measurement accuracy or within the PRT predicted life variations. There was no degradation on the heaters. Emissivity measurements were taken before and after the cycling on the Enhanced Martin Black sample. The observed surface emissivity variation was small, well within the allocated performance budget.

8 Performance Summary

Table 8 is a summary of the flight calibration source performances for a useful lifetime of 8.5 y based on the various measurements and calculations presented in this paper.

9 Conclusion

A dual function compact calibration source for the MOPITT instrument was described. Based on the test measurements and the calculations performed, both calibration source designs achieved a high emissivity in the thermal channels and were demonstrated to operate up to 500 K for the solar channels.

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