High fidelity cryothermal test of a subscale large space telescope

M.DiPirro[a], J. Tuttle[a], S. Ollendorf[a], A. Mattern[a], D. Leisawitz[a], M. Jackson[a], J. Francis[a], T. Hait[a], P. Cleveland[b], D. Muheim[a], A.J. Mastropietro[c]

[a]NASA/Goddard Space Flight Center, Greenbelt, MD 20771

[b]Energy Solutions International, LLC, 8705 Cathedral Way, Gaithersburg, MD 20879

[c]NASA/Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena CA 91109

ABSTRACT

To take advantage of the unique environment of space and optimize infrared observations for faint sources, space telescopes must be cooled to low temperatures. The new paradigm in cooling large space telescopes is to use a combination of passive radiative cooling and mechanical cryocoolers. The passive system must shield the telescope from the Sun, Earth, and the warm spacecraft components while providing radiative cooling to deep space. This shield system is larger than the telescope itself, and must attenuate the incoming energy by over one million to limit heat input to the telescope. Testing of such a system on the ground is a daunting task due to the size of the thermal/vacuum chamber required and the degree of thermal isolation necessary between the room temperature and cryogenic parts of the shield. These problems have been attacked in two ways: by designing a subscale version of a larger sunshield and by carefully closing out radiation sneak paths. The 18% scale (the largest diameter shield was 1.5 m) version of the SPIRIT Origins Probe telescope shield was tested in a low cost helium shroud within a 3.1 m diameter x 4.6 m long LN_2 shrouded vacuum chamber. Thermal straps connected from three shield stages to the liquid helium cooled shroud were instrumented with heaters and thermometers to simulate mechanical cryocooler stages at 6 K, 18-20 K, and 45-51 K. Performance data showed that less than 10 microwatts of radiative heat leaked from the warm to cold sides of the shields during the test. The excellent agreement between the data and the thermal models is discussed along with shroud construction techniques.

Keywords: cryogenic, space telescope, thermal testing, thermal modeling, subscale

1. INTRODUCTION

To fully exploit the advantage of space over ground based telescopes in the far infrared/submillimeter range of the electromagnetic spectrum it is necessary to cool the optics and instruments to 4 K or less. In the past this was accomplished using liquid helium dewars housing a modest sized telescope. IRAS, COBE, ISO, IRTS, Akari all had primaries that were 650 mm in diameter or less. Spitzer was the first to move the telescope out of the dewar, and cooled the telescope using the cold He vapor. Even with exceptional engineering which limited the heat load to the 850 mm diameter telescope to about 5.5 mW, to achieve its expected five year lifetime required a 360 liter dewar with a mass of about 137 kg. To scale up to the much larger telescopes of the future requires a change in the cooling paradigm away from the use of stored cryogens and toward using mechanical cryocoolers and more extensive use of passive cooling to achieve 4 K. Passive cooling can be achieved in a lightweight structure using double aluminized kapton (DAK) in multiple shields. The shields would be separated in a geometry that would block sunlight and thermal energy from the spacecraft, but at the same time would radiate to deep space in the perpendicular direction. Such a system is being developed for the James Webb Space Telescope (JWST). Modeling these shields and verifying their thermal performance is challenging[1], particularly when extending their performance to lower temperatures and much lower heat loads than for JWST.

In the case of Spitzer, a full thermal balance test was not affordable, and the compromise test performed at the payload level resulted in a measured 52 mW input to the telescope rather than the predicted 5.5 mW or the on orbit measured 6 mW. To correct this for future 4 K telescopes we have tested a subscale model of a large telescope's passive/active cooling thermal system using a low cost liquid helium cooled shroud and a test article and a strategy of "fencing off" the warm high radiation sections from the colder more sensitive sections while not interfering with the normal radiative and conductive heat transport within the test article.

An earlier paper[2] gave a progress report on the fabrication of this experiment, predictions of performance, and studies of the effects of wrinkling. Material property measurements of DAK thermal conductivity and emissivity at low temperature were also given. This paper describes the final configuration of the experiment and the results of the test. JWST is planning a subscale test of its sunshield. We ae planning to incorporate lessons learned from this test into that verification.

2. TEST ARTICLE

The test article was designed as an 18% scale model of an early passive shield design for the Space InfraRed Interferometric Telescope (SPIRIT)[3,4]. In this design the full size primary was 2 m in diameter. There were four deployable shields surrounding a cylindrical telescope baffle that would be cooled to the same temperature as the telescope. SPIRIT would be launched into an Earth-Sun L2 orbit which provides a benign, relatively constant thermal environment for the telescope. The shields were designed to take advantage of the fact that Sunlight, Earthlight, Moonlight and spacecraft thermal radiation would be coming from roughly the same direction. 4 shields were chosen as a compromise between performance and complexity and cost. Compromises were made in the geometric scaling of the support structure to allow the use of off-the-shelf composite tubes. This increased the conducted parasitic heat relative to the radiated parasitic heat, but did not overwhelm it. An ordinary single DAK sheet was used for each of the shields held in place by graphite composite battens.

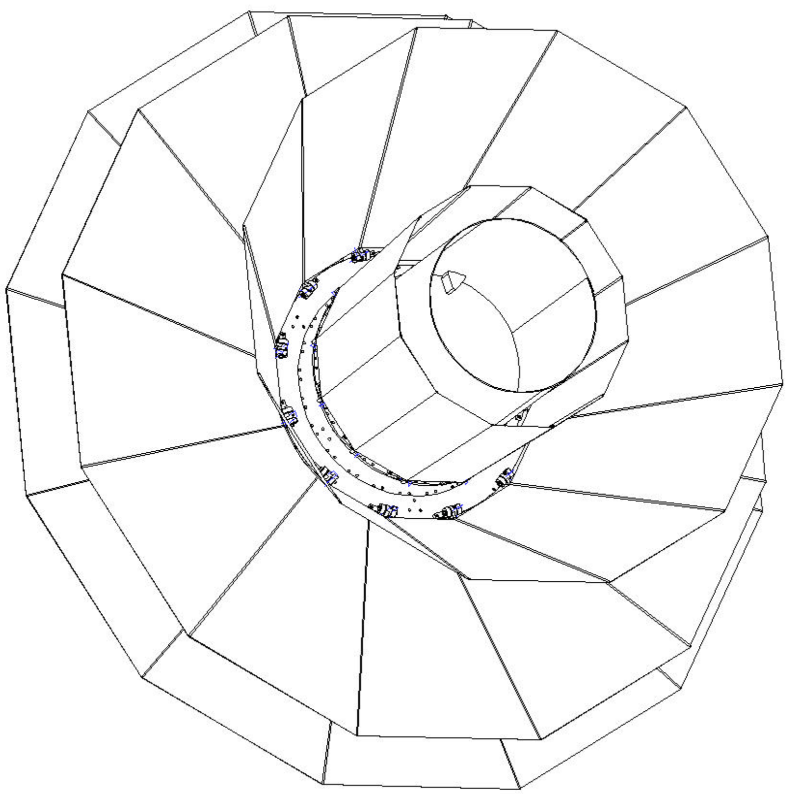

Figure 1. Line drawing of the subscale radiation shields showing the approximate operating temperatures. The central cylinder represents a barrel baffle that would surround a 4 K telescope at roughly the same temperature.

The shields were circumferentially symmetric allowing for simpler analysis and fewer thermometers. The shields are numbered 1-4, warmest to coldest. Each shield terminated at a like numbered hub in the center. The shields were carefully designed and fabricated such that each shield could only see its next neighbor –

there was no view factor of shield #2 to #4, for instance. The G-10 support tubes connected these hubs together and to the warm spacecraft simulator and to the cold baffle. Shield #3 had its outside surface covered with aluminum tape which provided more isothermal conditions, simplifying the analysis of the coldest shield #4, which was anticipated to be the most challenging. Three thermometers were located on each shield, except for the isothermal shield #3, at varying distances from the hub. Each hub had its own thermometer. Two types of thermometer were used: Cernox™ for the lowest temperature and most sensitive shield locations, and silicon diodes at all other locations[5]. There was a concern that the thermometer leads would thermally short the relatively poor lateral thermal conductance of the DAK. For this reason 0.05 mm diameter Cu-Ni coated stainless steel leads were used. Each of these leads is conductively equivalent to a 2 mm wide extra layer of DAK, and would therefore not perturb the shield temperature significantly. In addition the shield wires were routed along expected isothermal lines on the shield (that is circumferentially) before running down the graphite epoxy batten to the hub. A low power heater was located on each hub in order to stimulate the system, thereby calibrating and more fully testing the model. All thermometer and heater wires were routed from hub to hub, exiting the test item at the spacecraft simulator, which would be controlled at room temperature. While the thermometer leads were fabricated from low conductance small gauge stainless steel wire, the heater leads were fabricated from copper to allow significant current to be applied. The conductance of these heater leads was greater than the G-10 supports at each stage. In a future test these would be more carefully sized resulting in even better ultimate temperature performance of the shields.

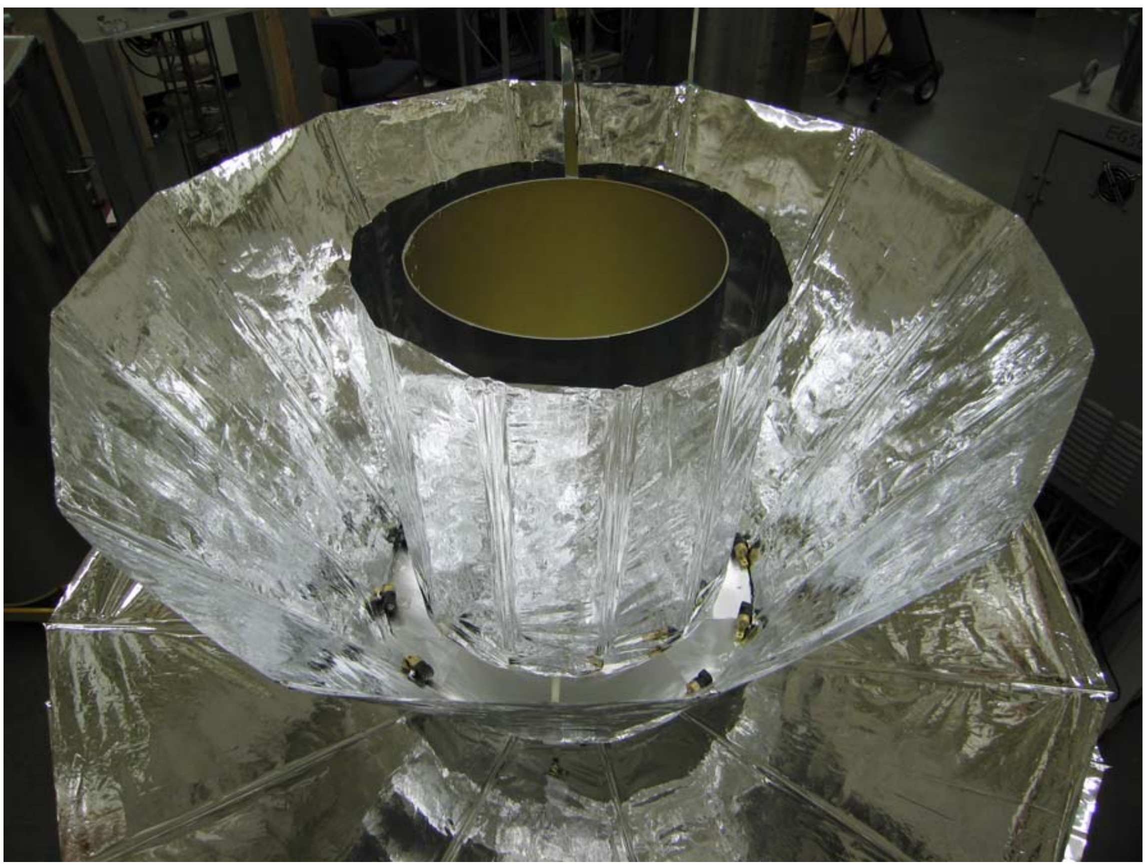

Figure 2. Assembled test article. The thermal described in the following section can be seenextending above shield #3, shield #4, and the 4 K optical baffle simulator.

3. THERMAL SHROUD AND INTERFACES

The test article was placed into a relatively close fitting, specially designed, liquid helium cooled shroud which covered the test article to the top of shield #2. The space between shields #1 and #2 radiated to the walls of the LN2 cooled outer chamber to better isolate the very sensitive lower temperature components from those running significantly above 100 K. The shroud was constructed of aluminum honeycomb panels (6.3 mm diameter cells 25 mm tall) painted black with Chemglaze 306 and epoxied with Stycast 2850 to copper sheet metal plates. See Figure 3. Samples of this construction were thermally shocked by dunking in an LN_2 bath and were manually flexed to verify the adhesion of the paint and the epoxy. 12 identical plates formed the sides of the shroud and one 12 sided cover was the top. Both top and sides had copper tubing attached that carried the liquid helium coolant. The inside of the shroud was 450 mm tall and 1600 mm wide and designed to clear the edges of the test article by at least 12 mm. This was necessary to ensure that any thermal communiction between non-neighboring shields would be captured in the test. This also tests the immunity of the shroud to radiation reflections. Even without very black paint, the honeycomb is predicted to be effectively black due to multiple reflections[6].

A key feature of the thermal test apparatus is to exclude warmer radiation from bouncing off the walls of the chamber and falling on the colder parts. Even though the effective emissivity of the helium shroud is close to 1, it is not perfect. The difference in radiation effects between 300 K and 30 K is 4 orders of magnitude or more. We have therefore taken steps to remove the warmer parts of the test article from within the liquid helium cooled shroud. To accomplish this a device to close out the gap between shield #2 and the bottom of the 4 K shroud was devised. This close out consisted of a moveable piece of copper connected directly to the 4 K shroud and a kapton sheet coated with a nominal 100 nm of aluminum on the warm facing side. A Dacron net, commonly used for spacing multilayer insulation layers, was applied to the uncoated colder side of the kapton. This unit (Figure 3) is then positioned to completely block out any light passing between the the test item and the shroud (Figure 4). The Dacron net provides minimal thermal contact between this close out, which would be at a nominal 4 K, and shield #2 which operates somewhere over 100 K.

Figure 3. Left: aluminum honeycomb painted black and epoxied to a sheet metal copper plate. Right: one of 12 close out segments made of copper, single aluminized kapton and Dacron netting.

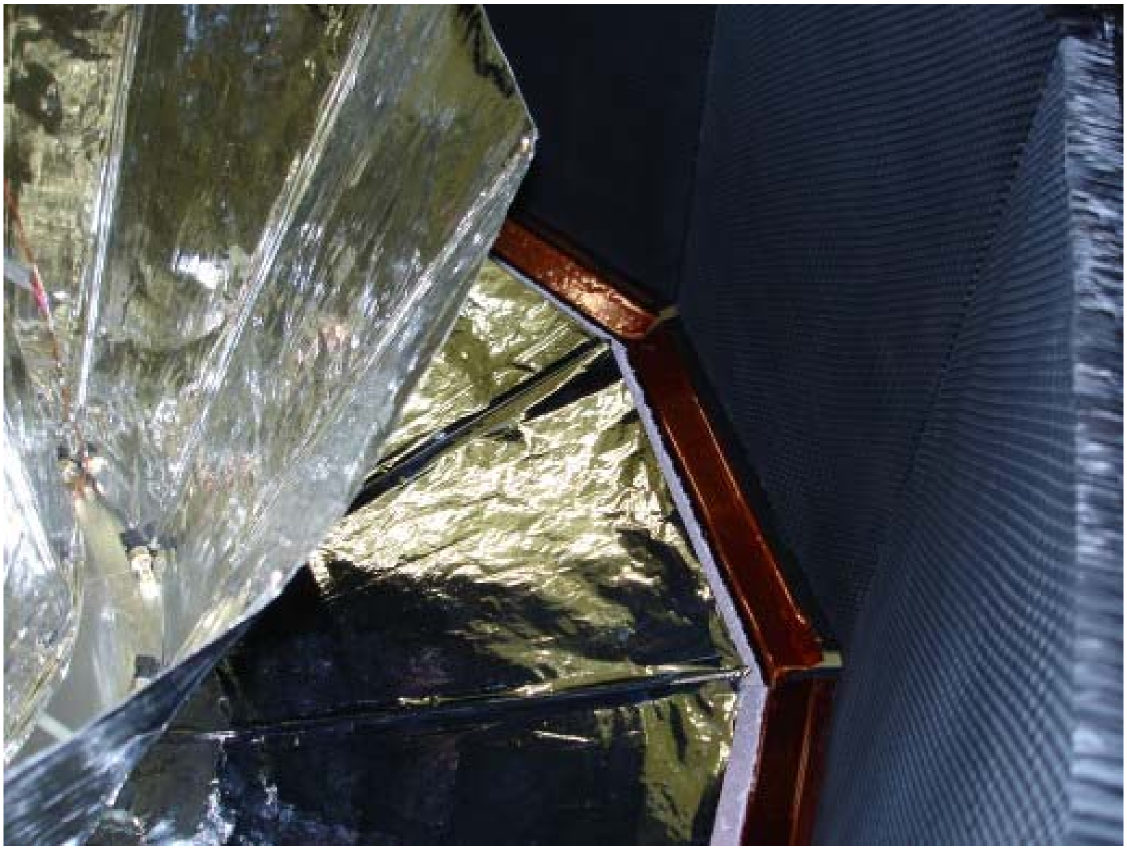

Figure 4. Picture of close out in position at the base of the shroud.

For simplicity and cost, the cryocooler cooling function was simulated using copper straps. These straps labeled A, B, and C, ran from the 4 K shroud to shield #3, shield #4, and the 4 K baffle respectively. (See Figure 5.) Each strap was instrumented with a heater and two thermometers so that it could be temperature controlled and simultaneously the heat flow to and from the heat sink could be determined.

To simulate the Sun and the spacecraft thermal effects there were two heater plates located just below shield #1. The spacecraft simulator operated at room temperature and was located just below and was the same size as hub #1. The solar simulator was located coplanar with the spacecraft simulator and was an annulus with an outer diameter slightly smaller than shield #1. To complete the sun simulation, the lower surface of shield #1 was uncoated kapton with a thickness of 0.05 mm. The upper surface of shield #1 was coated with a nominal 100 nm of vapor deposited aluminum. This configuration allows an approximately room temperature heater plate to produce the desired temperature on shield #1. See Figure 6.

To keep the shroud light tight, no large pumping paths were made in the shroud or its close outs. Instead, naturally occurring small gaps allowed air to escape during a slow pump out of the chamber.

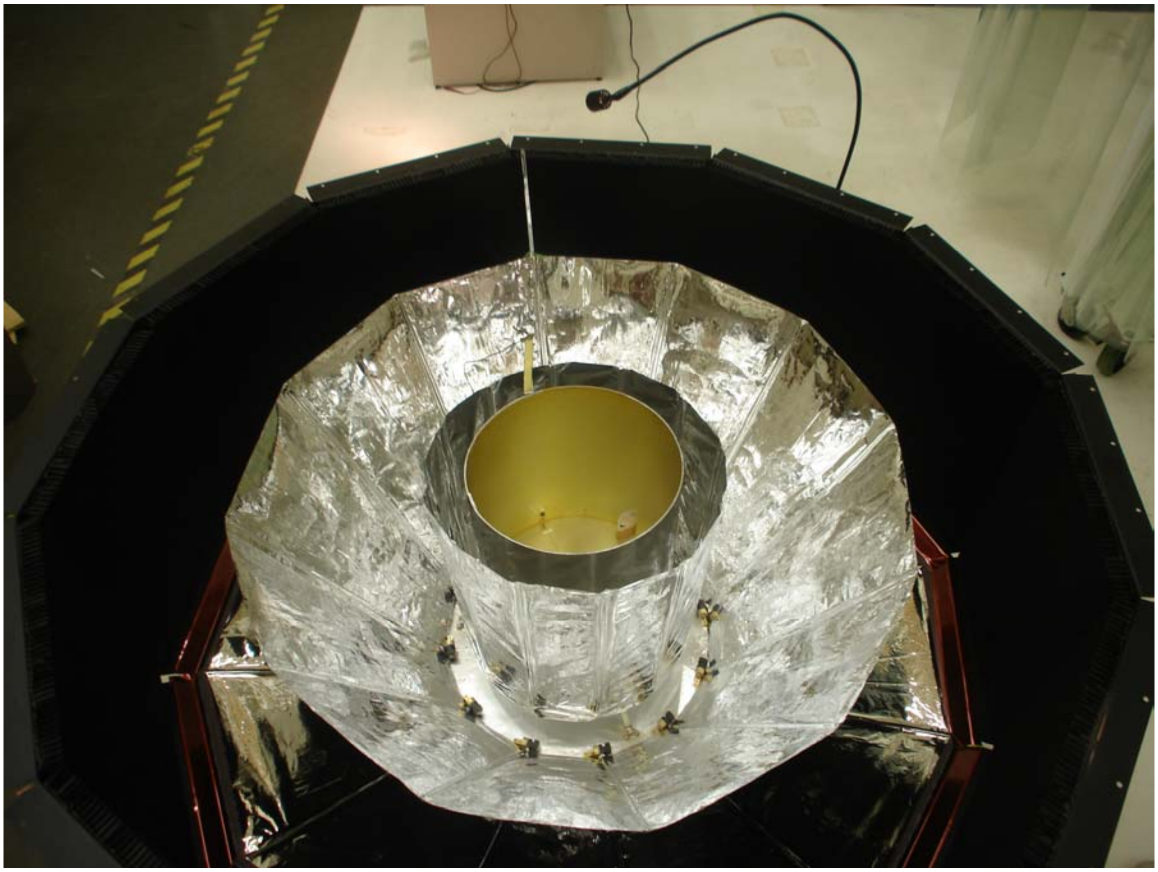

Figure 5. Picture of the test article in the 4 K shroud. The shroud cover is not shown. The outer diameter of the shroud is 1.8 m. Note that one of the DAK covered copper thermal straps is protruding from the test article at the 12 o'clock position.

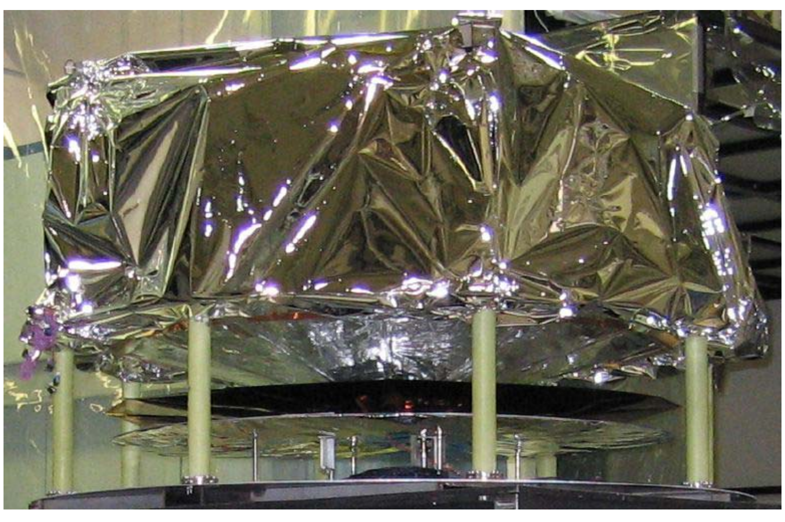

Figure 6. The subscale test article fully assembled into the LHE shroud which is covered with a multi-layer insulation blanket. The lowest disk is the mounting platform. The next disk up is the sun simulator which is blanketed on the bottom. The next disk, which looks dark, is shield #1 which is single aluminized kapton.

4. TEST RESULTS

The test was run in 8 days from insertion into the thermal vacuum chamber. This time includes evacuation of the chamber, cool down to liquid nitrogen (LN_2) temperature, cool down to LHe temperature, and data taking. The chamber was evacuated slowly to prevent shield #2 from pulling through the closeouts due to differential pressure. The cool down was very slow due to the late decision to not lightweight the shield hubs to save cost and schedule. Their heat capacity and the relatively weak thermal links to the 4 K shroud caused stable thermal equilibrium to be reached only after 7 days, leaving one day for data taking. It was decided not to spoil the vacuum with low pressure helium gas since the uncertain effects of residual gas after pump out were crucial to the very small heat flows involved. A residual gas analyzer, which had a background of 10^{-9} torr of He throughout the test, showed no change during liquid helium flow, verifying that there was no leak in the liquid helium plumbing to the shroud. The boundary conditions shown in Figure 7 were obtained on Day 8. The sun simulator did not achieve the desired 270 K on shield #1 due to inadequate wiring in the chamber.

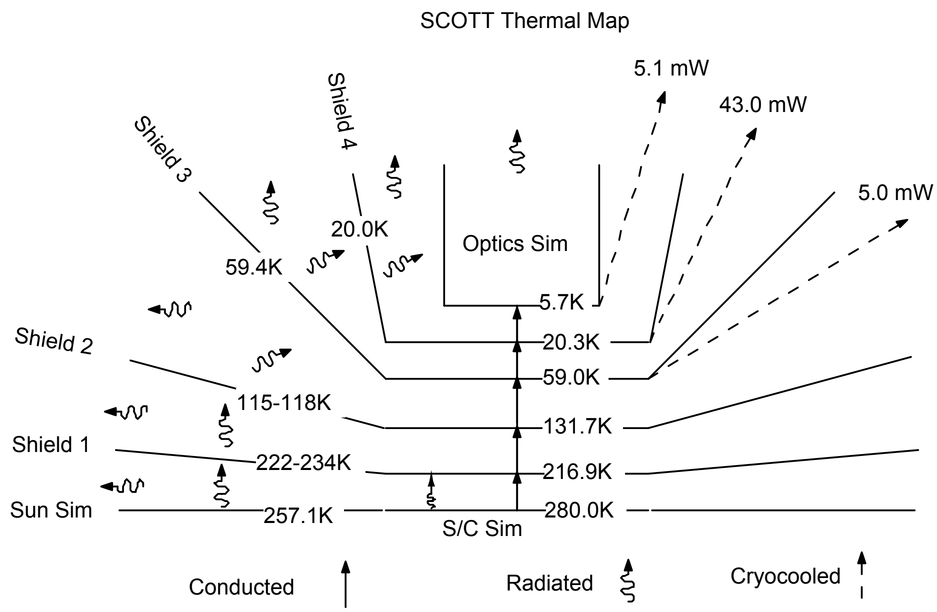

Figure 7. The heat flow schematic indicating measured temperatures (temperature ranges for the shields) and heat flows through the cryocooler simulator straps.

5. MODEL RESULTS

The initial thermal model for this test was generated using a completely cylindrically symmetric geometry and Thermal Synthesizer System (TSS)[7] and Systems Improved Numerical Differencing Analyzer (SINDA)[8] thermal analysis software. This model was used to make estimates of the temperatures and gradients for positioning of the thermometers and 4 K shroud. The model was then refined using Thermal Desktop[8] to include the actual 12 sided geometry, and more realistic boundary conditions. The DAK was treated as fully specular. No allowance for wrinkles or other non-ideal geometry was made, but would realistically show up as a change in effective emissivity.

In the early development the model contained an error which allowed unphysical direct communication between shields #2 and #4. This error caused shield #4 to rise by 3 K over its measured value with a heat flow of only 200 microwatts. Because our actual temperatures on shield #4 were 20 K +/- .03 K, it showed that we did not have such a stray radiation path (such as bounces off the 4 K shroud walls or through sneak paths in the shields or close outs) to a level of 10 microwatts or lower.

An example of the thermal model results is shown in Figure 8. Shield #4 is shown by itself. This shield has the most sensitive response to stray thermal energy. The fact that the model matches the measurements to better than 0.1 K implies that any stray thermal energy is minimal.

Several runs were accomplished with the same boundary conditions which are included in Table 1. In each of these runs the properties varied were the emissivity of the shields and their temperature dependence and the method of tying the battens into the model. While the entire system was modeled, most of the attention was paid to the results for shield #4, the lowest temperature, and therefore the most crucial shield in the system. In the last set of runs, the details of the hubs, which were previously modeled as single nodes, were taken into account as well as remeshing shield #4 to explicitly handle the battens as nodes.

Recent data[9] show a low temperature deviation from the Hagen-Rubens relation for the emissivity vs. temperature and resistivity. This effect becomes very apparent below 40 K. A future run of the model will take these new data along with the dependence of emissivity on wavelength as well as temperature into account.

Note that all of the models match the results of shield 4 very well, which means for the geometry tested, the details of the model are not critical to the energy balance of the coldest shield. That top level result is that even for a shield temperature as low as 20 K, the shield can keep itself cold by radiation as long as the conducted heat is removed by a cryocooler.

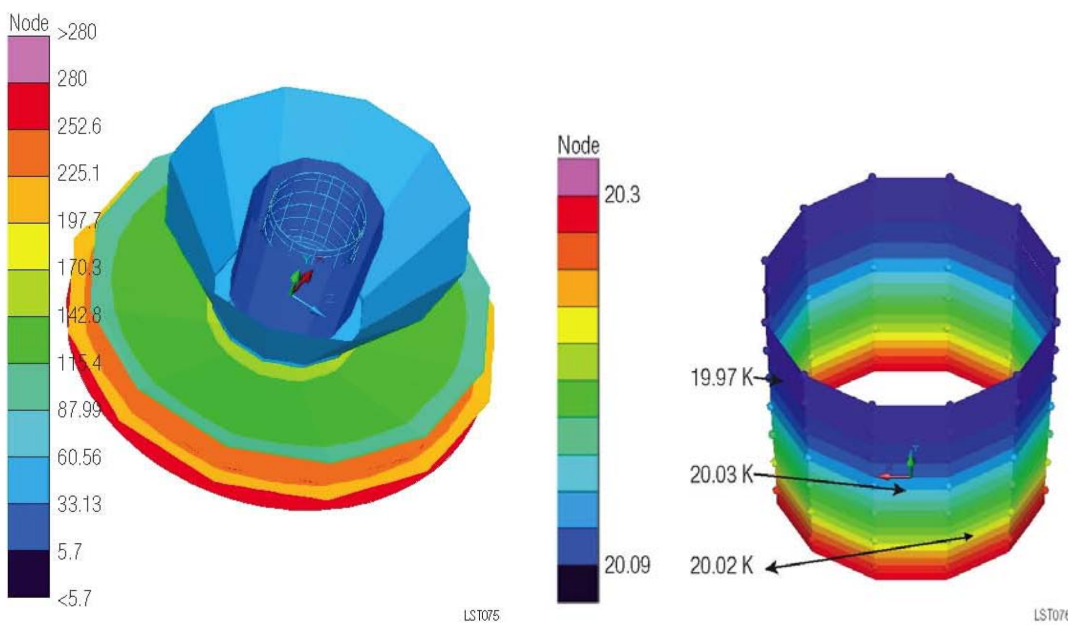

Figure 8. Model results showing detail on shield #4. Note the color (grayscale) temperature scales are not the same. The temperatures and locacting arrows shown correspond to the three thermometers on shield #4.

Table 1. Model results for various parameters.

Case	battens	rays	e	Hub 3	Shield 3	Hub 4	shield4 Near	shield4 mid	shield4 far	Optics sim
Test				**59.00**	**59.40**	**20.30**	**20.02**	**20.03**	**19.96**	**5.70**
5	yes	10k	H-R				20.27	20.24	20.21	
6	no	10k	H-R				20.24	20.16	20.12	
7	yes	10k	0.01				20.24	20.15	20.11	
8	no	10k	0.01				20.14	19.93	19.86	
9	no	63k	H-R				20.20	20.15	20.12	

6. SUMMARY

This work has demonstrated the viability and accuracy of testing a reasonable sized shield and simulated cryocooler spanning the range from room temperature to less than 6 K. The test was accomplished using a subscale model of a future 4 K space telescope. Such a test int the future could validate the modeling and design of an actual flight system for a small fraction of the cost of a full scale thermal balance test. The techniques for achieving a black chamber and limiting communication between warm and cold parts of a system were demonstrated. The room temperature parts of the system radiated of the order of 100 W, while the cold shield #4 was sensitive to less than 10 microwatts, thus an attenuation of better than 1 part in 10^7 was demonstrated. The thermal model was verified to a small fraction of a Kelvin, proving that the lowest temperature shield at about 20 K can still cool itself as long as the conductive heat loads through the wires and structure are eliminated by local cooling provided by a cryocooler. Further analysis using recently obtained low temperature effective emissivity of DAK will be done. Finally, the shield design used is fairly immune to wrinkling and other imperfections in the shield itself.

REFERENCES

1. Cleveland, P.E. and Parrish, K.A., "Thermal system verification and model validation for NASA's cryogenic passively cooled James Webb Space Telescope (JWST)", Proc. Soc. Automotive Engineers, 051CES-236 (2005).
2. DiPirro , M, Tuttle, J., Mattern, A., Ollendorf, S., Leisawitz, D., Jackson , M., Francis, J., Bichell, J., and Hait, T., "Subscale cryo-thermal tests of a large 4 K space telescope," Proc. SPIE **6275**, pp. 62750F 1-11 (2006).
3. Leisawitz, D., Baker, C., Barger, A., Benford, D., Blain, A., Boyle, R., Broderick, R., Budinoff, J., Carpenter, J., Caverly, R., Chen, P., Cooley, S., Cottingham, C., Crooke, J., DiPietro, D., DiPirro, M., Femiano, M., Ferrer, A., Fischer, J., Gardner, J.P., Hallock, L., Harris, K., Hartman, K., Harwit, M., Hillenbrand, L., Hyde, T., Jones, A., Kellogg, J., Kogut, A., Kuchner, M., Lawson, W., Lecha, J., Lecha, M., Mainzer, A., Mannion, J., Martino, A., Mason, P., Mather, J.C., McDonald, G., Mills, R., Mundy, L., Ollendorf, S., Pellicciotti, J., Quinn, D., Rhee, K., Rinehart, S.A., Sauerwine, T., Silverberg, R.F., Smith, T., Stacey, G., Stahl, H.P., Staguhn, J., Tompkins, S., Tveekrem, J., Wall, S., and Wilson, M., The Space Infrared Interferometric Telescope (SPIRIT): High-resolution imaging and spectroscopy in the far-infrared, J. Adv. Sp. Res., in press (2007), doi:10.1016/j.asr.2007.05.081
4. DiPirro, M., Cottingham, C., Boyle, R., Ollendorf, S., and Leisawitz, D., "The SPIRIT thermal system", submitted for publication in Proc. SPIE **6687.**
5. Lakeshore Cryotronics, 575 McCorkle Blvd., Westerville, OH 43082.
6. Lu Yan, Han Jun, and Gong Tiequan, "Theory analysis and test study of cold black target for space radiative cooling environmental simulator", *Adv. Cry. Eng*. **41**, pp.1181-1188 (1996).
7. Space Design, PO Box 1045, Houston TX, 77251.

8. Cullimore and Ring, 9 Red Fox Lane, Littleton, CO 80127.
9. Tuttle, J., DiPirro, M., Canavan, E., and Hait, T., "Thermal properties of double-aluminized kapton at low temperatures," submitted for publication in Adv. Cry. Eng. **53** (2008).