Correlation of Effective Emissivity of Light-weighted Beryllium Mirrors during JWST Thermal Vacuum Testing

Russell B. Schweickart[1] and Randy Franck[2]
Ball Aerospace, Boulder, CO, 80302
Sang Park[3]
Smithsonian Astronomical Observatory, Cambridge, MA 02138

The James Webb Space Telescope (JWST), scheduled for launch in 2018, must be cooled to temperatures below 50 K as part of a rigorous set of ground tests to verify operational performance. Some of the components that drive the time required to cool down the assembly to this temperature are the beryllium optics. Two properties of these optics that determine the cool down time are mass and surface emissivity. The mass of these optics, including the primary comprised of 18 hexagonal segments, a secondary and a tertiary, have all been reduced by machining pockets into the back side of the substrates. One difficulty in predicting the time required to cool these optics is estimating how their pocketed back sides affects their emissivity. Component-level tests of these optics at operational temperatures have allowed for verification of their cryogenic optical performance. These tests have also allowed for estimates of mirror back effective emissivities based on correlating thermal models of the tests. This paper will describe the subassembly tests and show correlated results for mirror back effective emissivities.

Nomenclature

AOS	=	Aft Optics Subsystem
FSM	=	Fine Steering Mirror
JSC	=	Johnson Space Center
JWST	=	James Webb Space Telescope
MSFC	=	Marshall Space Flight Center
NASA	=	National Aeronautics and Space Administration
OTIS	=	OTE and ISIM Assembly
PMSA	=	Primary Mirror Segment Assembly
SINDA/FLUINT	=	Systems Improved Numerical Differencing Analyzer (C&R Technologies)
SMA	=	Secondary Mirror Assembly
TM	=	Tertiary Mirror
XRCF	=	X-Ray Calibration Facility

I. Introduction

SUCCESS of the James Webb Space Telescope mission depends, in part, on careful engineering and testing during the development phase of the program. One aspect of this engineering is accurately predicting changes that will occur in the performance and mechanical properties of telescope components as the assembly cools from room temperature to operating temperatures near 40 K. Due to the size and complexity of the telescope, transient thermal models used to predict these changes require significant computational processing capacity. Thus, any methods of simplifying the modeling process while maintaining accuracy is beneficial. All of the mirrors associated with the optical train have been light-weighted by machining a matrix of pockets into the back of the reflecting surface. A technique for simplifying the process of accounting for the radiative heat transfer to and from these

[1] Staff Consultant, Cryogenic and Thermal Engineering Dept., 1600 Commerce St, Boulder, CO 80301.
[2] Senior Engineer, Cryogenic and Thermal Engineering Dept., 1600 Commerce St, Boulder, CO 80301.
[3] Staff Consultant, Smithsonian Astronomical Observatory, 60 Garden St., Cambridge, MA 02138.

pockets is to simulate the back of the mirror as a flat plate and use an effective emittance, rather than model the detail of the pockets and use a measured surface emittance.

Prior to testing the mirrors in telescope subassemblies within thermal vacuum chambers, the effective emissivity of the back of the mirrors could only be estimated from previous studies. After the subassembly tests, however, models of the test configurations could be used to correlate temperature results and derive mirror effective emissivities. This paper summarizes the process used to arrive at effective emissivities for the back surfaces of each of the optics within the James Webb Space Telescope for temperatures above about 170 K.

II. JWST and Component Level Testing

A schematic of the complete JWST is shown in Figure 1 including the locations of the optic surfaces. While a full telescope system level test is happening currently in the seven-story high Chamber A at NASA's Johnson Space Center (JSC) in Houston, TX (see Figure 2), the optics assemblies have been tested numerous times in thermal vacuum chambers to verify their optical performance at cryogenic temperatures. One of these was Primary Mirror Segment Assembly (PMSA) testing in the X-Ray Calibration Facility (XRCF) chamber at NASA's Marshall Space Flight Center (MSFC) (see Figure 3). This figure shows the machining done on the back of a PMSA substrate for light-weighting purposes, creating about 600 pockets per segment. Evaluation of the Secondary Mirror Assembly (SMA) and Aft Optics Subsystem (AOS) optics, including the Tertiary Mirror (TM) and Fine Steering Mirror (FSM), performance was conducted in the RAMBO chamber at Ball Aerospace in Boulder, CO. Figures 4 and 5 show the machining done to the backs of the beryllium secondary and tertiary mirrors respectively.

Nearly all of the testing conducted to date included venting low levels of helium gas into the chambers after they had been evacuated in order to accelerate the rate at which the flight components were cooled to, and warmed from, operational temperatures. Simulating the effects of cooling and warming test hardware with rarified gas is a topic also addressed with this testing,[1] but there were periods during the cooling parts of this testing when the chamber was evacuated. During these periods, and especially at higher temperatures, radiative heat transfer from the optics dominates their cool down rate, and can thus be more easily correlated to derive mirror back effective emissities.

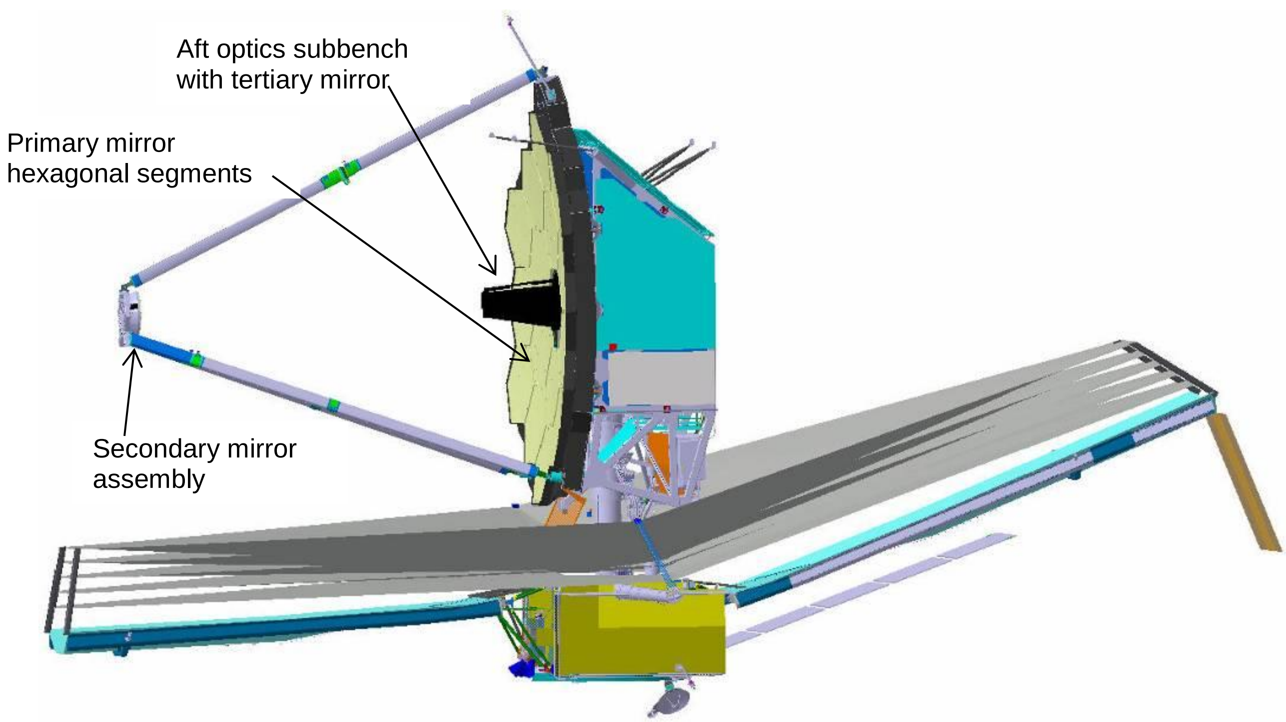

Figure 1. JWST flight configuration with optical element locations.

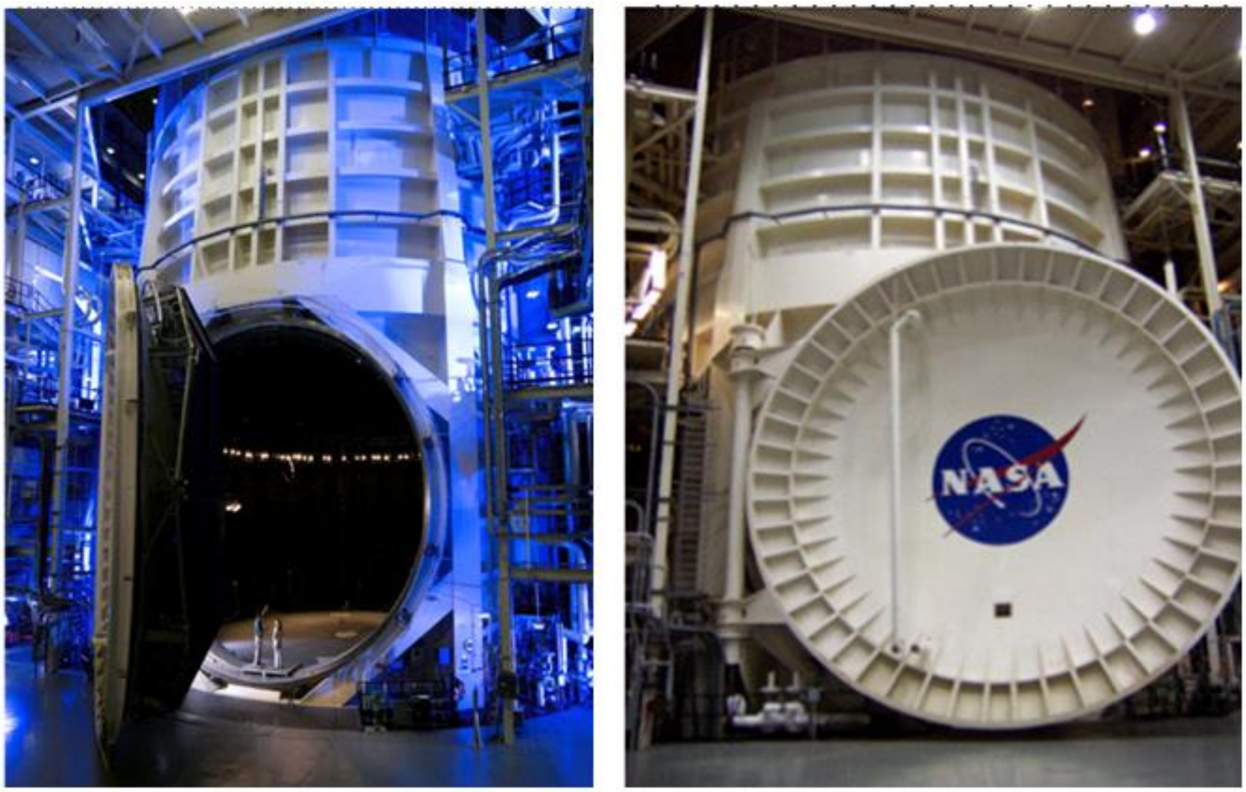

Figure 2. Chamber A at Johnson Space Center for conducting system level testing of JWST.

Figure 3. Optical testing of PMSA arrays in XRCF.

Figure 4. Light-weighting pockets in the back of the secondary mirror substrate.

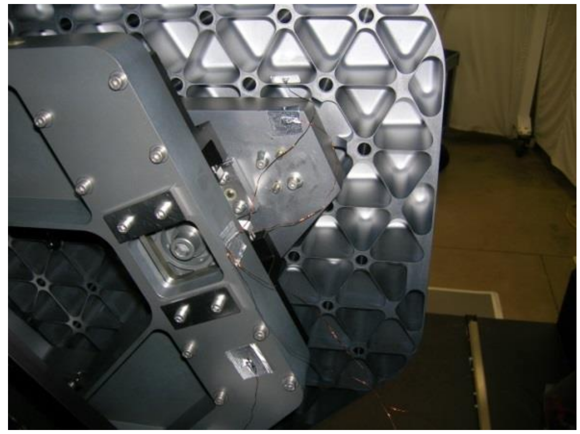

Figure 5. Light-weighting pockets in the back of the tertiary mirror substrate.

III. Effective Emissivity

Radiative heat transfer between two surfaces is derived from the Stefan-Boltzmann law, and is given as

$$Q_{net} = \mathcal{F}_{1-2}\sigma A_1(T_1^4 - T_2^4) \quad (1)$$

where

$\mathcal{F}_{1\text{-}2}$ is the real body view factor between the two surfaces, a function of shape factor, $F_{1\text{-}2,}$ and surface emissivities, ε,

σ is the Stefan Boltzmann constant,

A_1 is the area of surface 1, and

T_x are the respective surface temperatures.[2]

With the very complex surfaces shown in Figures 3, 4 and 5, predicting heat transfer from these surfaces is considerably less computationally intensive if the area is represented by a flat plate (A*) with an effective emissivity (ε*). Typically, ε* is determined empirically.

IV. Pre-Test Predictions of Mirror Back Emissivity

While the method of simplifying thermal modeling of complex surfaces as a flat surface with an effective emissivity has been well established,[3,4] determining an effective emissivity a priori is a difficult process. The method used by NASA to establish a pre-test prediction involved creating a ray-trace model of a single pocket, and determining, while also accounting for specular reflection, the ratio of rays leaving the pocket with an assumed surface emissivity to that if all rays were absorbed (emissivity = 1).[5] The change in emissivity with temperature must also be taken into account and was estimated from that of other known surface materials. The results shown in Figure 6 were used in the original model for predicting PMSA thermal performance in the XRCF chamber.

For comparison, room temperature emissivity measurements with a Gier Dunkle model MS-251 of the mirror back surface finish, called Berylcoat D, gave an average emissivity of 0.11.

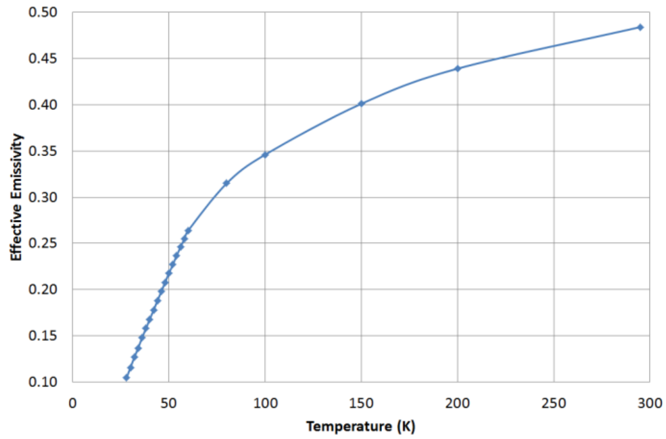

Figure 6. Predicted mirror back effective emissivity as a function of temperature.

V. Simulation of PMSA Testing in XRCF

The first cold optical tests of an array of primary mirror segments occurred in the XRCF chamber in Sept. 2002. Figure 7 shows the geometric model used in Thermal Desktop to simulate these tests. SINDA/FLUINT fully accounts for changes in thermal mass (specific heat) as a function of temperature; however, accounting for changes in surface emissivity with temperature is more difficult considering radiative couplings are dependent on the temperatures of both surfaces. In order to avoid excessive computational run times, a transition analysis typically involves computing radiative heat transfer couplings at room temperature and at cryogenic temperatures, then switching between them when the bulk average hardware temperature reaches a specified intermediate temperature, for example at 100 K.

Evident in this figure is that the backs of the mirrors are represented by flat surfaces. To properly account for light-weighting of the mirrors with this representation, multiplying factors were applied to the substrate densities and to the conductive thermal couplings between the front and back surfaces of the mirrors.

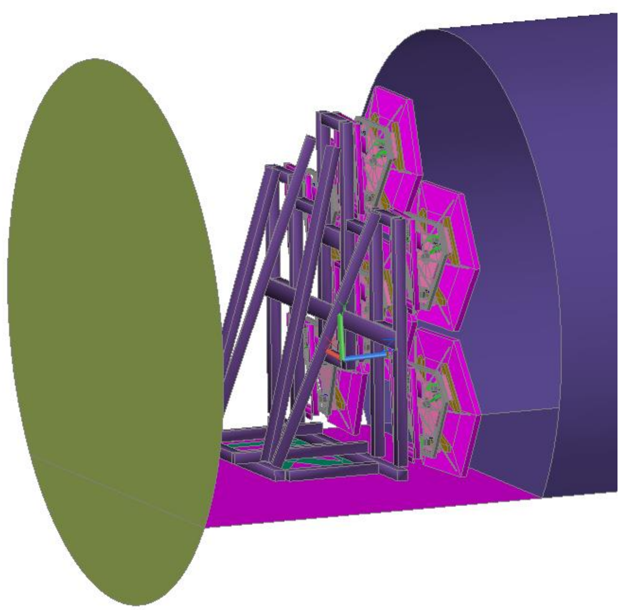

Figure 7. Thermal Desktop representation of PMSA mirrors in XRCF testing.

A. Initial XRCF Model Results

Initial model results were confusing. On one hand, using a variable effective emissivity between 0.5 and 0.2, similar to pre-test predictions, seemed to match test results as shown in Figure 8 (XRCF Test 8). On the other hand, the rate of decrease in effective emissivity with temperature needed to match the test data, as shown in Figure 9, was far greater than the pre-test predictions (compared to Figure 6). Typically, emissivity only decreases significantly at temperatures below about 100 K.[6] After further investigation, the cause became evident. Figure 10 shows that the helium pressure in the chamber began to rise early in the cool down. Even this small amount of rarefied gas caused significant heat transfer within a chamber, and accelerated the mirror cool down rate beyond what was expected from radiation alone.

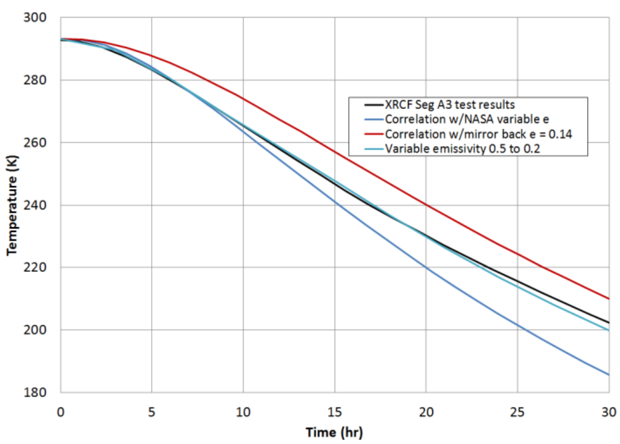

Figure 8. Cool down simulation predictions with various effective emissivities compared to XRFC Test 8 results.

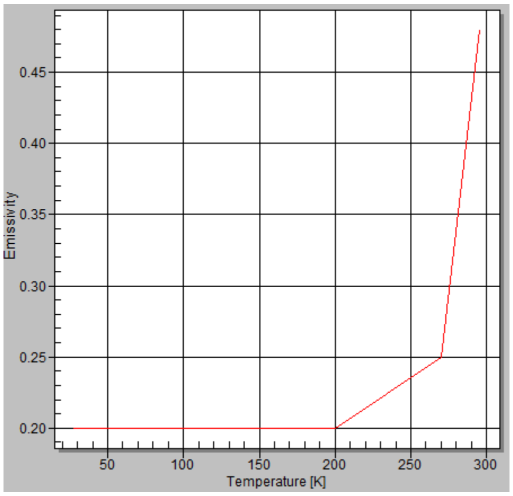

Figure 9. Rate of change in PMSA mirror back effective emissivity necessary to match test XRCF test results.

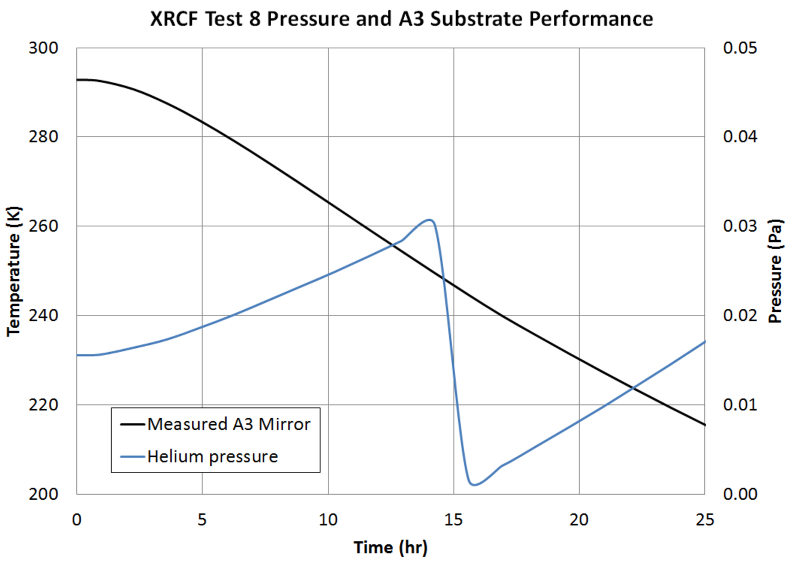

Figure 10. Helium pressure within XRCF chamber during PMSA cool down.

B. Better Vacuum Results

Another XRCF test (XRCF Test 6) showed that with a lower helium pressure in the chamber, the rate of change in PMSA temperature would be over predicted using the same variable effective emissivity that matched the test results in the previous simulation (see Figure 11). Using a fixed emissivity of 0.2 more closely matched the test results and even over predicts the cool down rate below about 260 K.

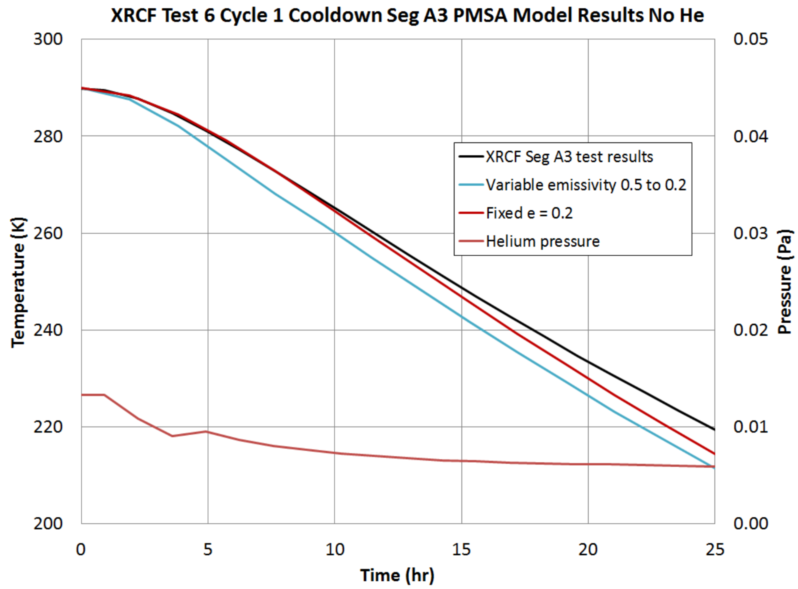

Figure 11. Cool down simulation predictions with various effective emissivities compared to XRCF Test 6 temperature and pressure results.

VI. Simulation of SMA in RAMBO

Subsystem level testing of the secondary mirror took place in the RAMBO chamber at Ball Aerospace in August 2014. While low levels of helium gas were used in this test also, the first 48 hours of cool down were in vacuum. Figure 12 shows the representation of the SMA as well as supporting structure in the thermal model. In this case, the back of the substrate is modeled slightly different than the PMSAs, but still represented by a flat plate. Simulation results correlated well with test results for the first 48 hours of cool down when the back of the mirror was assumed to have an effective emissivity of 0.21 as shown in Figure 13.

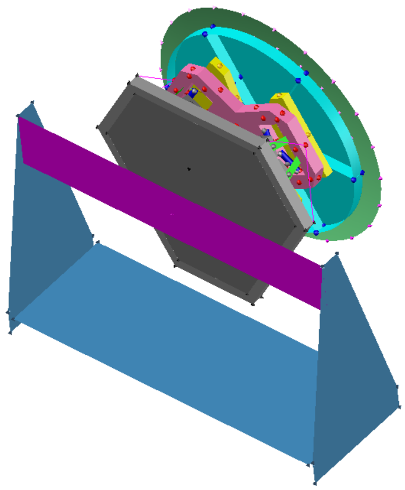

Figure 12. Representation of the SMA in RAMBO testing.

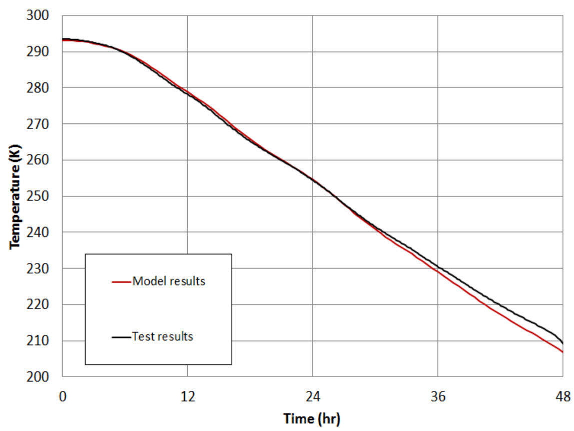

Figure 13. Simulation cool down prediction of SMA compared to RAMBO test results.

VII. Simulation of the Tertiary Mirror in RAMBO

Another optic tested in the RAMBO chamber at Ball Aerospace was the tertiary mirror within the AOS assembly. Figure 14 shows a comparison of the actual back of the tertiary mirror as compared to the flat-plate representation in the Thermal Desktop model.

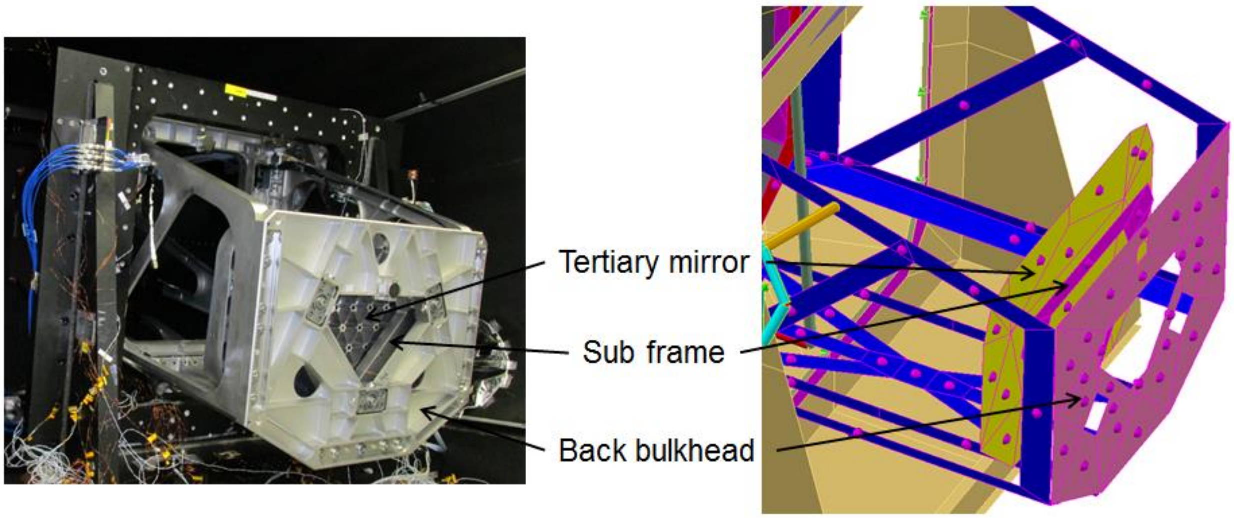

Figure 14. Actual and simulated tertiary mirror within the AOS assembly in RAMBO thermal vacuum chamber.

Evident from the picture in Figure 14 is the light-weighting of other components like the back bulkhead; however, the pockets are far larger than those in the mirror substrate as shown in Figure 6, and are thus less likely to cause a significant difference between actual surface emissivity and effective emissivity. For the case of the tertiary mirror, the model matches the test results best for the first 96 hours of cool down with an effective emissivity of 0.17 as shown in Figure 15. Also evident in Figure 15, as was the case in Figures 11 and 13, is that the mirror temperature predictions with a fixed emissivity show a cool down rate that is faster than actual at the coldest temperatures. This indicates a change in effective emissivity as a result of real decrease in surface emissivity with temperature.

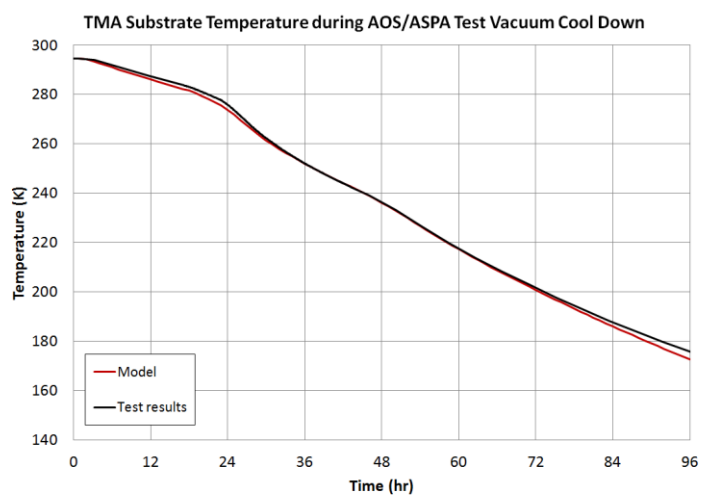

Figure 15. Cool down simulation of the tertiary mirror with an effective emissivity of 0.17 compared to RAMBO test results.

VIII. Limitations of Mirror Back Effective Emissivities

While estimates of emissivity as a function of temperature from room temperature down to 30 K were predicted by GSFC, deriving a similar function from the aforementioned test data is not possible, primarily because no data has been taken in high vacuum below about 170 K other than at operating temperatures near 40 K. For these cold steady-state cases, component temperatures were correlated to test conditions assuming effective emissivities on the backs of the optical components of 0.05.

The final system level test of the telescope planned for the summer of 2017 will provide an opportunity to derive equations of mirror back effective emissivities as a function of temperature since all testing will be conducted without rarefied helium.

IX. Application of Derived Effective Emissivity

In May of 2015, a system level test, called OGSE1, was conducted in Chamber A at the Johnson Space Center. This test evaluated the performance of many flight-like components including the secondary mirror assembly. While the test included adding helium to the chamber to accelerate the thermal transition process, the first 5 days of the cool down were conducted at high vacuum. An OGSE1 test thermal model had been generated for the purpose of estimating cool down durations and timing of test operations. Due to size of the model and the substantial computational time required of SINDA/FLUINT to incorporate emissivity as a function of temperature, only a single emissivity value was used in the OGSE1 cool down simulation. Figure 16 shows how well the model predicted the secondary mirror substrate temperature using an effective emissivity of 0.2 and less well with a value of 0.3 during the 5 day high vacuum period. These results show the effectiveness of this modeling technique and that the technique can be applied with the simulated optic in multiple testing configurations.

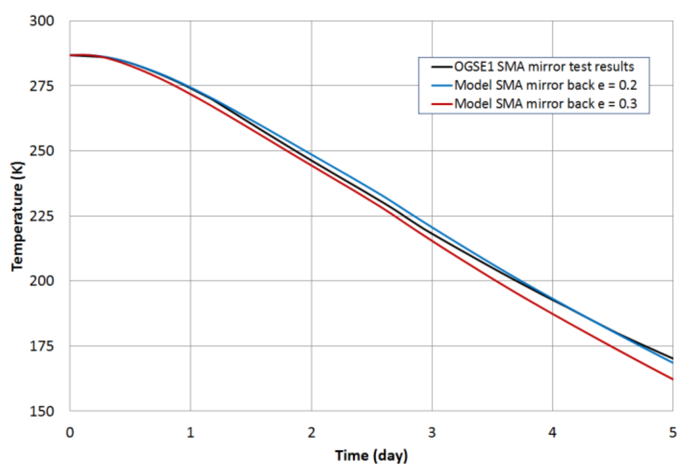

Figure 16. Comparison of simulated SMA mirror temperatures to test data during the JWST OGSE1 system level test

X. Conclusion

Subsystem level testing of JWST mirror assemblies has not only allowed for verification of optical performance, but the transient sections of the tests have also provided cool down data that has been used to correlate the effective emissivity of the back of each mirror. The large difference between analytic predictions of effective emissivity and those found empirically with test result shows the necessity of generating and correlating subsystem level thermal models. These results can, however, be used to better estimate the effective emissivity of other similarly light-weighted mirrors.

References

[1]Schweickart, R.B., and Franck, R., "Correlation of Rarefied Gas Heat Transfer for Acceleration of Thermal Transitions during James Webb Space Telescope (JWST) Thermal Vacuum Testing," ICES-2015-233, *45th International Conference on Environmental Systems*, Seattle, WA, 12-16 July, 2015.

[2]Lienhard, J. H., *A Heat Transfer Textbook*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1981, pp. 29, 445.

[3]Ono A., *Theory and Practice of Radiation Thermometry (Methods of Reducing Emissivity Effects)*, John Wiley & Sons, Inc., New York, 1988, pp. 565-623.

[4]Bradford R.E., *Theory and Practice of Radiation Thermometry (Calculation of Effective Emissivities of Cavity Sources of Thermal Radiation)*, John Wiley & Sons, Inc., New York, 1988, pp. 653-772.

[5]Thomson, S.., "Calculation of Primary Mirror Rear Surface Effective Emissivity," NASA, Goddard Space Flight Center, TR-11-008, Greenbelt, MD, April 19, 2011.

[6]Henninger, J.H.., "Solar Absorptance and Thermal Emittance of Some Common Spacecraft Thermal-Control Coatings," NASA Reference Publication 1121, Greenbelt, MD, 1984.