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LUVOIR Backplane Thermal Architecture Development Through the Composite CTE Sensitivity Study

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ABSTRACT

The Large UV/Optical/IR Surveyor (LUVOIR) is one of four 2020 Decadal Survey Missions, a concept for 'flag-ship' class space-borne observatory, operating across the multi-wavelength UV/Optical/NIR spectra. An Optical Telescope concept being considered is the segmented primary mirror architecture with composite backplane structure. In order to achieve the high-contrast imaging required to satisfy the primary science goals of this mission would require, roughly, 10 pico-meter wavefront RMS stability over a wavefront control time step of approximately 10 minutes. The LUVOIR primary mirror backplance support structure (PMBSS) requires active thermal management to maintain operational temperature while on orbit. Furthermore, the active thermal control must be sufficiently stable to prevent time-varying thermally induced distortions in the PMBSS. This paper describes a systematic approach to developing a thermal architecture of a modular composite section of the mirror support structure heavily guided by the sensitivity studies of the composite Coefficient of Thermal Expansion (CTE) values. Thermal and finite-element models, sensitivity studies against the absolute values and their variations of the composite CTE, the early findings from the thermal and thermal-distortion analyses are presented.

Keywords: LUVOIR, ATLAST, Thermal Distortion, pico-meter, Composite, CTE, CTE sensitivity, ULE, HST, JWST

1. NOMENCLATURE

ATLAST	= Advanced Technology Large Aperture Space Telescope
BFP	= Best Fit Plane
°C	= Degree Celsius
CTE	= Coefficient of Thermal Expansion
dT	= temperature differences
e	= Emissivity
FEM	= Finite Element Model
GSFC	= Goddard Space Flight Center
HST	= Hubble Space Telescope
IR	= Infrared
JWST	= James Webb Space Telescope
JPL	= Jet Propulsion Laboratory
K	= Kelvin
LOM	= Linear Optics Model

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LUVOIR	= Large UV/Optical/IR Surveyor
m	= Meter
mK	= Milli-Kelvin
MLI	= Multi-layer insulation
NASA	= National Aeronautics and Space Administration
NIR	= Near-infrared
pm	= pico-meter
ppb	= Parts Per Billion
PV	= Peak to Valley
RMS	= Root Mean Square
SAO	= Smithsonian Astrophysical Observatory
SFE	= Surface Figure Error
sec	= Seconds
ULE®	= Ultra-Low Expansion (ULE® is a registered mark of Corning)
UV	= Ultra-Violet
WFE	= Wavefront Error

2. INTRODUCTION

The Large UV/Optical/IR Surveyor (LUVOIR) mission concept builds upon key technologies developed for Hubble Space Telescope (HST) and James Webb Space Telescope (JWST). LUVOIR will leverage and further enhance the technological advances developed for JWST, such as deployable large segmented-mirror arrays. This mission concept is led by the NASA Goddard Space Flight Center in Greenbelt, Maryland and is currently studying the scientific, technical requirements, and costs associated with building a successor to HST and JWST.

The Large UV/Optical/IR Surveyor (LUVOIR) is under a pre-proposal concept study for a 9.2 to 15m aperture space-borne observatory operating across the UV/Optical/NIR spectra. The primary mirror for LUVOIR is a segmented architecture with pico-meter class wavefront stability. The observatory needs to be thermally and structurally very stable to achieve these ambitious goals, which can be achieved by operating in the Sun-Earth L2 orbit — the same orbit and environment chosen for the James Webb Space Telescope.

As a part of on-going LUVOIR conceptual architectural studies, a first-order study focused solely at the mirror segment level to characterize the local behaviors of mirror distortions induced by its thermal environment was completed. [1] The previously studied 'room temperature' segmented ULE® mirrors required active thermal management to maintain operational temperatures while on orbit. An active mirror thermal control system with nominally 1 milli-Kelvin level resolution satisfied the current goal to maintain the Wave Front Error (WFE) to less than 10 pico-meters over a wavefront control time step of 10 minutes. A follow on to the mirror segment level effort is this backplane level thermal-distortion study to guide the thermal architecture of the LUVOIR backplane. This follow on study is the topic of this paper and was methodically performed in a sequential manner to isolate individual heater control locations within the structural members of backplane assembly. This study showed the sensitivity to the heater control locations that may have impacts on the systems-level WFE due to the rigid body motion of the primary mirror segments. This study also assessed the systems-level WFE sensitivity due to the composite CTE and its variability at various locations within the backplane structure assembly.

Illustrated in Figure 1 below is the artist conceptual rendering of LUVOIR (formerly ATLAST) in the on-orbit operational configuration with the Sunshade and telescope elements fully deployed. [2]

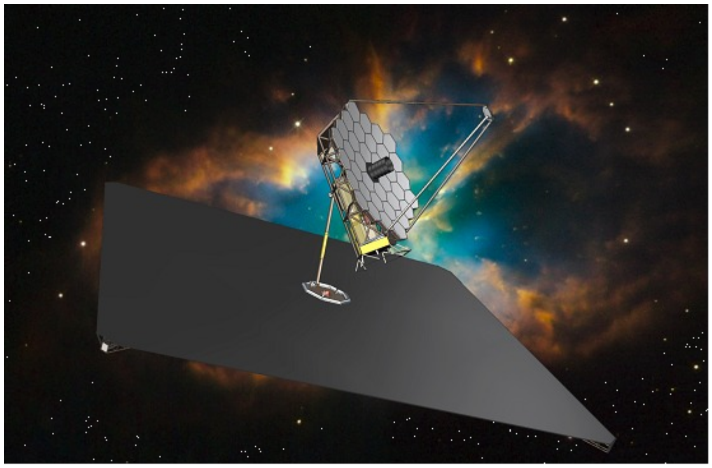

Figure 1 Artist conceptual rendering of 9.2m Aperture LUVOIR (formerly ATLAST) in the Sun-Earth L2 on-orbit operational configuration with the Sunshade and telescope elements fully deployed.

The LUVOIR study team is currently considering a 15m aperture telescope design, however, this study was performed using an earlier 9.2m telescope architecture. Depicted in Figure 2 below is the conceptual design of 9.2m LUVOIR (formerly ATLAST) Telescope Element with scientific instrument payload suite in the 'stowed' configuration for launch and the 'deployed' on-orbit operational configuration. Note that the concept of 9.2m aperture LUVOIR telescope includes 36 primary mirror segments and a steerable secondary mirror, both include baffles for stray light management.

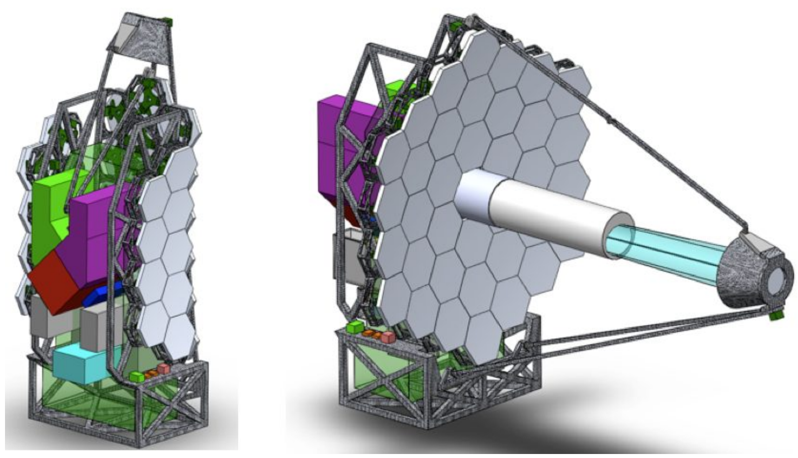

Figure 2 The conceptual design of LUVOIR Telescope Element with scientific instrument payload suite in the 'stowed' configuration for launch (left view) and the 'deployed' on-orbit operational configuration (right view).

3. ANALYTICAL MODELS

- **Structural Finite Element Model (FEM)**

A systems-level finite element model of a 9.2 m diameter 36 mirror segments with a central strip and 3 strip wings on each side was provided by the NASA GSFC ATLAST/LUVOIR team (See Figure 3). For this study we considered the effects of backplane temperature and CTE variation within a single strip so we chose the central strip that may be expected to produce representative results. The complexity of hinge lines will likely generate additional distortion in the structure but assessment of that effect is left for future studies when hinge concepts are available.

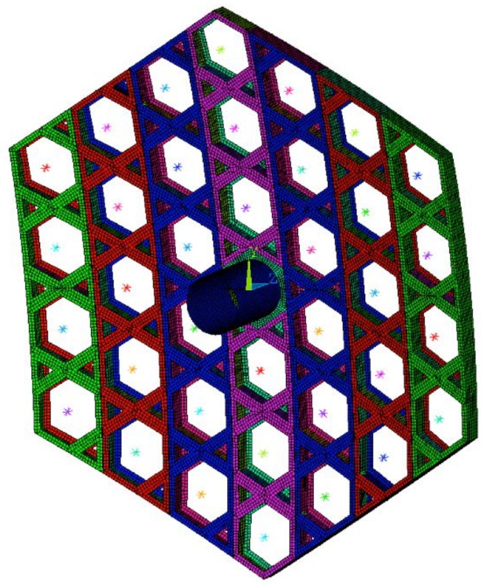

Figure 3 GSFC Provided ATLAST system FEA model

Lessons learned from the JWST design phase were applied to the GSFC model to enhance thermal stability. Design changes to the structural arrangement were applied to enhance thermal stability as long as we didn't adversely affect stiffness. The first was to project outward radially the hinge line cuts and the reinforcements from the center of curvature (See Figure 4 to Figure 6). The next was to replace the curved front and back panels with faceted flat panels. The third was to add a feature to mount mirrors (See Figure 5).

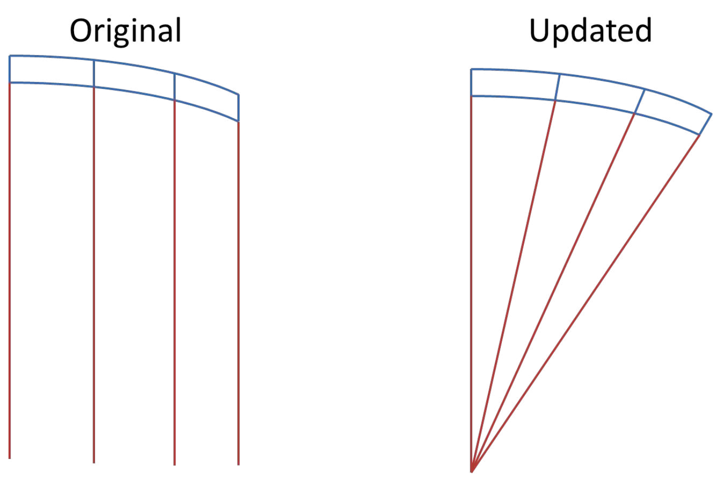

Figure 4 Parallel versus Radial hinge line Orientation

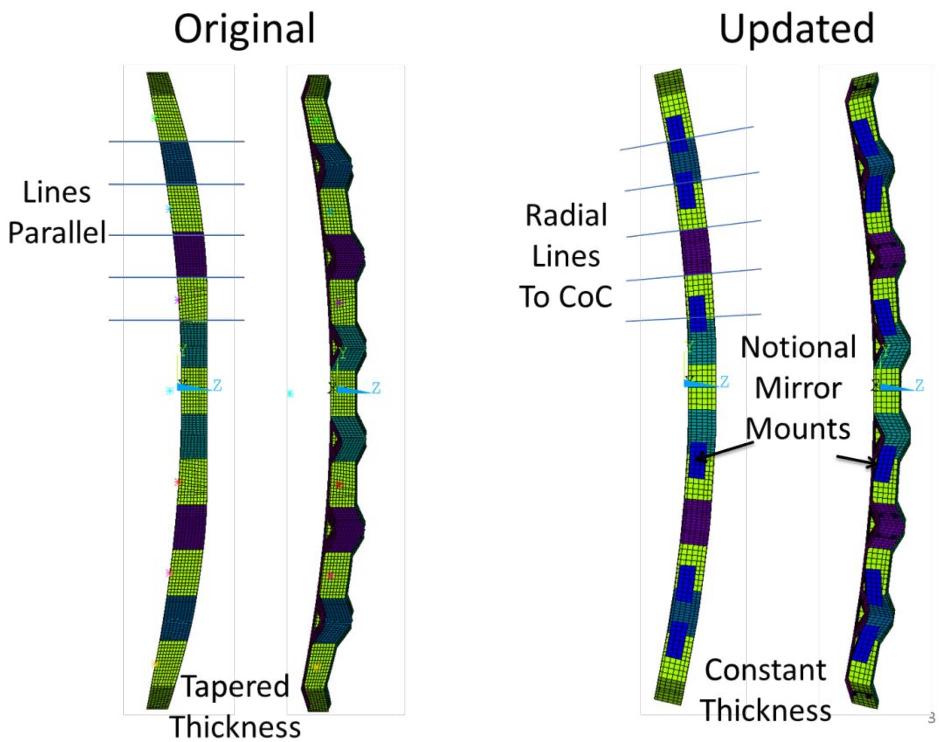

Figure 5 Structural element realignment to reduce internal shear and bending distortions

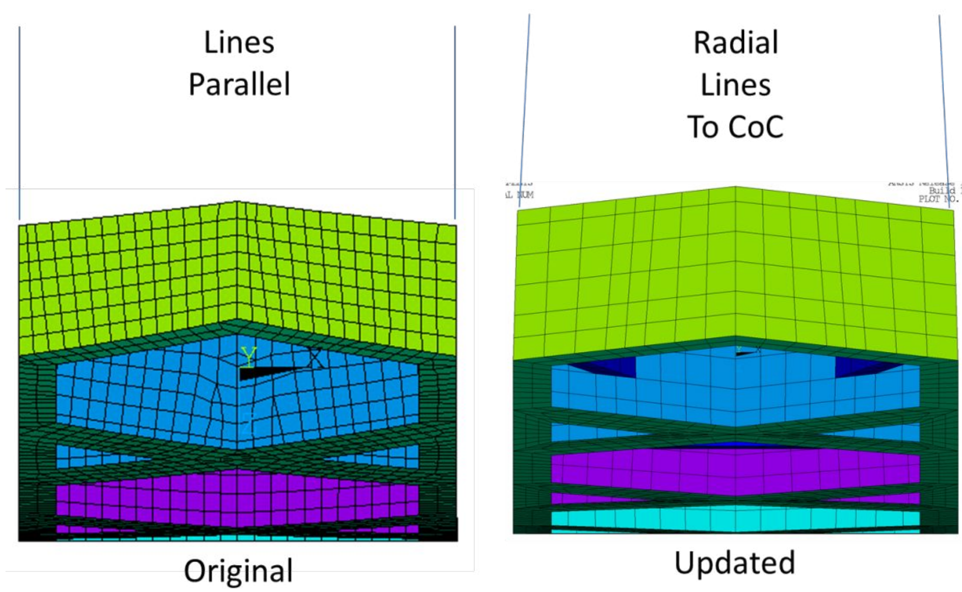

Figure 6 7 Wedge shaped segments align with PM surface orientation to reduce splaying deformations on PMSA mounts

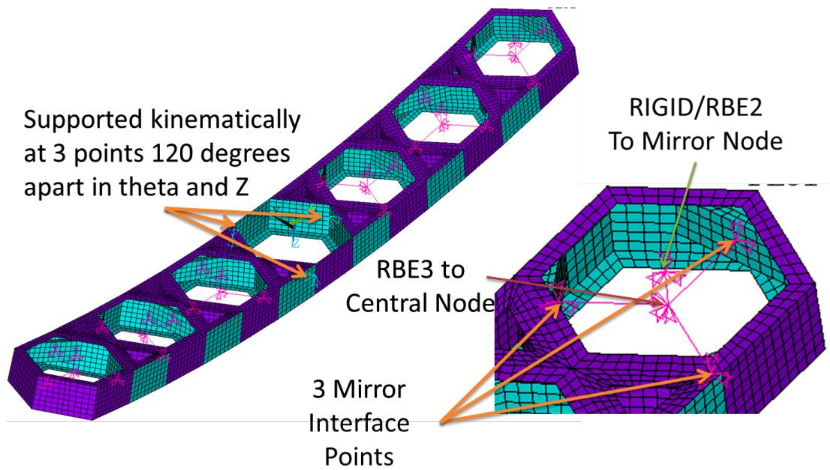

Figure 8 Mirror Attachment Details

- **Optical Metric**

We wanted a computationally simple optical metric to make relative comparisons between cases quickly. We developed a "Pseudo" Linear Optics Model (LOM) that took into account the relative piston and tilts between mirror segments while ignoring decenter and clocking. The normal (PMSA local piston) displacement and the tip and tilt rotations were extracted from the FEA model and applied to LOM (See Figure 9). In the LOM the mirror segments were flat and the displacements were applied axially. Surface RMS was reported with nothing removed, piston removed, or piston and tilts removed (Best-Fit-Plane (BFP)). Note WFE is equal to two times Surface Figure Error (SFE).

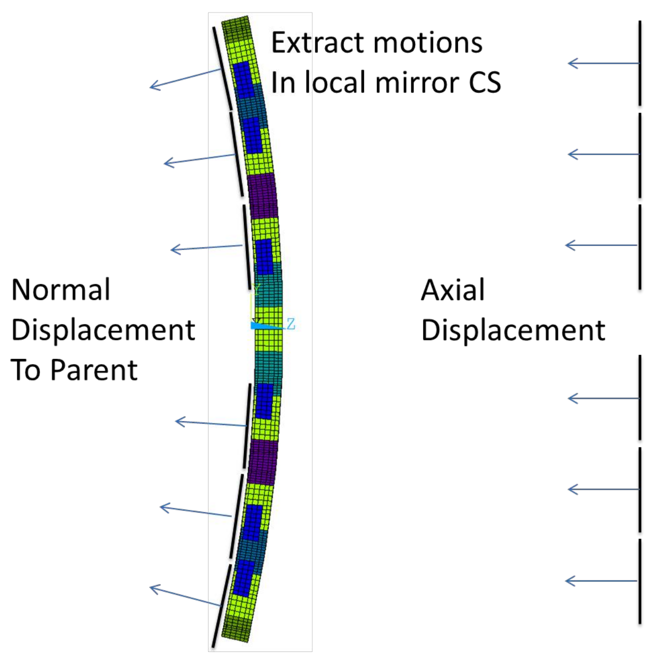

Figure 9 Pseudo LOM

- **Thermal Model**

A thermal model was generated using ThermalDesktop® by importing the ANSYS FEM with a coarser mesh size. This method provided a common geometry between the structural FEM and the thermal model where all edges of the backplane would line up properly. Furthermore, this method ensured all thermal nodes would be coincident with a node in the FEM; this minimizes interpolation error between thermal results to FEM. This thermal model was then enhanced with thermal features in order to predict somewhat realistic temperature gradients within the backplane assembly. These thermal features include additions of notional mirror surfaces, thermal insulation layers (Multi-layer Insulation, MLI) as the closeout on the back-side of the backplane, and heater logics were added at various locations in order to perform parametric sensitivity studies (See Figure 10). Then the thermal physical properties and thermal optical properties were added to generate a functional thermal model.

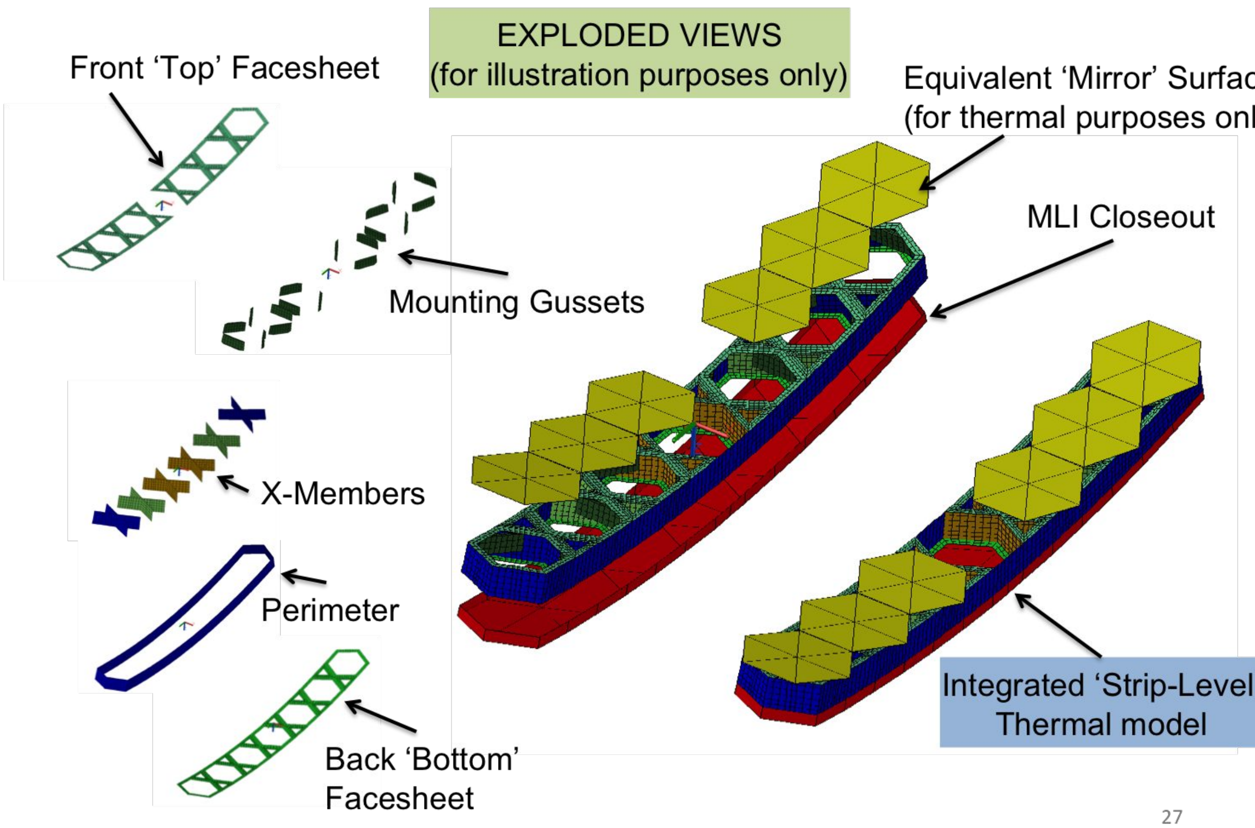

Figure 10 An integrated 'strip-level' thermal model of a strip portion of the backplane assembly includes various features of the structure, notional mirror surfaces, MLI closeout, and heater logic.

4. CASE STUDY

- **Nominal Uniform CTE with Bulk dT**

We first looked sensitivities for the case with uniform CTE and a bulk 1mK Delta T. The uniform Delta T was applied to the entire structure for one case and then applied each of the following components: Front Facesheet, Back Facesheet, Perimeter Outer Ring, X-members, and the primary mirror mounts. The intent was to look at the relative performance of each component as a location for thermal control sensitivity. For this study a uniform CTE of 80 ppb/K was assumed for all zones. The SFE results of this are summarized in Figure 11. The cases where the X-members and mirror supports were changed had the lowest SFE with BFP removed. These early parametric study results showed that the X-members and mirror supports may be good candidate locations to place the thermal control heaters. Conversely, heater control resolution would need to be much finer than 1mK if we were looking to place the heaters on other features of the backplane assembly. Furthermore, the results showed that the thermal controls on all backplane surfaces to 1mK resolution would produce a low SFE but the actual implementation of this concept may be very difficult to achieve. Also keep in mind that this study was performed with a thermally stable condition assumed.

Case	Back Facesheet	Front Facesheet	X-members	Perimeter	Mirror Support	RMS (pm)	RMS – Piston (pm)	RMS – BFP (pm)
'Soak' Case 1	20.000°C	20.000°C	20.000°C	20.000°C	20.000°C	0	0	0
'Soak' Case 2	20.001°C	20.001°C	20.001°C	20.001°C	20.001°C	19.15	11.00	11.00
'Soak' Case 3	20.001°C	20.000°C	20.000°C	20.000°C	20.000°C	859.25	517.27	516.38
'Soak' Case 4	20.000°C	20.001°C	20.000°C	20.000°C	20.000°C	219.53	148.82	139.14
'Soak' Case 5	20.000°C	20.000°C	20.001°C	20.000°C	20.000°C	95.88	94.70	6.40
'Soak' Case 6	20.000°C	20.000°C	20.000°C	20.001°C	20.000°C	688.80	409.58	392.54
'Soak' Case 7	20.000°C	20.000°C	20.000°C	20.000°C	20.001°C	3.02	2.56	2.56
'Soak' Case 8	20.001°C	20.001°C	20.000°C	20.000°C	20.000°C	646.76	378.13	377.46
'Soak' Case 9	20.001°C	20.001°C	20.000°C	20.000°C	20.000°C	469.62	297.78	297.71
'Soak' Case 10	20.001°C	20.000°C	20.000°C	20.000°C	20.000°C	183.21	86.39	81.30

No Central Hex   Just Central Hex

Figure 11 Surface RMS Thermal Trade Studies: dT sensitivity study

- **CTE Variation with uniform delta-T Analysis**

The FEA model was modified so that each flat panel had a unique material property assignment (See Figure 12). This allowed us to vary the CTE part by part in a Monte Carlo analysis. We ran a series of cases where both the nominal and variation in CTE varied independently for components and subjected the structure to a uniform 1mK Delta T. We also looked at cases where we varied one component CTE at a time: Front Facesheet, Back Facesheet, Edge Ring, X-braces, and the PMSA mounts. For each of these cases we reported the Quasi-LOM SFE with Best-Fit-Plane (BFP) removed. Figure 13 shows an example where each part in the structure was varied such that it had a nominal CTE of 0 ppb/K and a variation of ±5 ppb/K applied as a uniform probability distribution. A uniform probability distribution was chosen since it mimics an acceptance program with a nominal value and tolerance. The same methodology was used on JWST for studying CTE variation in the backplane. One thousand random cases were generated. A histogram of the distribution of CTE input is shown along with a histogram of the surface RMS with BFP removed. A 95% confidence value is reported by adding the mean and two times the standard deviation.

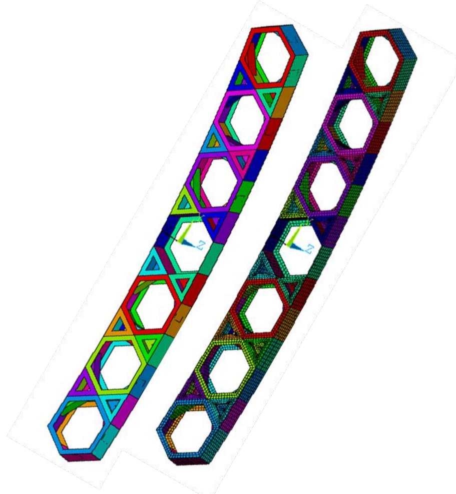

Figure 12 Material Property Discretization; each colored surfaces represent different material properties

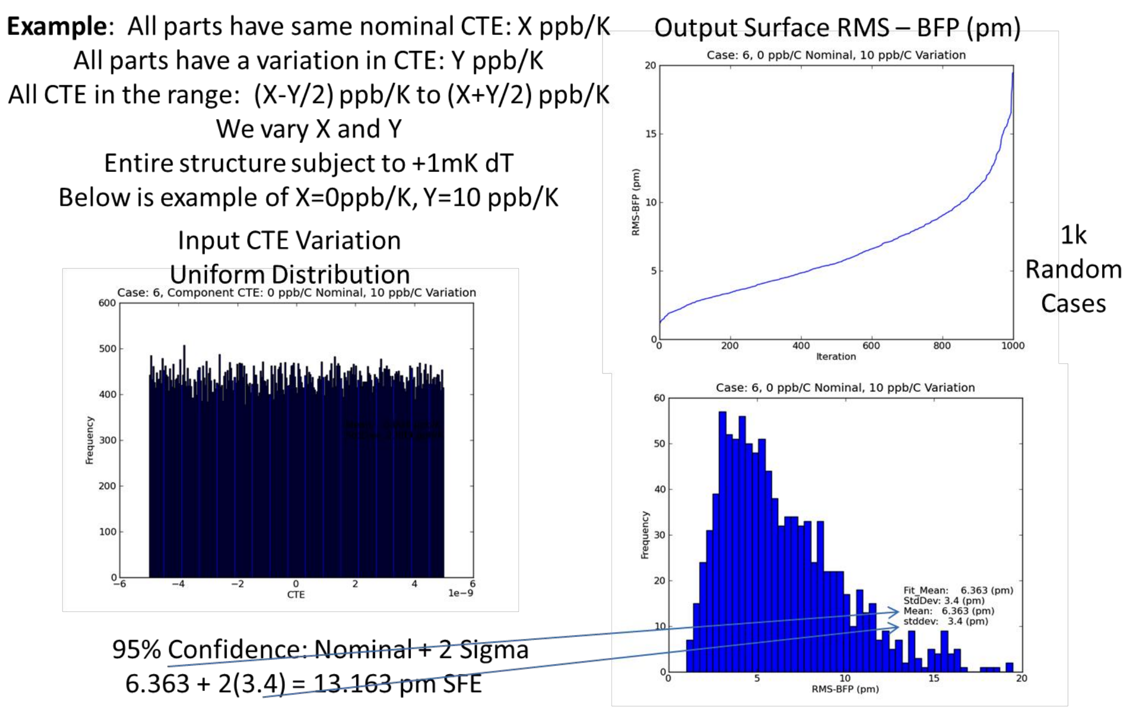

Figure 13 Example Monte Carlo Case

The nominal CTE (variable X) and the variation in CTE (variable Y) can both be varied over a range and the resultant 95% Confidence Surface RMS can be tabled and contoured. Figure 14 shows the result where all the parts of the structure are varied over the same range. One can compute the sensitivity to nominal CTE and variation in CTE from the results in the table. For nominal CTE we look at the case where variation was assumed to be zero and divide by the assumed nominal CTE. For this case we see 2.75 pm RMS SFE for a 20 nominal ppb/K CTE and a 1 mK delta T. This gives a sensitivity of 0.14 pm/(1 ppb/K nominal CTE)/(1 mK uniform dT). For variation in CTE we look at the case were the nominal CTE was zero divide by the assumed variation in CTE. For this case we see 39.49 pm RMS SFE for a 30 ppb/K CTE variation and a 1 mK delta T. This gives a sensitivity of 1.32 pm/(1 ppb/K variation in CTE)/(1 mK uniform dT). For this case where all parts were varied we see that we are much more sensitive (10x) to variation in CTE than the nominal CTE.

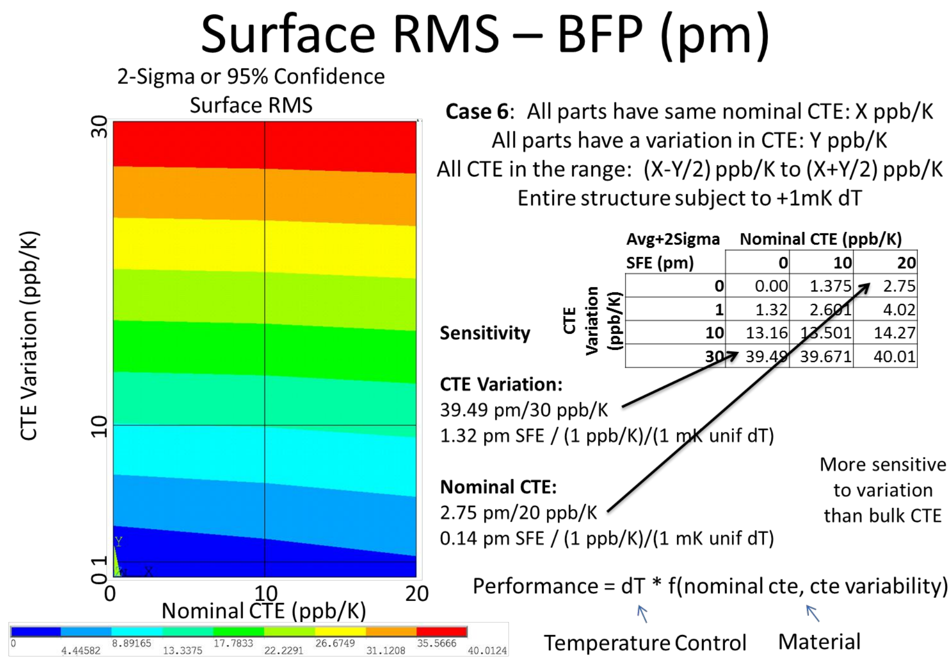

Figure 14 Example Response for varied Nominal CTE and CTE variation

A similar analysis was performed that varied the individual components while having 0 CTE (or 0 dT) on the other parts of the structure. The sensitivities for those cases are summarized in Figure 15. One can see that the cases where the X-members and the Mirror Supports were varied had the lowest sensitivity for both nominal CTE and CTE variation. Also worthy of noting are that thermally controlling the areas of Back facesheet, Front facesheet, perimeter, and mirror supports have higher sensitivity to the absolute nominal CTE variations while controlling the areas of X-members and the overall backplane have higher sensitivity to the variations within the CTE. This information is an important factor to consider during the development and manufacturing of composite materials for LUVOIR backplane.

						Sensitivity (pm SFE/(1 ppb/K)/(1 mK unif dT))	
Case	Back Facesheet	Front Facesheet	X-members	Perimeter	Mirror Support	CTE Variation	Nominal CTE
Case 1	Varied	0	0	0	0	1.064	6.455
Case 2	0	Varied	0	0	0	0.304	1.739
Case 3	0	0	0	Varied	0	0.659	4.907
Case 4	0	0	Varied	0	0	0.162	0.080
Case 5	0	0	0	0	Varied	0.018	0.032
Case 6	Varied	Varied	Varied	Varied	Varied	1.316	0.138

Figure 15 Summary of SFE sensitivity study with CTE variations

- **Various heater zones cases**

The CTE variation studies were conducted with the FEM by varying 1mK to only those areas under consideration. However, we took further steps using the thermal model to predict temperature gradients within the backplane assembly to understand the sensitivity to the changes in thermal state with the temperature gradients at various locations. The various locations for heater applications were consistent with the early FEM CTE variation study, those locations are the front facesheet, back facesheet, X-members, outer-ring perimeter, and all surfaces of the backplane strip. These thermal predictions not only provided the thermal gradients but they also provided the heater power required to maintain the controlled regions at 20°C nominally. Another thermal variable to characterize the heater power optimization was to vary the thermal optical properties of the structure surfaces, namely the emissivity (‘e’) of that surface. The results from these predictions are listed on the Figure 16 and Figure 17 below:

Depicted in Figure 16 are typical temperature contours of the backplane structure with heaters and its control points at various locations.

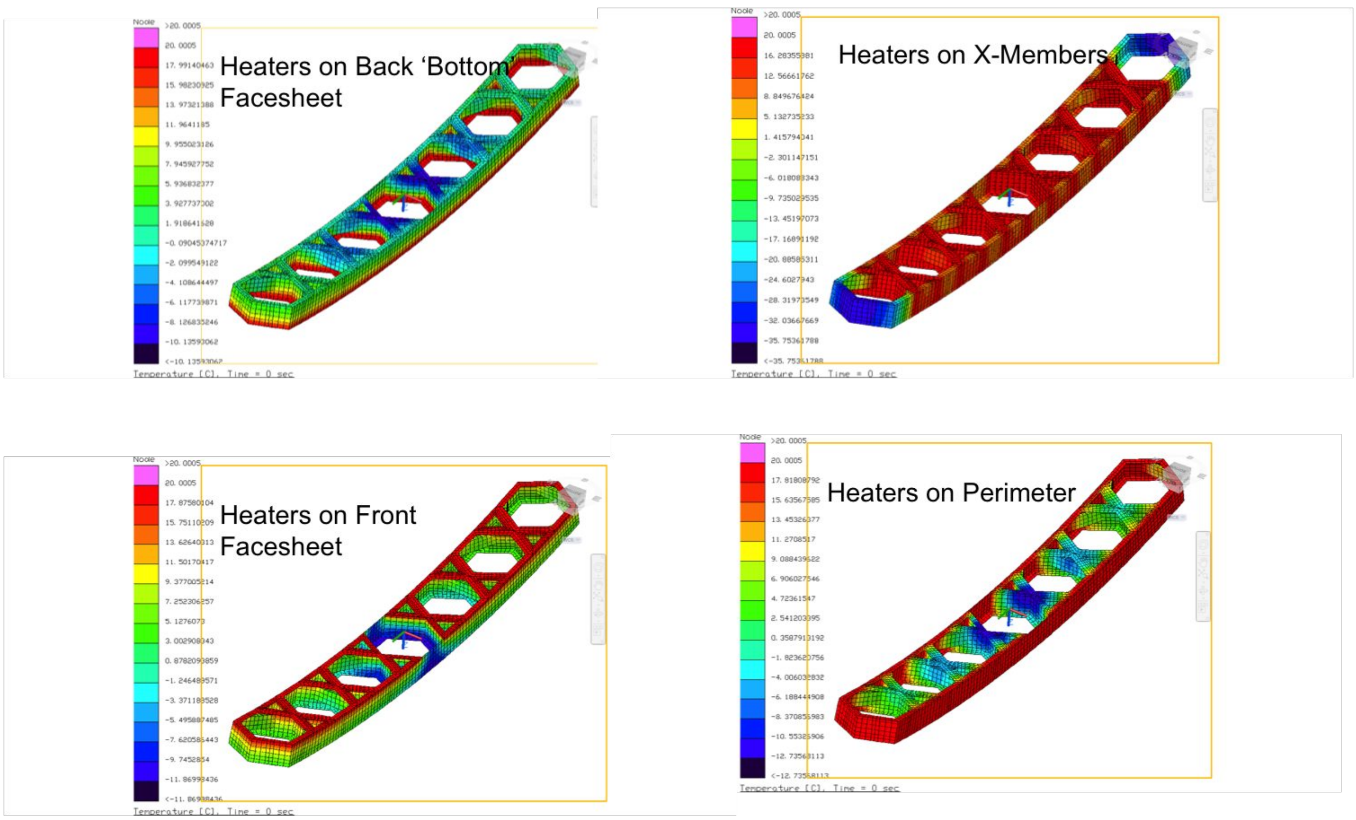

Figure 16 Typical predicted temperature contours of the backplane with the heater controls at various locations of the composite backplane assembly.

As depicted in Figure 17 below, using the thermal model, we solved for the steady state heater power required to maintain that specific locations at a nominal 20°C, and the dT (Maximum-Minimum) within the backplane structure. As stated earlier, applying heater power to the entire backplane surfaces while maintaining no thermal gradients may not be feasible. Among other surfaces considered, applying heaters to the perimeter resulted in the smallest thermal gradient but also required the highest heater power required. Note that we also varied the surface emissivity between 0.5 and 0.05. The predictions showed significant reductions in the resultant heater power and the predicted dT(maximum-minimum) for the case with the surface emissivity of 0.05. To emphasize again, this study is an early phase of the conceptual study, therefore there was no attempt to minimize the heater power. The heater power optimization will be a subject of future studies.

	'e' = 0.50 on All BP Surfaces				
	Back Facesheet	Front Facesheet	X-members	Perimeter	All_BP
(e=0.50) heater Power (at 20C) Watts	1769.3	1810.7	1935.3	2510.2	2672.1
(e=0.50) dT(Max-Min) deg-C	60.5	78.4	81.61	46.71	0
	'e' = 0.05 on All BP Surfaces				
	Back Facesheet	Front Facesheet	X-members	Perimeter	All_BP
(e=0.05) heater Power (at 20C) Watts	482.2	479.4	505.6	514.2	566.9
(e=0.05) dT(Max-Min) deg-C	30.14	31.87	55.75	32.74	0

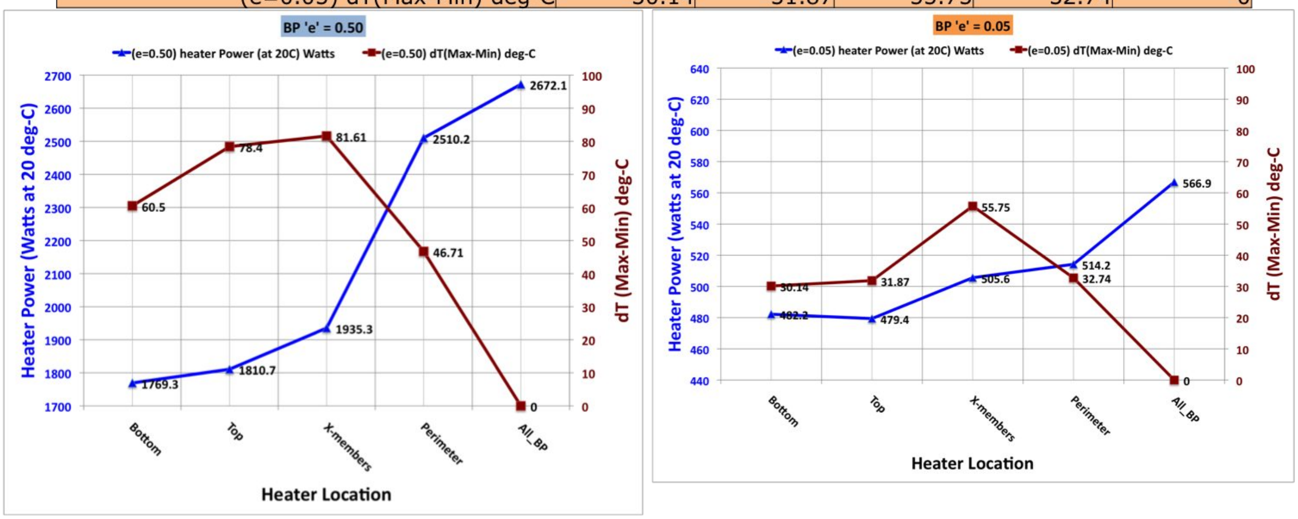

Figure 17 Results of the heater power and dT(Maximum-minimum) predictions of the backplane structure

The results from the thermal model predictions with thermal gradients were then mapped on to the FEM and solved for SFE. These temperatures were applied to the model with uniform 80 ppb/K CTE so they can be compared to the previous uniform dT results in Figure 11. The results from the SFE calculations are listed in Figure 18 below. During this phase of the study, it was noticed that the thermal gradient case with heaters on the perimeter also resulted in a lower SFE. This is due to the front and back facesheets following the perimeter temperatures via conduction heat transfer that was not captured during the FEM sole-centric sensitivity study.

Heater Case	RMS (pm)	RMS – Piston (pm)	RMS – BFP (pm)
Back Facesheet +0.001°C	212.5	128.2	127.8
Perimeter +0.001°C	35.0	23.6	16.3
Front Facesheet +0.001°C	207.7	125.1	124.5
X-Member +0.001°C	8.7	6.8	6.3

Figure 18 SFE calculations with various heater locations of the backplane using the thermal predictions with temperature gradients.

- **Multi-heater zone simulations**

Based on the sensitivity studies performed to date, the reasonable and logical places to 'control' temperatures are the BP Perimeter ('Outer-ring') and the X-Members (or the Mirror Mount Gussets). In this case study, multiple heater locations were considered, namely on the Perimeter and the X-members of the backplane. The X-members are somewhat 'insensitive' to a milli-K variation (~6pm RMS, - BFP). But the results so far showed that the perimeter temperature variations would need to be better controlled to something less than 1 milli-K, roughly a 0.5 milli-K on steady state basis. However, these variations in the heater performances may be dampened and managed through the thermal capacitance of the BP. With an assumption of the backplane composite thermal emissivity property of 0.05, the heater power required to maintain the heater control zones at their set points of 20°C was predicted to be 401watts with the dT(Maximum – Minimum) of 25.6K (See *Figure 19*). As a side note, the cold spot on the backplane shown in *Figure 19* is due to an empty cell where an additional optical assembly would be housed. However, a separate heater zone may be placed there in order to minimize the gradients. A lower emissivity would expect to result in even a lower heater power requirement and smaller dT.

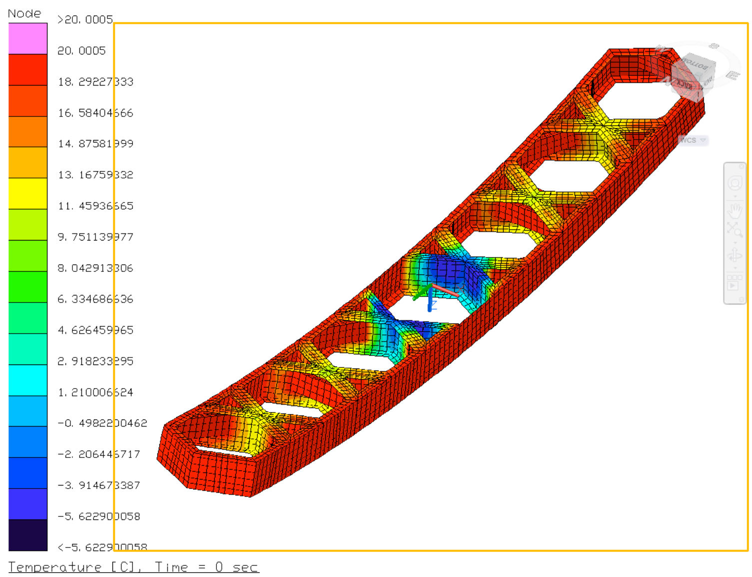

Figure 19 Thermal prediction results with multi heater control zones at the Backplane perimeter and X-members

The results from the thermal model predictions with thermal gradients were then mapped on to the FEM and solved for SFE. The results from the SFE calculations are listed in Figure 20 below. The multi-heater zones case showed that the SFE with BFP removed resulted in roughly ***5.2 pico-meter RMS***. Again, this analysis was performed in a purely thermal steady state conditions with a 1mK heater offset. However, it is expected that a future transient analysis would show a smaller SFE value when considering the thermal mass of the system.

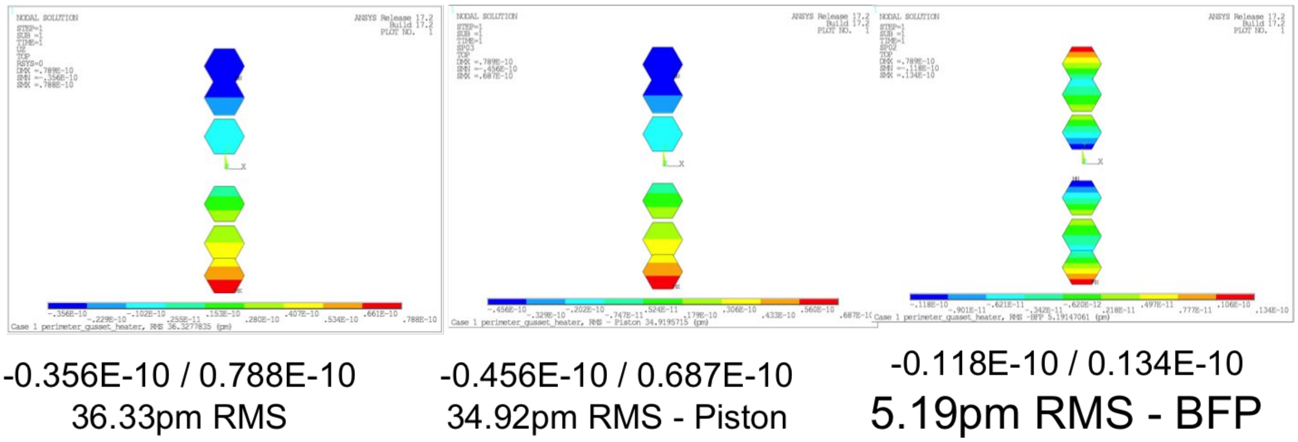

Figure 20 SFE calculation with multi heater zones on the perimeter and X-members of the backplane using the thermal predictions with temperature gradients

5. CONCLUSION

The LUVOIR Backplane thermal stability study was a first order feasibility assessment based on the JWST experiences of the current composite manufacturing technologies and capabilities along with the state of art thermal control and sensing technologies [5]. This study demonstrated the feasibility of a 9.2m LUVOIR composite thermally ultra-stable backplane architecture to roughly 5pico-meter SFE (or roughly 10pm WFE). This study was conducted with the JWST demonstrated quasi-isotropic flight billet plate CTE variation of +- 80 ppb/K (variation of 160 ppb/K) from design value and +- 30 ppb/K (30 ppb/K) for tube billets [3]. These CTE measurements were conducted at the ATK Interferometric Measurement Facility (IMF) with the measurement 'noise-floor' of 3-6 ppb/K [4].

The optical performances are directly related to the stability of the telescope backplane, furthermore, the thermal stability of the composite backplane assembly is a function of the absolute nominal CTE and its variations with while being manufactured, and the resolution of thermal sensing and control system. This study has shown that there isn't a singular variable that would solve all of the thermal stability issue. A proper combination of absolute CTE, CTE variability, and thermal control resolution at appropriate locations resulted in a pico-meter level ultra-stable composite backplane. To meet the 10 pm over 10 minutes WFE goal for LUVOIR, the JWST capabilities will be pushed to its limits. Although the lower CTE and lower variability CTE composite materials could come through with lower acceptance tolerances and increased billet scrap rates. However, in order to add margins to the future design challenges associated with the ultra-stable backplane and also in an anticipation of a larger telescope concept, further technology developments in the areas of lower composite CTE such as uses of nano-carbon tube technologies, and with improved manufacturing control of the variations in CTE. Also, better thermally insulating composite surface finishes, low emittance values that would match the effective emissivity of a MLI thermal blanket, and finer sub-milli-K thermometry system with improved heater control logics would all contribute towards the required design margins for missions such as LUVOIR.

The analytical model results from this study do show that a 'right' combination of these variables could deliver the pico-meter level stability demanded by the challenging LUVOIR mission objectives. Furthermore, the control and precision of the material and environmental control variables all need to improve eventually to give us margins in our future designs.

6. REFERENCES

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