

**MEASURING THE SPECTRAL EMISSIVITY OF
THERMAL PROTECTION MATERIALS DURING
ATMOSPHERIC REENTRY SIMULATION**

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ABSTRACT

Hypersonic spacecraft reentering the earth's atmosphere encounter extreme heat due to atmospheric friction. Thermal protection system (TPS) materials shield the craft from this searing heat, which can reach temperatures of 2900° F.

Various thermophysical and optical properties of TPS materials are tested at the Johnson Space Center Atmospheric Reentry Materials and Structures Evaluation Facility, which has the capability to simulate critical environmental conditions associated with entry into the earth's atmosphere. Emissivity is an optical property that determines how well a material will reradiate incident heat back into the atmosphere upon reentry, thus protecting the spacecraft from the intense frictional heat. This report describes a method of measuring TPS emissivities using the SR5000 Scanning Spectroradiometer, and includes system characteristics, sample data, and operational procedures developed for arc-jet applications.

INTRODUCTION

Background

Hypersonic spacecraft reentering the earth's atmosphere encounter extreme heat due to atmospheric friction. As the speeding craft rips through the air, its movement agitates and compresses the gaseous molecules in the upper atmosphere, surrounding the craft with a shock wave and converting the vehicle's kinetic energy to thermal energy. The resulting heat is so acute that it tears electrons away from the air molecules, producing a plasma of hot particles. Reentry temperatures, which can reach 2900 °F, are thwarted by Thermal Protection System (TPS) materials developed to absorb and reradiate the heat, keeping the aluminum airframe of the spacecraft below its threshold of 350 °F.

The Atmospheric Reentry Materials and Structures Evaluation Facility (ARMSEF) at the Johnson Space Center is a convective (plasma arc-jet) heating facility, capable of simulating critical environmental conditions associated with entry into the earth's atmosphere. While undergoing reentry simulation, TPS materials are tested for a variety of thermophysical and optical properties, evaluated for mission life and operational limitations and investigated for flight anomalies.

Tests have been conducted to obtain thermophysical and optical properties of two TPS materials that have been proposed for use on the single-stage-to-orbit ACRV/X35¹ vehicle. The proposed materials are the Silicon Impregnated Reusable Ceramic Ablator (SIRCA) developed by the Ames Research Center and the ACUSIL 1 ablator developed by the Aerotherm Corporation. The test objectives were to obtain the relevant properties of the materials, provide correlations to thermal math models, and provide qualitative evaluation of the materials at the flight conditions expected during the ACRV/X35 reentry flight.

An important optical property governing the effectiveness of a TPS is that of emissivity. Roughly speaking, emissivity is a measure of how well a material will reradiate incident heat back into the environment. A TPS material of high emissivity is desired as it will better protect the spacecraft from incineration during atmospheric reentry.

In 1992 an improved technique for determining the spectral emissivities of TPS materials was implemented at the ARMSEF. This technique utilizes the SR5000 rapid scanning spectroradiometer procured from CI Systems. The instrument was supplied with a custom built filter to record emissions of TPS surfaces within the range from 0.7 microns to 8.0 microns, this range providing the most useful data for the temperatures encountered in the Shuttle and ACRV/X35 programs.²

The emissivities of the ACRV/X35 experimental ablators were measured at the ARMSEF using the PC-based scanning spectroradiometer and its accompanying software. This report describes the method of obtaining emissivity measurements with the spectroradiometer and does not report data pertaining to the proprietary materials that were scanned.

THEORETICAL

Blackbody Radiation

Every object in the universe continuously emits and absorbs energy in the form of electromagnetic radiation. The radiated energy originates from the internal energy associated with atomic and molecular motion and the accompanying accelerations of electrical charges within the object. For an object to maintain thermal equilibrium its rates of emission and absorption of energy must be equal. This equality leads to *Kirchhoff's Law* that, if $M_\lambda(T)$ (spectral radiant emittance) is the power emitted per unit area per unit of wavelength at the wavelength λ , and $\alpha_\lambda(T)$ (spectral absorptance) is the fraction of the incident power per unit area per unit of wavelength, all objects in thermal equilibrium at the same absolute temperature T have the same ratio of $M_\lambda(T) / \alpha_\lambda(T)$. It follows that an object having the maximum possible absorptance [$\alpha_\lambda(T) = 1$] also has the maximum possible spectral radiant emittance [$M_\lambda^b(T)$]. Such a perfect absorber and perfect emitter is called a *blackbody* and the electromagnetic energy it emits is called *blackbody radiation*. (Theoretically, a blackbody TPS material would reradiate all of the absorbed heat back into the atmosphere). No true blackbody exists, but a small hole through which radiation escapes from an isothermal enclosure is an excellent approximation. Any real substance is characterized by a spectral emissivity $\epsilon_\lambda(T)$ [$0 < \epsilon_\lambda(T) < 1$] expressing its spectral radiant emittance as some fraction of that of a blackbody at the same temperature, $M_\lambda(T) = \epsilon_\lambda(T) M_\lambda^b(T)$. With this, Kirchhoff's Law becomes $\epsilon_\lambda(T) = \alpha_\lambda(T)$. This is an important result--a good emitter of thermal radiation is also a good absorber. It follows also that a good reflector is a poor emitter.³

$$\text{Emissivity:} \quad \epsilon_\lambda(T) = \frac{M_\lambda(T)}{M_\lambda^b(T)}$$

Graybody Radiation

As shown, the spectral emissivity of a material is the ratio between the radiation emitted of it and the radiation emitted of a blackbody at the same temperature, in all wavelengths. For the most part, $\epsilon_\lambda(T)$ varies only slowly with temperature, but rather more with wavelength. For a large number of materials, however, $\epsilon_\lambda(T)$ is approximately constant over a fairly wide wavelength range. These

are called *graybodies* . Many TPS materials radiate as graybodies. Their emissivities can be determined by measuring their spectral radiant emittance with the scanning spectroradiometer, then dividing the specimen scan by a blackbody scan of the same temperature. The emissivity of a graybody TPS material is a measure of how well it approximates a blackbody, and therefore, how well it reradiates incident heat back into the atmosphere.

EXPERIMENT

Reentry Simulation Chamber

The reentry simulation tests were conducted in Test Position 2 of the ARMSEF (Fig. 1). A segmented, constricted arc heater is used to generate a high temperature plasma flow. Test gases (23% O₂ and 77% N₂ by mass) are heated by an electrical arc discharge within the constrictor column of the arc heater. The highly energized gas is then injected into an evacuated chamber through a water-cooled conical nozzle that has a 15° half-angle. TPS test specimens, located inside the chamber, were subjected to constant surface heating cycles. By varying the current to the arc heater, the surface temperature of the test specimens was kept constant, as recorded by the optical pyrometer.

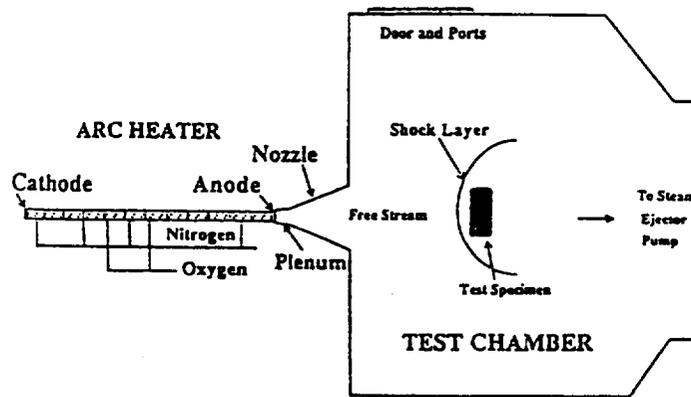


Figure 1.—General setup of arc heater and evacuated reentry simulation chamber.

Scanner Setup

The scanning spectroradiometer was mounted on a tripod and placed just outside the atmospheric reentry simulation chamber (Fig. 2), where it could collect TPS radiation through a 5" diameter zinc selenide transmission window installed in a

porthole of the chamber door. A gold first surface Pyrex mirror was mounted near the nozzle exit to reflect the TPS specimen radiation into the instrument's optical system. To minimize directional effects the specimen distance to the nozzle exit diameter was selected to permit viewing at 45° or less from the normal to the test surface. This distance was set at 14". An aluminum tunnel was used to enclose the optical path between the chamber door window and the scanner detector head to allow a nitrogen purge, thus removing the atmospheric attenuation due to water and carbon dioxide.

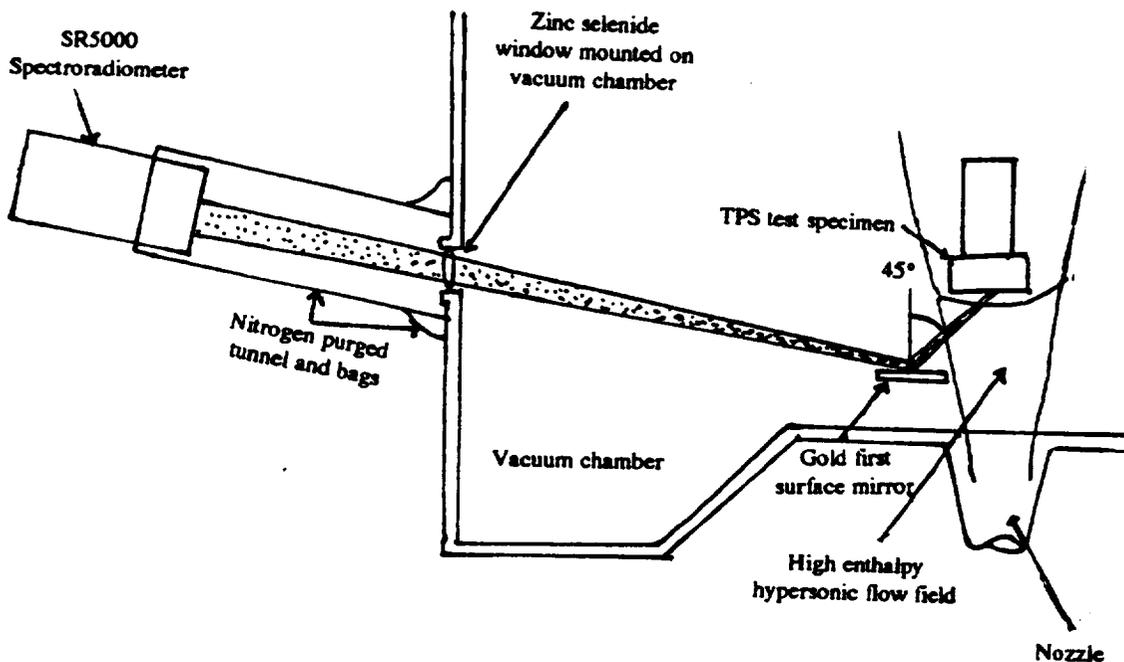


Figure 2.--Scanning spectroradiometer experimental setup.

Calibrating the system by scanning a blackbody in the chamber was not possible because of the facility's demanding test schedule. Instead, a blackbody was scanned alongside of the chamber at the correct tripod to TPS test specimen distance (141") with a gold first surface mirror and a zinc selenide transmission window in the optical path. Because of the severe atmospheric attenuation due to water and carbon dioxide, an aluminum enclosure was built to permit the optical path from the detector head to the blackbody to be purged by nitrogen. In this way, the system could be calibrated in a humidity-free optical path as required by the evacuated chamber. A smaller aluminum enclosure was used when running the experiment so that the path between the detector head and chamber window could be purged.

OBTAINING EMISSIVITY MEASUREMENTS

Design Theory

The SR5000 Scanning Spectroradiometer is used to measure the spectral radiant emittance of a TPS material undergoing atmospheric reentry simulation. The radiation emitted by this material is directed toward the instrument, where it is collected, focused on the first focal plane and chopped by a precision rotating wheel with blades (Fig. 3). After entering the field stop it is refocused by an ellipsoidal mirror onto the detector, which outputs an amplified AC signal. This signal and the synchronous reference signal from the chopper are processed through a synchronous detection circuit. Now a DC signal, it is further amplified, digitized and transferred to the computer for additional processing and display.

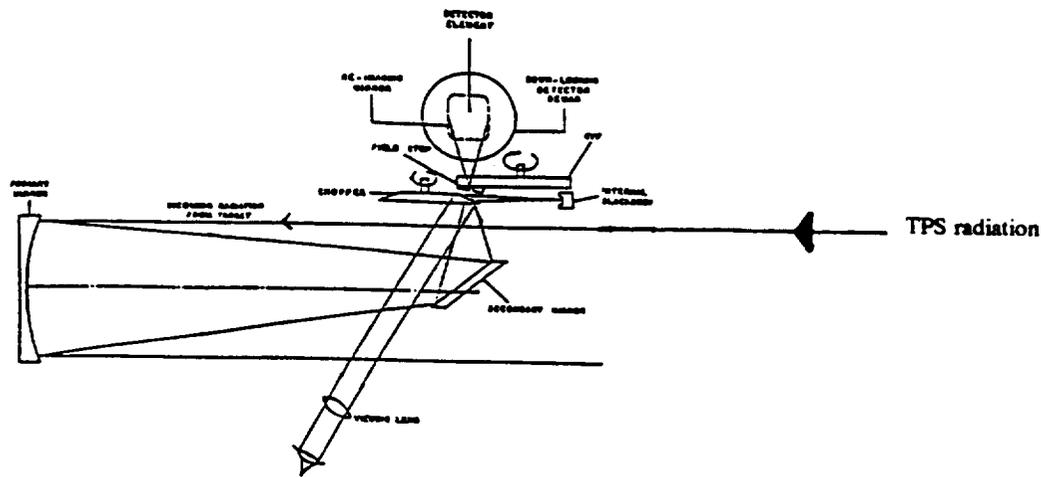


Figure 3.--Optical layout for the scanning spectroradiometer.

So that a quantitative result may be obtained, the precise amount of radiation seen by the detector when the chopper obstructs the TPS radiation must be known. For this reason, when the chopper obstructs the field of view, it exposes the detector to the radiation of a reference blackbody. The blackbody temperature is continuously and precisely monitored digitally by the computer in order to be used in the calibration procedure and in the calculation of the spectral radiant emittance.

Through a combination of calibration procedures and mathematical processing of the instrument signal output, the spectral radiant emittance is converted to the *spectral radiance*.⁴ Spectral radiance is measured in units of watt/sterad.micron.cm², as a function of wavelength.

Data Processing

Emissivity data was obtained with the accompanying SR5000 software, run on a 386 PC. Plots of TPS spectral radiance vs. wavelength were superimposed on blackbody curves of the same temperature (Fig. 4). Plots of TPS emissivity vs. wavelength were then obtained by dividing the specimen plot by the blackbody plot (Fig. 5).

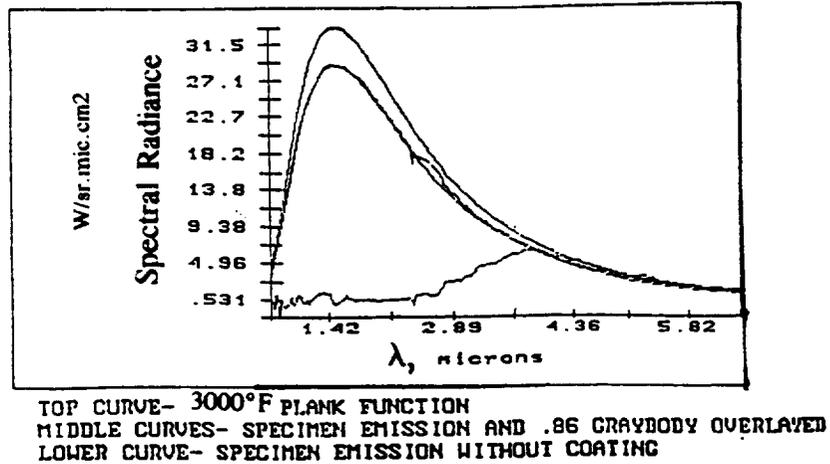


Figure 4.--(Above) A sample monitor display of spectral radiance vs. wavelength for a Planck blackbody curve (generated by SR5000 program), a TPS graybody curve (obtained with scanner) and a TPS non-graybody curve (obtained with scanner).

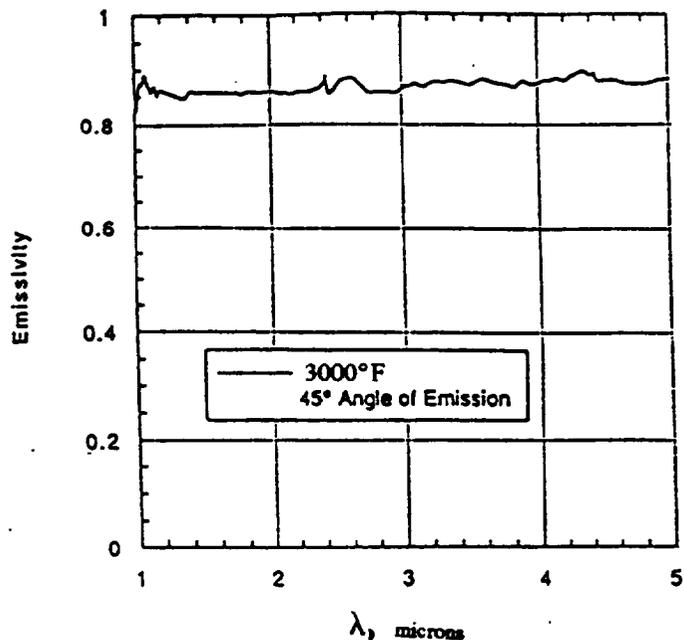


Figure 5.--A sample plot of TPS emissivity vs. wavelength, as obtained by dividing the TPS graybody plot by the Planck blackbody plot.

DISCUSSION

Currently, estimates of emissivities and temperatures for uninstrumented test articles are made manually by trial and error fitting of graybody curves for various emissivities and temperatures to the test data. The ARMSEF plans to eventually incorporate a program that will select the best fit based on iterative minimization of the area between the graybody curve and the test data.

REFERENCES

1. Note: The ACRV/X35 is a reusable single-stage-to-orbit launch vehicle currently under development as part of the National AeroSpace Plane (NASP) program. It combines a liquid hydrogen/liquid oxygen Linear Aerospike rocket with a lifting body shape, allowing the vehicle to take off vertically and land horizontally like the Space Shuttles.
2. J. D. Milhoan, "A Technique for Measuring Spectral Emissivities of Thermal Protection Materials During Reentry Simulation Testing," NASA/JSC/ARMSEF, Bldg. 222 Memo, (1992).
3. R. E. Bedford, "Blackbody Radiation," Encyclopedia of Physics, 2nd Edition, VCH Publishers, Inc. (1991).
4. CI Systems, "The SR5000 Scanning Spectroradiometer: User's Manual," NASA/JSC/ARMSEF, (1990).