Gaps in Thermal Design Guidelines in the Goddard Space Flight Center GOLD Rules

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The GSFC (Goddard Space Flight Center) GOLD Rules (Goddard Open Learning Design; GSFC-STD-1000) provide a reasonably comprehensive list of guidelines for the design and testing of spacecraft and instruments based on the long heritage of successful GSFC missions. In general, all GSFC missions are required to comply with the GOLD Rules across a number of subsystems or to seek waivers to particular GOLD rules where compliance is not practical, either due to the risk posture of a mission or the cost and/or schedule associated with compliance. In thermal subsystems, GOLD Rules are applied to design margins throughout the project life cycle and include temperature margins, heater power margins, and two-phase transport margins. However, no explicit guidance is provided for two thermal design aspects: heater control authority (for stability requirements) and cryogenic design margins (which are often not reasonable to express in terms of temperatures). This can lead to ambiguity and inconsistency among projects when demonstrating GOLD Rules compliance. Two current GSFC projects, TIRS-2 (Thermal InfraRed Sensor 2) and WFIRST (Wide Field InfraRed Survey Telescope), are both missions with cryogenic aspects and active thermal control for stability. This paper seeks to outline the characterization of cryogenic margins during the design process for TIRS-2 and WFIRST as well as the project derived guidelines for heater control authority margin. This effort serves as potential first steps for updating the GOLD Rules to address these two areas in guiding thermal designs at GSFC.

Nomenclature

APG = *Annealed Pyrolytic Graphite*
COBA = *Cold Optics Baffle Assembly*
DTP = *Design Temperature Parasitics*
ETU = *Engineering Test Unit*
FCR = *Facility Cryogenic Radiator*
FPA = *Focal Plane Assembly*
GOLD = *Goddard Open Learning Design*
GSFC = *Goddard Space Flight Center*
MPA = *MOSAIC Plate Assembly*
PID = *Proportional-Integral-Derivative*
QWIP = *Quantum Well Infrared Photodetectors*
SCA = *Sensor Chip Assembly*
SCE = *Sensor Chip Electronics*
TBA = *Thermal Bus Assembly*
TIRS = *Thermal InfraRed Sensor*
WFC = *Wide Field Channel*
WFI = *Wide Field Instrument*
WFIRST = *Wide Field InfraRed Survey Telescope*

I. Introduction

DESIGN rules for space flight missions at Goddard Space Flight Center (GSFC) are specified in GSFC-STD-1000[1], which is known as the Goddard Open Learning Design (GOLD) rules. For the design of thermal control systems, the specific text is as follows for Phase B/C (from Preliminary Design Review through Critical Design Reviews), which are the major design phases for a mission: **"Thermal design concept produces minimum 5C**

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margins, except for heater controlled elements, which have a maximum 70% heater duty cycle, and two-phase flow systems, which have a minimum 30% heat transport margin." The rule specifically states that it does not apply to cryogenic systems. No additional rule at this time addresses appropriate design margins for cryogenic systems, leaving those decisions to be made at an individual project level. Unfortunately, this does not produce a consistent approach to cryogenic designs across multiple projects, which often base the acceptable design margin on each project's risk tolerance.

Furthermore, the design rules for Thermal Control Systems does not address a minimum heater power level to demonstrate control authority for trim heaters, which are used to maintain thermal stability for components based on their requirements. Often when components have a stability requirement, an active controller with feedback is implemented to provide the stability. This may be accomplished with a Proportional-Integral-Derivative controller which is adjusting either the cooling power of a cryocooler or thermo-electric cooler to adjust the cooling capability, or adjusting the heater power of a trim heater for a cold-biased system which has excess cooling capabilities. In either case, no guideline is provided by the GOLD rules for the minimum cooling capability to ensure that control can always be maintained. This may be expressed either as a minimum amount of cooling capability of a cooler or a minimum amount of heating for a cold-biased trim heater.

Two recent GSFC missions with both challenging stability requirements as well as cryogenic detectors include: the Wide Field Instrument (WFI) on the Wide Field InfraRed Survey Telescope (WFIRST) mission, and TIRS-2 (Thermal InfraRed Sensor), a rebuild of the TIRS instrument on the Landsat 9 satellite with minor modifications. WFI utilizes a passive, cryoradiator to cool the Focal Plane to below 95 K ±0.01 K with a trim heater for stability. TIRS-2 utilizes a cryocooler to achieve and maintain the detectors at 38 K as well as a cold-biased, telescope radiator to maintain the telescope around 190 ± 0.25 K (over 44 minutes) and a hot calibration target to within ± 0.1 K of the calibration temperature. This paper seeks to describe the design process and design margin approach for both of these projects to arrive at a set of recommendations for future GSFC missions.

II. Thermal Control System Description

WFIRST

The WFIRST[2] mission was selected as the top-ranked large space mission in the 2010 New Worlds, New Horizons Astronomy and Astrophysics Decadal survey, following in the footsteps of the great Astrophysics Observatories including: the Hubble Space Telescope, Chandra, Spitzer, and the James Webb Space Telescope. WFIRST will study dark energy, exoplanets, and the near infrared sky. Planned for launch in the mid-2020s, it will orbit around the L2 Earth/Sun Lagrange point. Front end optics provide the incoming light to one of two instruments: the Wide Field Instrument (WFI) and a CoronaGraph Instrument. WFI provides wide field imaging and slitless/sliced spectroscopic capabilities to probe dark energy, conduct a galactic planetary census, and provide a near-IR survey utilizing a 3x6 array of H4RG detectors to provide a Wide Field Channel (WFC) with a sky field of view over 100x larger than the Wide Field Camera 3 instrument on the Hubble Space Telescope. A second WFI science channel, the Integral Field Channel, uses a slicer and spectrograph to provide individual spectra of supernovae. A Thermal Bus Assembly (TBA) transports heat from the Focal Plane Assemblies (FPA) to a Facility Cryogenic Radiator (FCR) passively cooling them to near 100 K as shown in Figure 1.

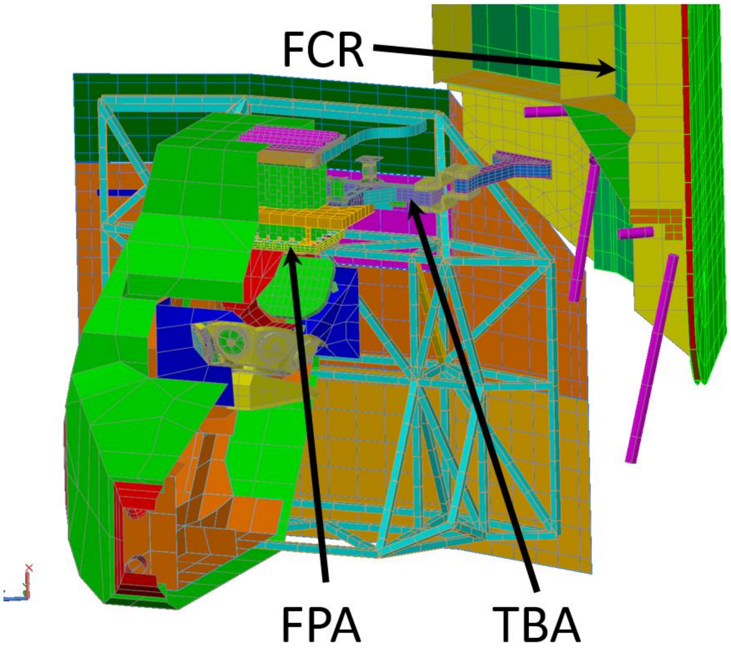

Figure 1. WFI Cutaway View: *cutaway view of WFI instrument showing the Focal Plane Assembly, Thermal Bus Assembly, and Facility Cryogenic Radiator*

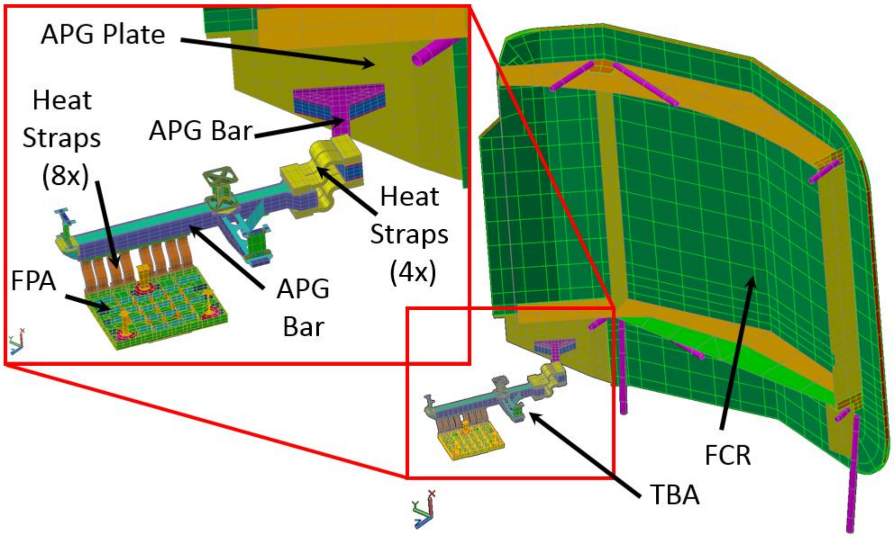

Figure 2. WFC Focal Plane Cooling: *Thermal path from Focal Plane Assembly to the Facility Cryogenic Radiator through components of the Thermal Bus Assembly*

The WFC focal plane Assembly (FPA) consists of 18 Sensor Chip Assemblies (SCA) mounted to a MOSAIC Plate Assembly (MPA) and is thermally isolated from the warmer structure which mechanically supports it. A Cold Optics Baffle Assembly (COBA) on the imaging side of the focal plane maintains a stable and cold temperature scene for the detectors and reduces the radiative heat load on the Focal Plane. Thermally isolating flexures and cables further minimize the conductive heat leaks into the Focal Plane. To cool the Focal Plane, the TBA conductively transports the heat from the Focal Plane to the FCR as shown in Figure 2. The TBA consists of 8 high purity aluminum heat straps that connect the Focal Plane to an aluminum bar which encapsulates Annealed Pyrolytic Graphite (APG) to improve the conductivity. Four additional high purity aluminum thermal straps connect this bar to a second APG assembly (Bar and Plate) which interfaces with the FCR. The two sets of straps isolate the Focal Plane from jitter effects from the FCR and the rest of the WFI instrument. The mechanical support of the first APG bar as well as the radiative loads absorbed by the TBA all represent additional parasitic heat loads that must be rejected by the FCR and could negatively impact the ability of the FCR to achieve required temperatures if not carefully tracked and mitigated if necessary.

TIRS-2

The TIRS-2 instrument[3] is a rebuild of the TIRS instrument which flew successfully on the LandSat-8 mission. It is designed to provide infrared capabilities for evapotranspiration for water cycle management. The TIRS instrument sensor unit is a 2-band thermal imaging sensor with a four-element refractive telescope and three quantum-well-infrared-photodetectors (QWIP).

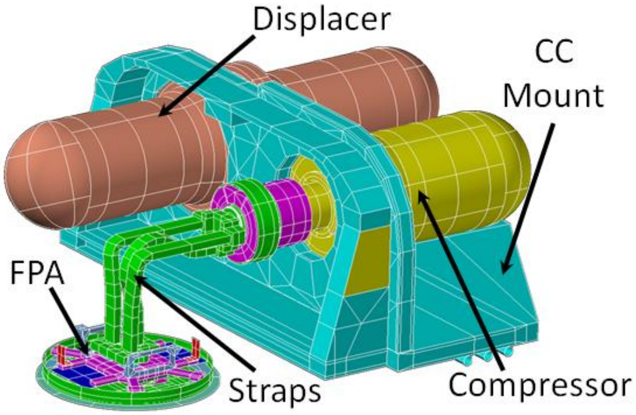

Figure 3. TIRS-2 FPA Cooling: *Thermal straps connect to the TIRS-2 FPA to provide cooling to 38 K. The cryocooler must remove the detector dissipations as well as all parasitic heat loads absorbed by the cryogenic region.*

TIRS-2 utilizes two different cooling methods for different parts of the instrument: 1) active cryo control for the detector assembly, and 2) passive telescope cooling (via a dedicated radiator with embedded ethane heatpipes) with active heater control for stability of the telescope at near-cryo temperatures. The TIRS-2 FPA consists of 3 QWIPs, mounted on a carrier bracket, and is thermally isolated from the surrounding mechanical support. A 2-stage mechanical cryo-cooler provides cooling to near 38 K. To minimize heat leaks in to the Focal Plane Assembly (FPA), a multi-level isolation scheme is utilized including isolation inserts and isolation shells. Additionally, the first stage of the cryo-cooler provides near-cryogenic cooling to the outer isolation shell to 105 K. To cool the FPA, a series of 3 high purity aluminum straps transport the heat from the detectors to the second stage cold tip of the cryo-cooler, as shown in Figure 3. The mechanical support of the FPA carrier bracket, heat leaks along the copper straps, and leaks from the isolation subsystem all represent additional parasitic heat loads that must be removed by the cryo-cooler. The cryocooler motor input power is transported via ammonia heat pipes to its own dedicated radiator.

The TIRS-2 telescope subassembly, shown in Figure 4, is passively cooled to ~170K by its own independent radiator. The telescope assembly is mounted to the aluminum outer cryo-shell; heat straps connect the outer cryo-shell to an APG bar, which then couples to the ethane heatpipes and telescope radiator. Proportionally controlled, programmable setpoint heaters provide the temperature, gradient, and stability control to meet telescope focus requirements. The telescope requirements specify active control over a range of 185K-195K with a gradient of 3K axially.

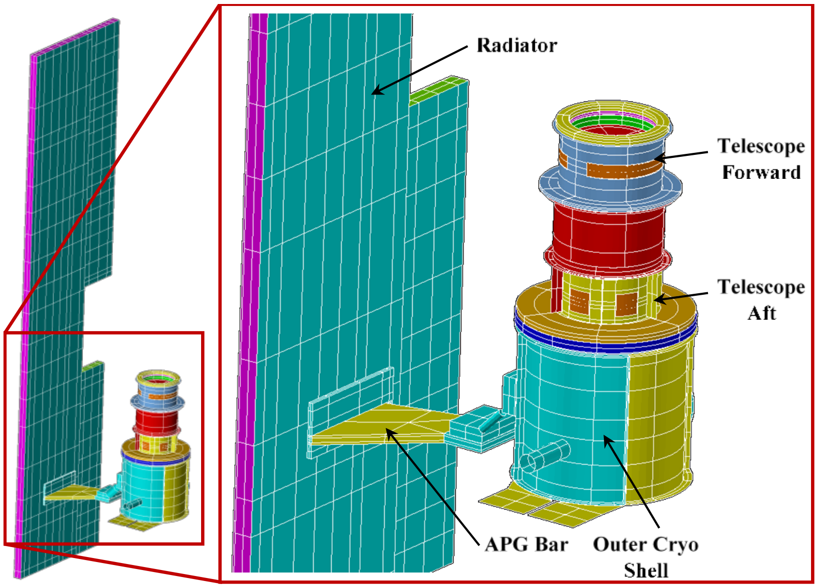

Figure 4. TIRS-2 Telescope Control: *Thermal path from Telescope Radiator to Telescope Subsystem through the cryoshell, straps, APG bar and heatpipes FPA is located internal to cryo shell*

Regardless of active or passive cooling for cryogenic systems, control of the parasitic heat leaks throughout the project life cycle is crucial to designing a system that will function within specification in flight. Systems must be designed to carry an appropriate level of margin to guard against unexpected heat leaks that threaten the ability of the cooling system to achieve its required temperatures.

III. Cryogenic Design Margin Approach

WFIRST

For WFIRST, the FCR is deliberately oversized to accommodate the need to reject both the design heat as well as any design margin carried. Cryogenic margin for the Focal Plane was initially characterized by temperature margin (K) from one design iteration to the next. An interesting correlation to note is that as the heat rejection capability of the FCR increases or the parasitic path conductance decreases, the Focal Plane temperature decreases; with a decrease in the focal plane temperature, the parasitic heat loads increase which generates a compounding effect if the Focal Plane temperatures are well below their design requirement. The parasitic loads for this uncontrolled case are shown in Table 1 under the “No Control” heading.

Discussions with the Focal Plane team also revealed that the intention was to operate the detectors at their design temperature of 95 K even if the thermal control system had additional capability to further cool the detectors. This was based on the planned characterization of the detectors at one operating temperature and not over an operating range of temperatures to reduce the cost of testing. Coupling this with the realization that the parasitic heat loads varied with the achieved temperature of the Focal Plane, a new approach was implemented that added a bias heater to raise the temperature of the Focal Plane up to its operating temperature even when coupled to the oversized FCR. The amount of heater power now became the metric that was tracked to demonstrate design margin of the system for the next iterations of the design. The parasitic loads for this controlled case are shown in Table 1 under the “MPA Control” heading.

At this same time, an additional metric began being tracked: the effective conductance of the TBA. Since both additional parasitic heat leaks and the thermal resistance of the TBA were potential threats to achieving the operating temperature of the Focal Plane, it was judged important to track both of these parameters through design iterations to ensure the design was evolving towards an optimum. One of the consequences of locating the control trim heater at the Focal Plane however was the penalty of necessitating the heater power to also flow through the TBA to the FCR. This imposed in essence a double penalty; each Watt of heater power (which represented a Watt of cooling margin) also resulted in an increase in the temperature difference from the Focal Plane end of the TBA to the FCR end. With a fixed heat rejection capability of the FCR and consequently the FCR end of the TBA, this translated back up the TBA into a further increase in temperature of the Focal Plane. In essence, the application of heat closer to the Focal Plane resulted in a larger increase in Focal Plane temperature than the application of heat along the TBA as a further point from the Focal Plane. This stressed the importance of the location of heat application along the TBA path, which also impacted the parasitic heat loads as well. Essentially, any heat loads (parasitic or applied) along the TBA close to the Focal Plane had a larger negative impact on the Focal Plane temperature than the same load further away.

The aforementioned issue necessitated a new two-heater approach to be implemented, with an offset heater on the TBA close to the FCR and a much smaller trim heater on the Focal Plane. The purpose of the offset heater is to be a fixed power heater that biases the temperature to just below the operating temperature with a second trim heater to use a minimal amount of power to maintain stability. The combination of offset heater power and trim heater power now became the metrics to be tracked to evaluate the impact of any design changes. The parasitic loads for this controlled case are shown in Table 1 under the “Baseline Control” heading.

	Parameter	SCA	MPA	8 Straps	APG Bar	4 Straps	APG Bar 2	APG Plate	FCR
No Control	Min Temp (K)	76.037	74.968	74.234	73.077	71.993	71.069	70.561	68.28
	Avg Temp (K)	76.476	75.859	74.502	73.545	72.388	71.273	70.711	69.773
	Max Temp (K)	76.774	76.224	74.726	74.013	72.783	71.697	70.954	125.82
	Lin Load (W)	1.275	0.71	0	1.157	0	0	0	1.113
	Rad Load (W)	0.442	0.342	0.141	0.273	0.107	0.089	0.464	2.015
	Applied Load (W)	0.468	0	0	0	0	0	0	0.167
	Total Load (W)	**2.185**	**3.237**	**3.378**	**4.808**	**4.915**	**5.004**	**5.468**	**8.763**
MPA Control	Min Temp (K)	93.604	92.182	89.839	86.86	84.087	82.101	81.034	76.539
	Avg Temp (K)	93.949	93.4	90.713	87.975	85.163	82.545	81.347	78.48
	Max Temp (K)	94.199	93.729	91.523	89.248	86.241	83.462	81.862	125.88
	Lin Load (W)	1.029	0.566	0	1.018	0	0	0	1.028
	Rad Load (W)	0.369	0.313	0.133	0.261	0.104	0.087	0.456	1.951
	Applied Load (W)	0.468	6.275	0	0	0	0	0	0.167
	Total Load (W)	**1.866**	**9.02**	**9.153**	**10.432**	**10.536**	**10.623**	**11.079**	**14.225**
Baseline Control	Min Temp (K)	93.484	92.559	91.767	90.684	89.465	88.435	87.002	80.948
	Avg Temp (K)	93.855	93.328	92.071	91.123	89.947	88.777	87.429	83.234
	Max Temp (K)	94.107	93.634	92.329	91.57	90.425	89.204	88.13	125.89
	Lin Load (W)	1.03	0.565	0	0.982	0	0	0	0.985
	Rad Load (W)	0.366	0.313	0.132	0.257	0.102	0.084	0.445	1.892
	Applied Load (W)	0.468	0.251	0	0	0	10	0	0.167
	Total Load (W)	**1.864**	**2.993**	**3.125**	**4.364**	**4.466**	**14.55**	**14.995**	**18.039**

Table 1. WFI Thermal Bus Assembly Parasitic Heat Loads: *The TBA picks up different loading along its components based on the control scheme and temperature profile along the TBA*

As seen in Table 1, the temperatures and parasitic heatloads are greatly affected by the control scheme. With no control, the temperatures are considerably lower and the total parasitic loads are 0.813 W higher than the MPA control case. Similarly, the Baseline Control case has total parasitics that are 0.162 W lower than the MPA control. Comparing the No Control case to the Baseline Control case shows nearly 1 W of additional parasitic + 10.251 W of heater power which would translate into about 17 K of temperature margin. It should be noted that the MPA Control case has slightly higher parasitics than the Baseline Control, even though the SCA and MPA temperatures are nearly identical. This is due to the overall biasing of the temperatures of the TBA higher by the offset heater, which results in slightly smaller temperature differences to the surroundings and consequently slightly lower parasitic heat loads for the Baseline control case. That said, both the MPA and Baseline control cases have parasitic values that are fairly similar, making for a more consistent means to compare design iterations. Conversely, the case with no control has parasitic loads that are considerably higher, which would make application of margin as a percentage of parasitics more difficult to implement in a case with no control, due to the temperature dependence of the parasitics.

TIRS-2

Similar to the WFIRST FCR, the TIRS-2 cryocooler and its radiator are intentionally oversized to reject the system design heat as well as any parasitics and/or design margin. The rapid development schedule of the previous TIRS-1 program dictated the cryogenic margin design approach. The QWIP detectors for TIRS-1 were a new technology and due to the low Technology Readiness Level, 100% margin was carried on the detector power. Similarly, the cryocooler was also a new design as well as a long lead item. To protect against the risk that the delivered cryocooler underperformed, 100% margin on the parasitic loads was also carried in the design phase. At the time of TIRS-1, the project schedule did not allow for the thermal control system design to wait for full characterization of the cryo-cooler performance. Therefore, the project decided to size the cryo-cooler radiator for the maximum cooler motor power of 160W and the available mechanical envelope.

The analytical models for both TIRS-1 and TIRS-2 do not simulate the control system for the cryocooler based on any temperature feedback. The cold tip and warm tip are both held at boundary nodes assuming the control system could achieve the desired setpoints. The full load of 160 W was used for design purposes to determine the radiator temperature predictions. The design sought to minimize as much as possible all the heat leaks into the cryogenic region with a robust thermal isolation system. By the time the cryocooler was delivered, the performance of the unit had been characterized. At this point both the estimated parasitic loads and the cryocooler performance could be predicted. In parallel to the cryocooler development, an Engineering Test Unit (ETU) test with a non-flight cryocooler unit allowed for the correlation and characterization of the parasitic loads in the flight design (albeit with ETU hardware). The combination of these two test campaigns gave the first look at potential system performance ahead of the instrument level test. Based on this data, the correlated parasitics were below the loads specified for the cryocooler and the performance metrics of the cryocooler met the requirements. As such, the estimated power needed to the cryocooler was well below the 160 W for which the radiator was sized. A portion of the radiator was blanketed for the instrument level test, where the final performance measurement and correlation was completed. In the end, for TIRS-1, approximately 60% of the cryocooler radiator was blanketed for flight, but the risk posture initially implemented by the project resulted in a successful mission.

TIRS-2 benefits from the knowledge gained during TIRS-1 development, with the TIRS-2 rebuild providing an opportunity to make limited design changes based on information not available at the same project life cycle point during TIRS-1. However, an appropriate level of margin should still be carried throughout the TIRS-2 development to protect against potential differences in parasitic loads and cryocooler performance as a function of workmanship. Furthermore, some of the design changes resulted in higher parasitic loads into the cryo region. A primary example of this was the requirement for TIRS-2 to have greater redundancy than TIRS-2, which necessitated additional harness for heaters and sensors in the cryogenic region, leading to larger parasitic heat leaks. That said, the uncertainty of TIRS-2 predictions is considerably lower than it was for TIRS-1 at the same life cycle point. The current predictions and cryocooler metrics for the TIRS-2 design are shown in Table 2. Analytically, the model does not place any margin on the parasitic loads or the dissipations in the cryogenic region, since the enforced boundary temperature will achieve the required cooling. However, this does potentially neglect the increase in the temperature gradient along the strap due to higher heat loads and the thermal resistance of the strap between the FPA and the Cold Tip.

Design Parameter	**Value**
Cold Tip Temperature	37 K
Detector Dissipation	0.429 W
Cold Tip Parasitic Heat Loads	0.396 W
Cold Tip Heat Lift (Excluding Cold Tip Shroud)	0.825 W
Warm Tip Temperature (Heater Controlled)	105 K
Warm Tip Parasitic Heat Loads (Excluding Warm Tip Shroud)	1.287 W
Warm Tip Heat Lift (Excluding Warm Tip Shroud)	6.807 W
Cryocooler Motor Input Power (In Model)	82 W
Reject Temperature	273 K
Radiator Temperature (Min)	256.32 K
Radiator Temperature (Average)	256.61 K
Radiator Temperature (Max)	256.86 K

Table 2. TIRS Critical Cryogenic Parameters: *Critical Temperature and Heat Loads for TIRS FPA Cooling*

IV. Cryogenic Design Margin Recommendation

WFIRST

This approach of a bias heater and a trim heater is recommended for future mission design approaches. This ensures that the design is consistent with an intended flight design at a particular temperature as specified by the thermal requirements. This approach also makes comparison of design iterations simpler since the temperature of the focal plane remains nearly constant regardless of the radiator heat rejection capability, parasitic loads, or conductance of the thermal path. It is also consistent for both passive and active (cryocooler) approaches in that the design temperature remains a fixed value and cooling to temperatures below the design goal is not necessary. This is referred to hereafter as the “Design Temperature Parasitic (DTP)” approach which calculates and tracks all metrics based on achieving the design temperature and not beyond.

The recommended level of margin using the DTP approach is to ensure that the system can meet temperature requirements with 100% of the design temperature parasitics applied at the appropriate locations. The DTP loads are calculated using whatever combination of offset and trim heating is reasonable to achieve temperature requirements. The transferred heat loads to all components along the cryogenic thermal path from the article being cooled to the heat rejection systems should then be calculated using results from this case. For radiative loads, this should be applied uniformly across the component. For linear loads, it should be applied at the point locations corresponding to the load. It is likely that the offset heater power as well as the trim heater power will need to be reduced or eliminated once the DTP loads are applied. An analytical case with the DTP loads and minimized trim and offset heating should result in a design temperature below the requirement. If it does not, then 100% margin has not been maintained. Throughout the project lifecycle, as a design matures and potentially less margin is required to establish confidence in the design, this level of margin may be reduced at project discretion.

Table 3 shows the predicted temperatures and parasitic heat loads with the values from Table 1 applied as additional loads to the model at appropriate locations. Based on applying 100% of the loads with No Control, the temperature requirement of 95 K is not met. With control at the MPA, the parasitic loads are lower, even with 100% of these loads applied.

	Parameter	SCA	MPA	8 Straps	APG Bar	4 Straps	APG Bar 2	APG Plate	FCR
No Control	Min Temp (K)	95.147	93.381	91.944	89.871	87.304	85.49	84.496	80.143
	Avg Temp (K)	95.879	94.878	92.502	90.751	88.31	85.898	84.793	81.954
	Max Temp (K)	**96.374**	95.489	92.973	91.587	89.317	86.737	85.272	125.9
	Lin Load (W)	1.005	1.262	0	2.905	0	0	0	0.971
	Rad Load (W)	0.353	0.31	0.132	0.258	0.102	0.089	0.449	1.91
	Applied Load (W)	2.185	0.342	0.141	0.447	0.141	0.085	0.464	3.383
	Total Load (W)	**3.543**	**5.457**	**5.73**	**9.34**	**9.583**	**9.757**	**10.67**	**16.934**
MPA Control	Min Temp (K)	93.833	92.196	90.821	88.836	86.418	84.699	83.754	79.599
	Avg Temp (K)	94.504	93.584	91.352	89.675	87.363	85.085	84.037	81.366
	Max Temp (K)	**94.959**	94.144	91.8	90.477	88.308	85.88	84.491	125.91
	Lin Load (W)	1.024	1.132	0	2.702	0	0	0	1.115
	Rad Load (W)	0.362	0.313	0.133	0.259	0.103	0.086	0.452	1.921
	Applied Load (W)	1.866	0.547	0.133	0.407	0.104	0.087	0.456	3.234
	Total Load (W)	**3.252**	**5.244**	**5.51**	**8.878**	**9.085**	**9.258**	**10.166**	**16.436**
Baseline Control	Min Temp (K)	93.836	92.184	90.762	88.728	86.284	84.545	83.592	79.401
	Avg Temp (K)	94.512	93.592	91.31	89.582	87.239	84.936	83.877	81.184
	Max Temp (K)	**94.971**	94.158	91.772	90.407	88.193	85.739	84.336	125.9
	Lin Load (W)	1.024	1.129	0	2.644	0	0	0	1.022
	Rad Load (W)	0.362	0.313	0.133	0.259	0.103	0.086	0.452	1.923
	Applied Load (W)	1.864	0.726	0.132	0.397	0.102	0.084	0.445	3.132
	Total Load (W)	**3.25**	**5.418**	**5.683**	**8.983**	**9.188**	**9.358**	**10.255**	**16.332**

Table 3. WFI Thermal Bus Assembly Parasitic Heat Loads with 100% Margin Applied: *The maximum SCA temperature requirement is met with 100% Margin for the Control Cases, but not with the No Control case, which has higher parasitic loads applied*

TIRS-2

The cryocooler performance with nominal loads was predicted by the thermal model. Margin for TIRS-2 is held as additional radiator area beyond what is needed to reject the expected cryocooler motor load. In flight, assuming that the realized heat loads are consistent with the modeling and the actual cryocooler performance is as expected, a portion of the radiator is blanketed to effectively reduce the radiator area. To evaluate analytical cases where the parasitic loads are higher to show robustness of the design, cases were run with partial removal and full removal of the notional blanket design in the current model. Cryocooler motor power loads were varied in the model in steps of 10 W over a reasonable expected power range for the cryocooler to generate the relationship between reject temperature and cryocooler power for the three blanket configurations. Plotting these relationships along with the expected cryocooler performance for removal of the expected loads and the margined loads shows the nominal operating points of the baseline design and the margined design as shown in Figure 5.

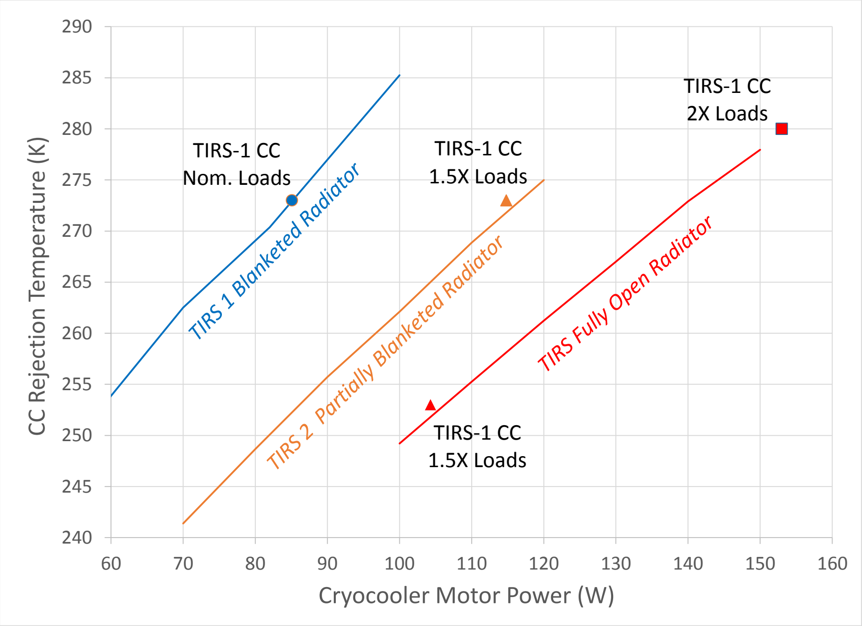

Figure 5. TIRS-2 FPA Cooling: *TIRS-2 predicted performance for nominal, 1.5x and 2x and margined cryocooler power expectations based on TIRS-1 cryocooler performance. A circle marker indicates the expected cryocooler operating conditions for nominal loads; a triangle indicates possible conditions for two blanket configurations; a square indicates the operating conditions for 2x nominal loads*

This 100% of DTP loads approach tends to be more conservative than the approach recommended by the Aerospace Corporation in the Spacecraft Thermal Control Handbook, Vol II – Cryogenics, which recommends 50% margin on cryogenic loads[4] but does not necessarily indicate if this should be at the design temperature or the resulting temperature from a system oversized for margin. Furthermore, the Aerospace Corporation recommendation reduces the margin through the project life cycle to a minimum of 25% for acceptance testing. Similar relaxations of the margin as a function of project life cycle are also being considered for the recommended cryogenic design margin approach, but have not yet coalesced into a solid recommendation.

V. Heater Control Authority

WFIRST

WFIRST has a stability requirement on the focal plane of ±0.01 K over a 180 s observation period. A trim heater at the focal plane coupled with a cold biased heat rejection system is utilized to achieve this stability as described in the previous sections. A PID (Proportional-Integral-Differential) control system is planned (although the D gain term is currently zero) to achieve and maintain the focal plane at the desired setpoint. But, as stated earlier, no design guidelines exist for what an appropriate level of heater power is to demonstrate that heater control authority will always be maintained. Various methodologies were considered to quantify control authority. It could be expressed as a percentage of available heater power (*e.g. Min Heater > 30% * Available Heater*), similar to the 30% margin (70% duty cycle), but this approach is not necessarily valid since simply using a smaller available heater can artificially result in meeting the requirement. Likewise, using the heater power value itself (*e.g. Min Heater > 0.05 W*) does not necessarily translate into an effective design margin since 0.050 W in one design may be far more impactful than in another design. Another possibility is to ensure that the heater power is a sufficiently large fraction of the total heat rejection capability (*e.g. Min Heater / Heat Rejection Capability > X%)*, but this does not necessarily address the case where the environmental instability is small and a minimal amount of heat is needed to provide for the stability, nor does it account for designs with heater power but no dedicated radiator. The last method considered, and the recommended approach, it to ensure that the minimum heater power is a percentage of the total range of expected heater powers. It is recommended to use 30% as the value, so for a 10 W range of heater powers, the minimum should be no less than 3 W. Intuitively this is logical as system with heater powers ranging from 4 to 8 W clearly has more control authority than a system ranging from 0.2 to 4.2 W. This approach accounts for the level of external instability that must be compensated by the control system.

One caveat to using this approach is that any margin in dissipation of the item being controlled must be removed from consideration when comparing heater powers. This may also include effects of boundary conditions (such as interface temperatures) which may also affect the heater power. When considering the maximum and minimum heater power over a mission, all cases should be analyzed with the maximum dissipation and interface temperature, which would result in the lowest required heater power. This is often not a condition analyzed in the typical process flow which biases all uncertain parameters in a direction to result in the hottest or coldest temperatures to compare against requirements. Table 4 includes the maximum and minimum heater power predictions for three components on the WFI instrument with tight temperature control requirements: the Sensor Chip Assembly, Sensor Chip Electronics, and Cold Optics Baffle Assembly. The recommended minimum heater power based on 30% of the range is also included. These differences represent the expected variation in heater power as a result of orientation, optical property, and solar flux variations over the mission.

Component	Max (W)	Min (W)	Range (W)	Recommended Min (W)
Sensor Chip Assembly	0.4552	0.3593	0.0959	0.02877
Sensor Chip Electronics	0.536	0.2515	0.2845	0.08535
Cold Optics Baffle Assembly	1.8936	1.8446	0.049	0.0147

Table 4. WFI Heater Control Authority: *Heater power range for WFI stability critical components*

This approach can also identify potentially oversized radiators. For the COBA, the minimum heater power is well above the recommended minimum. Since there is no dissipation on this component other than the heater power, the radiator could be resized to save mass. However, for components with a dissipation besides the heater power, reduction in radiator area should be approached carefully to not result in insufficient heater power to maintain temperature in the event that the actual dissipations are considerably smaller than the maximum expected values. If the available heater size and radiator areas are reduced, there is a risk that lower power dissipations could result in insufficient heater power on the cold end. In short, the combination of heater and radiators for stable thermal control must provide sufficient cooling capability and sufficient heating capability to maintain the desired temperature over the entire range of thermal disturbances encountered in a mission.

TIRS-2

The TIRS-2 telescope requires both temperature stability to ±0.25K (over 44 minutes) as well as a set gradient between lenses. A cold-biased heat rejection system coupled with 2 PID controlled heater circuits (for gradient control) is responsible for meeting the telescope requirements. A dedicated radiator with embedded heatpipes provides the cold-bias, with an APG bar and copper thermal straps facilitating the heat transfer from the warm telescope to the radiator. The required operational temperatures of the telescope system necessitates a radiator that utilizes ethane heatpipes as opposed to the more common ammonia heatpipes. The initial radiator sizing for TIRS-1 was constrained by mechanical envelopes driven by the initial sizing of the cryo-cooler radiator. The telescope performance for TIRS-1 met all required science objectives but performed with less than ideal heater control authority for telescope temperatures at the lowest end of the temperature range in flight. The TIRS-2 rebuild provided an opportunity to implement several reasonable design changes, including: reallocation of radiator area and revisiting the setpoint and gradient requirements.

The amount that could be reallocated was constrained based on several restrictions: 1) no addition or modification of existing heatpipes was allowed; (2) mounting locations on the structure must be preserved; and (3) the mechanical envelope for the instrument could not be violated. The intent of this reallocation was to gain additional heater control authority at the lower end of the operational range, which showed minimum heater power in flight for TIRS-1. Additionally, the science team approved an adjustment of the telescope gradient to 3K from 2.5K. Both of these design changes yielded improvements in the telescope control authority.

Component	Max (W)	Min (W)	Range (W)	Recommended Min (W)
Telescope Aft	2.694	2.068	0.626	0.188
Telescope Fore	1.351	1.270	0.081	0.024
Scene Select Mechanism	5.763	4.195	1.567	0.470
Focal Plane Electronics	6.231	1.415	4.816	1.445
BlackBody Calibrator	4.768	2.702	2.066	0.620

Table 5. TIRS-2 Heater Control Authority: *Heater power range for TIRS-2 stability critical components*

VI. Conclusions and Path Forward

Two new design guidelines are presented to address margins in cryogenic designs and ensuring sufficient heater control authority to meet stability requirements. Both the WFIRST and TIRS-2/LandSat9 missions include cryogenic designs and temperature stability requirements and were used as test cases against the proposed design guidelines. The intent of this work is to establish guidelines for these design margins for future projects.

For cryogenic designs, the parasitic heat loads should be computed at the expected design temperature. Achieving these temperatures in a passive system will likely require additional heat to be artificially added to the system to compensate for the design margin. Application of this heat at location further from the cooling sink will result in warmer temperatures along the path to the heat sink. Once computed, 100% of this margin should be artificially applied as heat loads to each component along the path (e.g. heat straps, conduction bars, heat pipes, etc). Where point loads can be identified (such as harness connections or mounting features), the load should be applied locally. For more generic radiative loads (or through insulation), it should be applied as a uniform flux to the entire component. Any bias heat should be removed and the design analyzed with these additional loads, which may also include 100% uncertainty on power dissipations. The results of this case should demonstrate that even with the additional loads, the design is capable of maintaining the temperature at or below the requirement. Reduction of the 100% recommendation could be considered for later parts of the project lifecycle as uncertainties and risks are reduced through component level testing or model maturation.

For heater control authority margin, the full set of mission possibilities should be investigated, which is often accomplished for determination of the worst case hot and cold cases. For control authority, the concern is typically when uncertain parameters result in increased heating (power dissipations, higher setpoints, interface temperatures, etc.), which results in minimum heater power. A robust design should never have heating effects from these uncertain parameters that causes a loss of control in the form of no required heater power. To probe the range of expected (but low) heater powers, a minimum of two cases should be run: (1) hot biased environments, properties, and orientations and (2) cold biased environments, properties, and orientations. All other variables should be set to the values that result in minimum heater power needed. The minimum amount of heater power needed should be greater than 30% of the range of heater powers between these two low heater power cases to demonstrate sufficient control authority. Consideration should be given to increasing this percentage for non-dissipating components under heater control, since some of the heater control authority is hidden in the radiator sizing for the maximum expected dissipation, whereas this is not the case for non-dissipating components.

Implementation of these two design guidelines will be pursued for future incorporation into the GSFC-STD-1000 to provide some guidance for thermal designs. In the meantime these recommendations are being evaluated to internal adoption within the GSFC thermal Engineering Branch to establish consistency and provide concrete design guidelines for cryogenics missions and missions with stability requirements. Furthermore, the verification by testing of these margins presents a challenge that has not yet been addressed. Future efforts may also determine appropriate testing approaches to verify that the hardware demonstrates sufficient design margin for heater control authority and cryogenic margin. These approaches may also be considered for incorporation into the GSFC-STD-7000[5] (General Environmental Verification Standard or GEVS) document typically used by GSFC to specify appropriate testing levels and verification of flight hardware.

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