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Thermal Design and Analysis of an ISS Science Payload – SAGE III on ISS

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The Stratospheric Aerosol and Gas Experiment III (SAGE III) instrument is the fifth in a series of instruments developed for monitoring aerosols and gaseous constituents in the stratosphere and troposphere. SAGE III will be launched in the SpaceX Dragon vehicle in 2017 and mounted to an external stowage platform on the International Space Station (ISS) to begin its three-year mission. The SAGE III thermal team at NASA Langley Research Center (LaRC) worked with ISS thermal engineers to ensure that SAGE III, as an ISS payload, would meet requirements specific to ISS and the Dragon vehicle. This document presents an overview of the SAGE III thermal design and analysis efforts, focusing on aspects that are relevant for future ISS payload developers. This includes development of detailed and reduced Thermal Desktop (TD) models integrated with the ISS and launch vehicle models, definition of analysis cases necessary to verify thermal requirements considering all mission phases from launch through installation and operation on-orbit, and challenges associated with thermal hardware selection including heaters, multi-layer insulation (MLI) blankets, and thermal tapes.

Nomenclature

BATC	=	Ball Aerospace and Technologies Corporation
BOL	=	Beginning of Life
CDR	=	Critical Design Review
CMP	=	Contamination Monitoring Package
DMP	=	Disturbance Monitoring Package
DOE	=	Design of Experiments
ELC	=	ExPRESS Logistics Carrier
EOL	=	End of Life
EOTP	=	Enhanced ORU Transfer Platform
EVA	=	Extravehicular Activity
ExPA	=	EXPRESS Payload Adapter
ExPRESS	=	Expedite the Processing of Experiments to Space Station
FOD	=	Foreign Object Damage
FRAM	=	Flight Releasable Attachment Mechanism
GMM	=	Geometric Math Model
GSE	=	Ground Support Equipment
GSFC	=	Goddard Space Flight Center
H_2O	=	Water Vapor
HEU	=	Hexapod Electronics Unit
HMA	=	Hexapod Mechanical Assembly
HPS	=	Hexapod Pointing System

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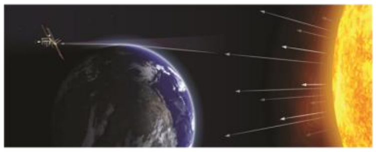
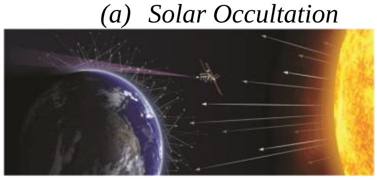
IA	=	Instrument Assembly
IAM	=	Interface Adapter Module
ICE	=	Instrument Control Electronics
In	=	inches
IP	=	Instrument Payload
IR	=	Infrared
ISS	=	International Space Station
JSC	=	Johnson Space Center
LaRC	=	Langley Research Center
MBS	=	Mobile Base System
MCR	=	Mission Concept Review
MLI	=	Multi-layer Insulation
MRAD	=	Mission Resource Allocation Document
MSS	=	Mobile Servicing System
MT	=	Mobile Translator
NESC	=	NASA Engineering Safety Center
NO_2	=	Nitrogen Dioxide
NVP	=	Nadir Viewing Platform
O_2	=	Oxygen
O_3	=	Ozone
ORU	=	Orbital Replacement Unit
PDR	=	Preliminary Design Review
PEL	=	Power Equipment List
PRT	=	Platinum Resistance Thermometers
PTCS	=	Passive Thermal Control Systems
ROBO	=	Robotics Operations
RTD	=	Resistance Temperature Detectors
SA	=	Sensor Assembly
SAGE	=	Stratospheric Aerosol and Gas Experiment
SARJ	=	Solar Array Rotary Joint
SINDA/FLUINT	=	Systems Improved Numerical Differencing Analyzer/Fluid Integrator
SIR	=	Systems Integration Review
SPDM	=	Special Purpose Dexterous Manipulator
SRR	=	System Requirements Review
SSRMS	=	Space Station Remote Manipulator System
TAS-I	=	Thales Alenia Space – Italy
TD	=	Thermal Desktop
TFAWS	=	Thermal and Fluids Analysis Workshop
TMM	=	Thermal Math Model
TRASYS	=	Thermal Radiation Analyzer System
TRRJ	=	Thermal Radiator Rotary Joints
TVAC	=	Thermal Vacuum
V	=	Volts
W	=	Watts
YPR	=	Yaw, Pitch, Roll

I. Introduction

The Stratospheric Aerosol and Gas Experiment (SAGE) III instrument is the fifth in a series of instruments developed for monitoring aerosols and gaseous constituents in the stratosphere and troposphere. SAGE III was launched in the SpaceX Dragon vehicle in February 2017 and mounted to an external stowage platform on the International Space Station (ISS) to begin its three-year mission. SAGE III measures solar occultation, as shown in Figure 1a and lunar occultation in a similar fashion. SAGE III also measures the scattering of solar radiation in the Earth's atmosphere (called limb scattering) as shown in Figure 1b. These scientific measurements provide the basis for the analysis of five of the nine critical constituents identified in the U.S. National Plan for Stratospheric Monitoring. These five atmospheric components include the profiles of aerosols, ozone (O_3), nitrogen dioxide (NO_2), water vapor (H_2O), and air density using oxygen (O_2).



(a) Solar Occultation



(b) Limb Scattering

Figure 1: SAGE III Measurement Techniques.

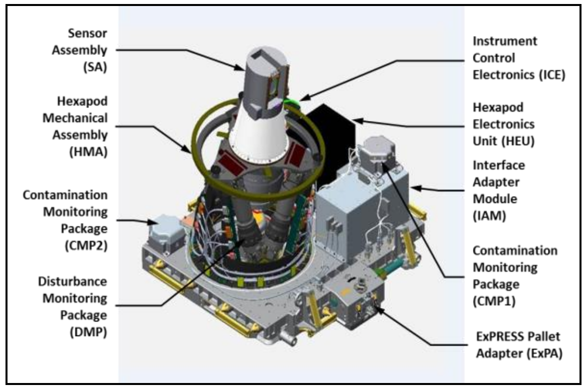


Figure 2: Instrument Payload (IP).

The SAGE III project is a partnership between LaRC, Thales Alenia Space – Italy (TAS-I), and Ball Aerospace and Technologies Corporation (BATC). SAGE III consists of two payloads – the Instrument Payload (IP) and the Nadir Viewing Platform (NVP). The IP, shown in Figure 2 is broken down into several subsystems including the Instrument Assembly (IA), Hexapod Pointing System (HPS), Interface Adapter Module (IAM), Contamination Monitoring Package (CMP), and Disturbance Monitoring Package (DMP). The IA and HPS are existing hardware from the heritage SAGE III on ISS mission while the IAM, CMP, and DMP are being developed. The NVP is shown in Figure 3, which attaches to both the IP and the ISS via standard ISS Flight Releasable Attachment Mechanisms (FRAMs).

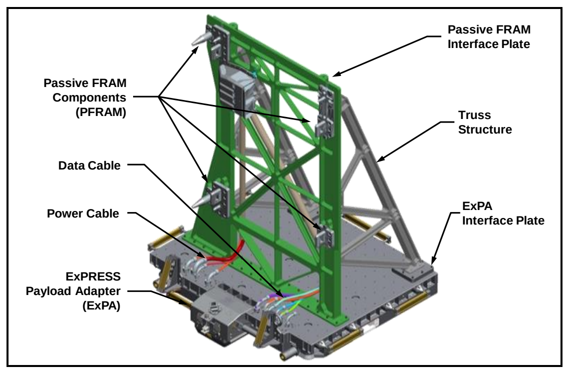


Figure 3: Nadir Viewing Platform (NVP).

Figure 4 shows the IP and NVP installed in the Dragon trunk. The purpose of the NVP is to orient the IP so that it is nadir-facing; this is required for the IA to collect science data. SAGE III will be mounted on the Expedite the Processing of Experiments to Space Station (ExPRESS) Logistics Carrier (ELC)-4 on the port-facing side of the ELC-4 at site 3, as shown in Figure 5.

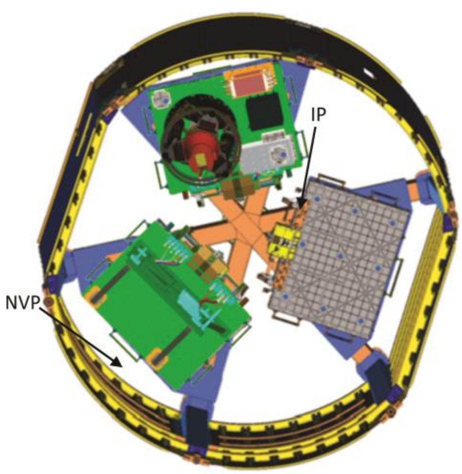


Figure 4: SAGE III IP and NVP in Dragon Trunk.

The IP thermal design includes various types of thermal hardware including thin-film heaters for survival and operation, multi-layer insulation (MLI) blankets, and thermal tapes. Thermal hardware was selected in order to ensure that the payload would remain within an acceptable temperature range for all phases of the mission. During the design phase, it was necessary to consider ISS requirements and constraints when specifying the details of the thermal hardware.

Many types of thermal analyses were required to ensure that the SAGE III payload would remain within acceptable limits during all phases of the mission. Configurations included those with the payload mounted in the Dragon capsule, on the EOTP during transfer from

Dragon to ELC-4, and at the payload's final location on ELC-4. Analysis runs were performed to determine the worst-case orbital parameters for this payload and this location on ISS, standard runs to evaluate the payload thermal behavior during test and in all operational phases, and mapping of thermal results to a structural model to evaluate thermally-induced stress and deflection.

A detailed thermal model of the SAGE III payloads mounted to the ISS was developed at NASA Langley Research Center (LaRC). This model was used for the majority of the analyses, and many methods were developed to make the model more efficient and effective in order to expedite this large amount of thermal analysis[1,2]. A low-fidelity model was created and delivered to SpaceX and the ISS Passive Thermal Control Systems (PTCS) team for integration into their Dragon and ISS models, respectively. SpaceX performed mission-specific analysis for the time between launch and berthing to ISS and the PTCS team performed detailed analyses to make temperature predictions for the transfer of the IP from the Dragon trunk to the ELC-4.

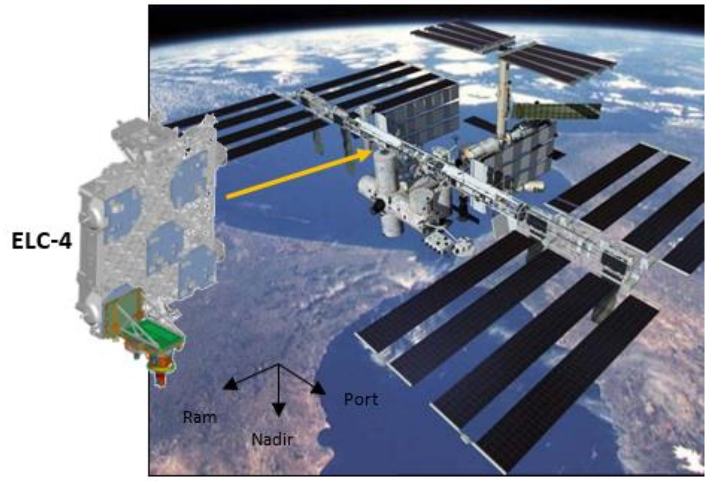


Figure 5: SAGE III Location on ISS.

II. Thermal Design

The IP is thermally controlled via a combination of active and passive design elements. Thermal control is not required for the NVP because it has no active electronics or other temperature-sensitive items.

The active thermal control of the IP is achieved using Kapton thin film heaters with 3M 966 adhesive which are operated in a bang-bang (simple on/off) mode using mechanical thermostats. The IP heater power has a different configuration depending on where the IP is mounted during the different phases of the mission. These phases include the Dragon trunk as it travels to and berths with the ISS, the Enhanced Orbital Replacement Unit (ORU) Transfer Platform (EOTP) as the payload is being moved from Dragon to its final location, and the IP's final location at ELC-4. Table 1 shows the power busses available during each mission phase, along with their voltage ranges. In the Dragon trunk and on the EOTP, only the main contingency power bus is available to provide heater power to the IP. While on the ELC-4 for nominal operations the operational (120V) bus, the main contingency bus, and the auxiliary contingency bus are available to provide heater power to the IP. The SAGE III survival heaters were sized based on the limiting power case which occurs while SAGE III is mounted on the EOTP. Heater resistances were specified based on nominal power values. Minimum powers, corresponding to the minimum voltages at each SAGE III location (Dragon, EOTP, and ELC-4), were used in the thermal model to verify that the heater power is sufficient to maintain acceptable temperatures. Maximum powers, corresponding to the maximum voltage for the SAGE III mission (which occurs on ELC-4), were used to verify that the total heater power consumption remains within the limits defined by ISS. Maximum voltages were also used to determine the heater watt density.

Table 1: Voltage Ranges.

Mission Phase	Bus	Voltage (V)		
		Min	Nominal	Max
Dragon	Main Contingency (120V)	113	120	126
EOTP	Main Contingency (120V)	103.6	120	124.6
ELC	Operational (28V)	25	28	31
	Operational (120V)	106.5	120	126.5
	Main Contingency (120V)	106.5	120	126.5
	Auxiliary Contingency (120V)	106.5	120	126.5

Each subsystem has one operational heater and two survival heaters (one main and one auxiliary), with the exception of the Sensor Assembly (SA) for which the same heaters are used for operation and survival. The main and auxiliary heaters for a given subsystem are of identical specification. Watt density is taken into account when specifying heaters because higher watt densities represent higher risk for heater failures, primarily because in the event that a portion of the heater becomes detached from the hardware on which it is installed, a local hotspot could develop. Within the thermal community, the standard practice for maximum watt density varies considerably. Based on a Goddard Space Flight Center (GSFC) procurement specification[3], the SAGE III thermal team originally set a goal to keep heater watt densities below 3.5 W/in^2 (note that this is conservative since that guideline relates to a heater suspended in air, while the SAGE III heaters are all mounted to metal surfaces); however, this was not possible in the case of the CMP due to its small size and required heater power. Guidelines provided in Tayco Engineering, Inc. specification documentation[4] stated that "normal satellite usage is less than 3 W/in^2; however, depending on application methods, power density can go up to 25 W/in^2" and "heaters with watt densities of 3-7 W/in^2 should be secured using epoxy around the perimeter." Based on this guidance, the watt densities for the CMP heaters were limited to a maximum of 7 W/in^2.

Standard practices for heater installation vary. The SAGE III heaters were installed using a procedure written at LaRC which was developed based on a review of a GSFC procedure[5] for installing Kapton heaters and on guidance received from the heater manufacturer and others in the NASA and industry thermal community[6]. To minimize the risk of creating bubbles in the heater surfaces during installation, the SAGE III heaters are all simple shapes (rectangles and circles) and were mounted on flat surfaces, with the exception of the CMP survival heaters which encountered a small amount of curved surface. Per GSFC recommendation, heat was applied to the heater surfaces using a clean-room compatible heat gun to remove as much moisture and residual solvent as possible. After thoroughly cleaning the surface to which the heater was to be applied, the heaters were installed by exposing the film adhesive and carefully rolling the heater onto the surface, keeping the heater at an angle of approximately 30° and slowly removing the protective backing paper. Uniform finger pressure was applied to ensure good contact. Small beads of epoxy were applied around the perimeter of each heater as a way to prevent the edges of the heater from peeling up. While this may not be necessary for heaters with very low watt densities (below 3 W/in^2), there is no drawback to using the method besides the necessity of ensuring that there is enough physical space for the epoxy beads.

While some groups maintain that aluminum over-tape should be used on Kapton heaters as a heat-spreader or to prevent the heater edges from curling up, the SAGE III team (along with the heater manufacturer Tayco) believes this is not necessary when heaters are being mounted to a metal substrate that is sufficiently thick to provide adequate heat sinking capability. In the case of SAGE III, all of the surfaces to which heaters were mounted were at least 50 times thicker than the aluminum tape. Additionally, Tayco does not recommend the use of over-tape due to concerns that it prevents gas and moisture from escaping the Kapton surface when placed in a vacuum environment. This could lead to the formation of bubbles, and thus local hot spots and potential heater failure. There is successful flight heritage for both configurations (with and without over-tape). SAGE III determined that it was prudent to follow manufacturer recommendations unless there is a compelling reason not to do so. This decision and the background research was thoroughly documented in a project report[6] and interested readers may contact the author for more information. Additionally, the report will be posted on the NASA Engineering Safety Center (NESC) Passive Thermal community website (https://nen.nasa.gov/web/pt) after it is approved for public release. With the exception of the Instrument Control Electronics (ICE) heaters, which were installed prior to the SAGE III team discovering Tayco's recommendation not to use over-tape, the SAGE III heaters were installed without the use of aluminum over-tape. After discussing the various options, the SAGE III team decided that the risk of making modifications to the ICE heaters outweighed the potential benefits. Removing the aluminum tape carries a high risk of damaging the heater surface and creating a gap in the existing epoxy, which could lead to damage of the heaters or the ICE chassis. Thermal predictions indicate that there is very little risk of the heater surfaces reaching temperatures at which the aluminum tape would de-bond; additionally, if this were to occur in flight the tape would be contained within the ICE bracket and as such would not pose any risk of Foreign Object Damage (FOD) to SAGE III or ISS.

As shown in Figure 6 and Table 2, the passive thermal control of the IP was achieved using multilayer insulation (MLI) blankets, thermal tapes and surface coatings for radiators (used to obtain the required thermo-optical properties),

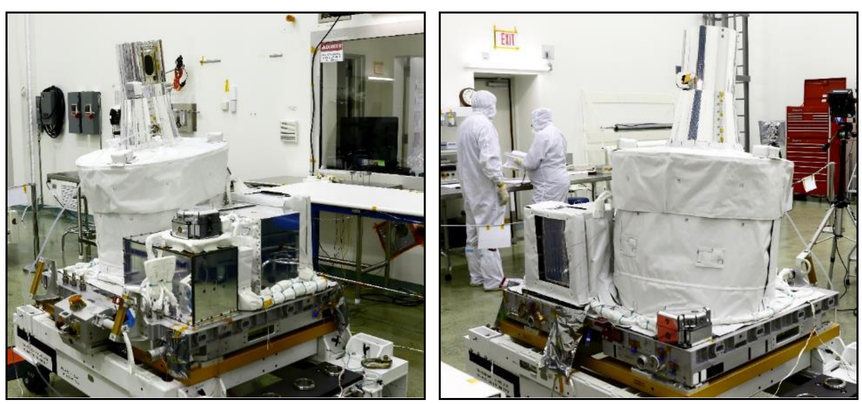


Figure 6: IP MLI and Surface Coatings As-Built.

Table 2: IP Passive Control Summary.

IP Subsystem	Blankets	Coatings
Interface Adapter Module (IAM)	• MLI with aluminized beta cloth exterior on wake side • Triple-layer beta cloth connector boots on connectors not covered by MLI	• 5 mil silver Teflon on all sides except wake (ram side partially obscured by cables) • Small portions not covered by tape are irridite or hard anodized aluminum
Contamination Monitoring Package (CMP)	• Triple-layer beta cloth connector boots • Four-layer beta cloth finger guard around CMP1 isolators	• 5 mil silver Teflon except over connectors and on bottom • Small portions not covered by tape are hard anodized aluminum
Disturbance Monitoring Package (DMP)	None	Painted with Aeroglaze Z-307 except bottom which is clear anodized
Sensor Assembly (SA)	None external	• 5 mil perforated silver Teflon on scan head and azimuth thermal housing • Aluminized side of aluminized Kapton on spectrometer thermal housing
Instrument Controller Electronics (ICE)	• MLI with aluminized beta cloth exterior covers ICE, bracket and connectors on all sides except wake and nadir • Four-layer beta cloth finger guard around standoffs	• 10 mil silver Teflon on wake and nadir facing surfaces (legacy material) • 2 mil aluminized Kapton on bottom of bracket • Black anodized aluminum on portions not covered by tape
ExPA	3 MLI blankets with aluminized beta cloth exterior cover all exposed portions of ExPA except part of the starboard-facing side and keep out zones	• 5 mil silver Teflon under HEU • 2 mil aluminized Kapton under ICE and within HMA enclosure • Clear anodized aluminum on remainder
Hexapod Mechanical Assembly (HMA)	2 MLI blankets with aluminized beta cloth exterior	Black anodized aluminum
Hexapod Electronics Unit (HEU)	MLI with aluminized beta cloth exterior on port side (igloo extending from HMA blanket)	• 5 mil silver Teflon on all sides except port • Small portions not covered by tape are black anodized aluminum • Kapton tape is on the bottom of the HEU

thermal interface materials used to maximize conductive heat transfer, and thermal isolation. Three different MLI layups were used on the IP. The ExPRESS Payload Adapter (ExPA), ICE, and IAM MLI blankets consist of 15 total layers with an additional aluminized beta cloth outer layer (aluminizing is on the inside). The inner (hardware-facing) layer was intended to be Kapton-out for all of these blankets; however, due to an error in the fabrication process the IAM blanket has the inner layer with the aluminized side out. Impacts of this difference are considered to be negligible. The Hexapod blankets consist of 21 total layers with an additional aluminized beta cloth outer layer. Aluminized beta cloth was used (in lieu of plain beta cloth) to ensure that a light-blocking layer was present to prevent the MLI from getting too hot. The MLI blankets are vented in the wake, port, and starboard directions using Spectra mesh filters. The design is such that no venting will occur toward the CMPs, SA, or silver Teflon surfaces to minimize contamination. To prevent the possibility of astronauts' fingers becoming trapped anywhere on the SAGE III payload during an Extra-Vehicular Activity (EVA), plain beta cloth finger guards (4 layers) where installed around the wire-rope isolators that attach the CMP1 to the IAM, and around the standoffs that attach the ICE to the ExPA. Connector "boots" made with 3 layers of plain beta cloth were installed on all connector backshells that were not already covered by an MLI blanket. MLI blankets, finger guards, and connector boots were installed primarily with Velcro, although buttons were used in limited cases where Velcro was not practical. Drawstrings were used to secure the connector boots around cable bundles. All cables not covered by MLI blankets were wrapped in plain beta cloth (single layer with 50% overlap).

The IP uses silver Teflon tape to create its radiator surfaces and aluminized Kapton tape to minimize radiative coupling between selected surfaces within the IP. All tapes used on the IP are attached via pre-applied acrylic 966 adhesive. As with the heaters, the SAGE III team developed a procedure at LaRC based on review of various procedures including manufacturer-provided documentation[7] and procedures from GSFC. As was the case with the Kapton heaters, surfaces were thoroughly cleaned and the tape was carefully rolled onto the hardware surface. For dimpled areas such as recessed bolt heads, the trapped air volume was eliminated by cutting a small slit or excising an area of tape directly over the recessed area. Since materials do not adhere well to Teflon, it was necessary to leave several 1" diameter cut-outs to allow for installation of test thermocouples prior to thermal vacuum (TVAC) testing. Cutouts were circular to avoid sharp corners which may catch or peel up more easily. Following testing and removal of the thermocouples, circular patches were installed at cut-out locations to recover silver Teflon coverage on the hardware. It is important to note that silver Teflon must be handled very carefully as it can be damaged (scratched) relatively easily; this can lead not only to deterioration of thermal properties, but can be a contamination concern depending on the sensitivity of the payload. Because of an ISS requirement related to minimizing the view factor of reflective surfaces to the ISS and other payloads, it was necessary to obtain concurrence from the ISS Passive Thermal Control Systems (PTCS) group early in the design process for the extensive use of silver Teflon that was planned for SAGE III. In addition, to verify that the heat flux from the radiators would be acceptable for the ISS, the heat rate was found for each component with silver Teflon to all of the ISS in the worst hot case, at the hottest time point. The power transfer to ISS was summed over all the silver Teflon surfaces on each component, and summed over all ISS surfaces that each component transfers heat to; this total is not reduced by the heat input to the component from any ISS surface. These values were provided, along with the total heat loss to space from each component, to the ISS for concurrence during the requirements verification process.

Table 3: IP Thermal Contact.

IP Subsystem	Description of Thermal Contact
IAM	In good thermal contact with the ExPA using NuSil CV-2946. There is a section with material removed to reduce mass under the Flight Computer under which an aluminum filler plate is mounted. The interface between the IAM and the filler plate also contains NuSil CV-2946.
CMP1	Thermally isolated from the IAM because it is mounted on wire-rope isolators for structural reasons.
CMP2	In contact with the ExPA with no interface material.
DMP	Interfaces to the ExPA with an interface mounting plate made of Aluminum 6061.
SA	Attaches to the HMA and uses Ti-6Al-4V standoffs and washers for thermal isolation.
ICE	Installed within a bracket which interfaces with the ExPA via twelve titanium standoffs and washers for thermal isolation.
HMA	Uses 5mm zirconia thermal washers for thermal isolation of each bolt attached to the ExPA. For each bolt, 2 washers are used to decouple the HMA from the ExPA. One washer is below the head of the bolt and the other is between the HMA offset flange and the ExPA.
HEU	Hard-mounted to the ExPA. Due to the shape of the chassis, only the feet of the HEU are in contact with the ExPA.

Table 3 summarizes the thermal contact between each subsystem and its conductive interface. Some of the conductive interfaces within the IP were designed for the purpose of thermal isolation while others were designed to facilitate good thermal contact. The IAM interface design was particularly challenging because the electronics dissipate a significant amount of heat which cannot all be dissipated through the radiative interface with space. Furthermore, the available footprint for the IAM was limited due to the fact that all SAGE III subsystems had to fit on the standard ExPA provided by ISS, and the chassis is only fastened to the ExPA on two sides (fasteners ~20" apart) which does not provide continuous contact pressure along the full length of the chassis. Various options were considered, including indium foil and gap pad 2200SF, but the interface material finally selected was NuSil CV-2946. The design iterations and challenges encountered are described in a presentation made at the 2015 Thermal and Fluids Analysis Workshop (TFAWS)[8]. Readers who wish for more information may contact the author.

A total of 98 sensors are used to monitor the temperature of the IP. Most of the temperature sensors are 10k thermistors; however, there are also several Resistance Temperature Detectors (RTDs) and 1k Platinum Resistance Thermometers (PRTs). Six channels of temperature measurements are available via the ISS ELC data stream when the IP is powered off. The placement of these sensors was critical, since they provide the only information to initially assess payload health and readiness to begin activation following installation on ISS. No SAGE III temperature data is available while in the Dragon trunk (although there are three sensors mounted to trunk structure, the data is not payload-specific) or on the EOTP. For this reason, it is critical for ISS payloads to develop a thermal model that can accurately predict thermal time-to-limit in the Dragon and robotic transfer scenarios (discussed further in Section V).

III. Detailed Thermal Model Development

A detailed thermal model of the SAGE III payloads mounted to the ISS was developed using Thermal Desktop (TD) and the combined IP and NVP model is shown in Figure 7. This integrated model was used for all SAGE III analyses performed at LaRC, with the exception of initial subsystem model development. This included all of the analysis required for on-orbit operations on the ISS, launch and transit to ISS in Dragon (additional analysis was performed by SpaceX and the PTCS team using their models), and predictions related to ground testing. The definition of SAGE III analysis cases is discussed in Section V. The model includes a detailed representation of the SAGE III payload and reduced representations of the ISS and Dragon.

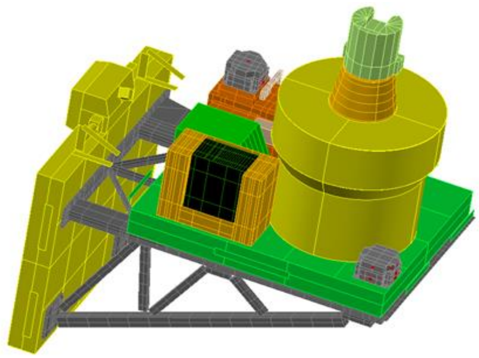


Figure 7: Detailed SAGE III Thermal Model (IP and NVP).

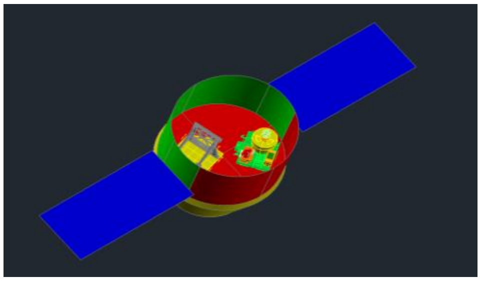


Figure 8: SAGE III Integrated with Dragon.

The model is shown integrated with Dragon in Figure 8 and with ISS in Figure 9. Additionally, it includes models of two TVAC chambers in which SAGE III ground testing occurred and the Ground Support Equipment (GSE) associated with each test. Figure 10 shows the IP configured with its GSE for the system-level TVAC configuration (chamber is not shown for clarity). The model utilizes flags to define which submodels should be built for various scenarios. Having all configurations housed within the same model was extremely beneficial because it prevented branches of the model held by different analysts from falling out of sync and reduced the likelihood of changes being inadvertently left out when branches of a model were re-integrated[2].

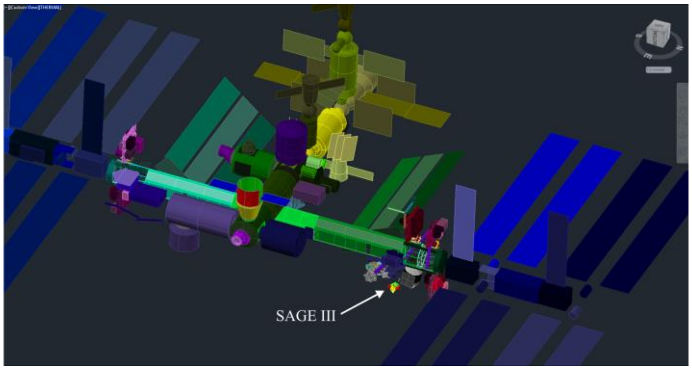


Figure 9: SAGE III Integrated with ISS (v6r4).

The TD model of the ISS was provided to the SAGE III thermal team by the ISS PTCS team at The Boeing Company (Houston) and Johnson Space Center (JSC). The PTCS team worked closely with the SAGE III team to ensure that the models were integrated properly; lines of communication remained open throughout the project for SAGE III analysts to request guidance on the use of the ISS model for analyzing various scenarios and/or verifying thermal requirements. This model, which is a simplified version of the full ISS model specifically intended for use by hardware developers to determine the induced thermal environment imposed by the ISS[9], was imported into the SAGE III thermal model and translated to metric temperature units for consistency with the SAGE III modeling approach[1]. The SAGE III model can be run in either set of temperature units, °C or °F, by setting the associated register. The ISS model provided a much more accurate solution than would have been possible by making assumptions for boundary conditions and blocking surfaces. The model has the flexibility to simulate key operational aspects of the ISS (visiting vehicles, control of solar arrays and radiators, changes in ISS attitude, etc.)[9].

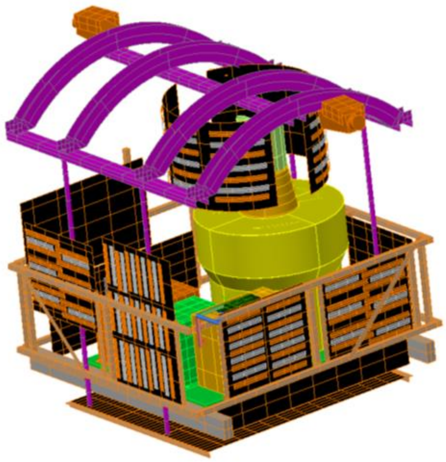


Figure 10: IP in System-Level TVAC Configuration.

The initial version of the ISS model that was included in the SAGE III model in 2011 was v6r1. Due to the complexities involved with removing and re-importing the ISS model (primarily a result of the units conversion and addition of symbols for tracker control), the SAGE III team did not update the ISS model with each revision; however, the SAGE III and JSC PTCS teams worked together to determine when updates were appropriate and the decision was made to update the ISS model once during the SAGE III design and analysis process. The current version of the SAGE III model includes v6r4 (January 2012) of the ISS model. The most recent version of the ISS model released to payload developers is v7r1; the SAGE III team is currently assessing the usefulness of updating the ISS model for future on-orbit predictions. The logic for the ISS model is contained within three blocks: the main block to generate nodes and conductors, register data, and setting boundary temperatures for hot and cold cases. Only radiative heat exchange between SAGE III and ELC-4 is modeled because the contact is very minimal and it is reasonable to assume no conductive heat transfer; this also helps satisfy an ISS requirement stating that payloads cannot not rely on the ISS for a conductive heat sink.

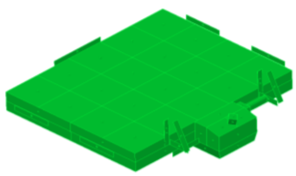


Figure 11: ExPA Model.

The ExPA model was provided separately and the v3 model is included in the SAGE III detailed model. The ISS program requires use of the standard ExPA model that was created by the ISS PTCS team to aid in payload thermal analysis. The SAGE III thermal model includes two ExPAs, one for the IP ExPA and one for the NVP ExPA. Thus, this ExPA v3 model was imported twice, and placed on the correct articulators and at the correct location for each ExPA. The imported ExPA model is as shown in Figure 11. Due to the coarseness of the mesh, it was necessary to use contactors to include the radiation from the ICE, HEU, and HMA to the un-insulated parts of the ExPA. The ExPA model utilizes RadCAD surfaces which are not used to create SINDA nodes. Instead, the nodes and conductors (linear and radiative) are created in logic blocks within the model. Logic blocks are also used to create the arrays for temperature-dependent materials.

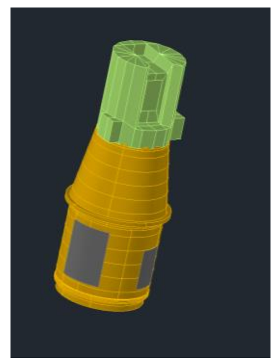


Figure 12: SA Thermal Model.

Table 4: Description of Submodels

Subsystems	**Manufacturer / Model Developer**	**Number of Nodes**
HMA	TAS-I / TAS-I	1058
HEU	TAS-I / LaRC	1070
SA	BATC / BATC	1489
ICE	BATC / LaRC	2192
IAM	LaRC / LaRC	2142
CMP1	LaRC / LaRC	425
CMP2	LaRC / LaRC	392
DMP	Honeywell / Honeywell	10
	Total IP	8778
NVP	LaRC / LaRC	1233
	Total SAGE	*10011*
ExPA (x2)	JSC / JSC	222
EOTP	JSC / JSC	94
ISS	JSC / JSC	3538
Dragon	SpaceX / JSC	44
	Total Integrated Model	***13909***

The SAGE III team also incorporated a reduced version of the Dragon model into the system-level model, which was provided by the ISS PTCS team. Along with the model itself, PTCS provided a guidelines document that defined modeling

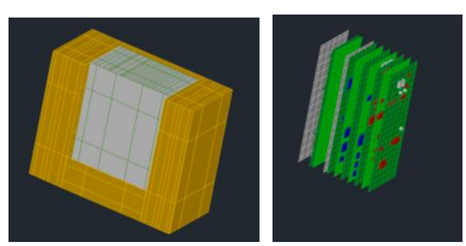


Figure 13: ICE Thermal Model.

assumptions and analysis cases. As was the case with incorporation of the ISS model, the PTCS team worked closely with the SAGE III team to ensure that the Dragon model was properly incorporated and that the cases were set up to properly complete the analysis. The initial version of the Dragon model provided to SAGE III was v1r1 and an update was later made to v3r1. The Dragon model v3r1 includes several changes to the orbits that are required to be run. These orbits were substantially different than the orbits in the earlier Dragon model. In order to facilitate import of these orbits and other orbits in potential future releases of the Dragon model, symbols were used to change the orientation of Dragon and SAGE III assemblies so the imported Dragon orbits could be used directly, without alteration of orientation.

The initial baseline thermal model was developed in support of the SAGE III Mission Concept Review (MCR) in August 2011 and the model was continuously updated as the SAGE III design matured. Model updates and current results were presented at each major SAGE III project life-cycle review with the last documented update occurring at the Systems Integration Review (SIR) in May 2015. The model was correlated at the subsystem level for the majority of the subsystems (SA, ICE, IAM, CMP, and HEU) and again at the system level following IP TVAC testing[10].

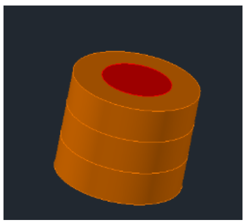


Figure 14: DMP Thermal Model.

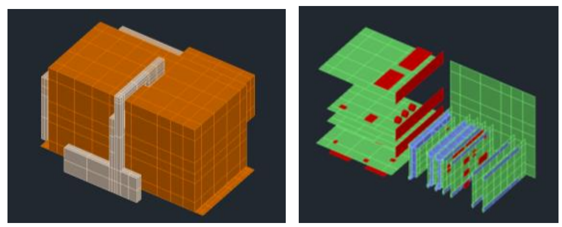


Figure 15: IAM Thermal Model.

The SAGE III thermal team at LaRC consisted of multiple analysts, with a total of six analysts working on the model over the course of the project. Three analysts from BATC and TAS-I worked on the subsystem models that were provided to LaRC. The model was stored on a shared drive along with an excel spreadsheet which was used to track changes that were made to the model (including version history) and results summaries over time. The model was version-controlled using a system of major (numerical) and minor (alphabetical) version names. The final version of the model prior to beginning on-orbit operations was v59c. Many efficiency-improving methods were implemented during the development of this model related to the use of assemblies, logic, and symbols in TD[1,2].

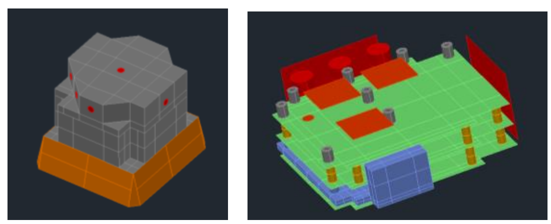


Figure 16: CMP1 Thermal Model.

Because the SAGE III project was a partnership between several organizations, submodels developed by various partners were delivered to the LaRC thermal team who created the integrated model. All models were provided in TD; although earlier versions of some of the models of heritage components were in other software, BATC and TAS-I provided LaRC with TD models for incorporation into the system-level thermal model. LaRC also developed detailed models for the subsystems that were built at LaRC. Table 4 provides a list of the subsystems, information about who built the hardware and the model, and the number of nodes for each subsystem as well as the integrated model. The SAGE III subsystem models are shown in detail in Figure 12 through Figure 19. The CMP2 model is not shown because it is very similar to the CMP1 model which is shown in Figure 16.

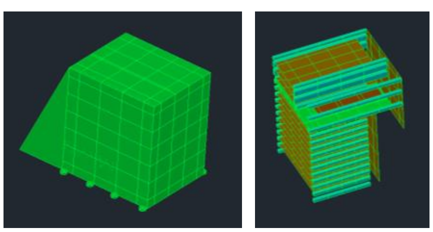


Figure 17: HEU Thermal Model.

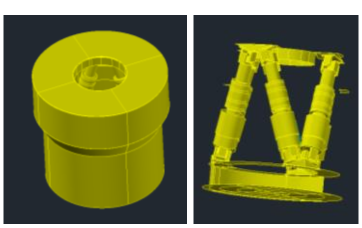


Figure 18: HMA Thermal Model.

Each electronics box includes a board-level internal model where components with significant power dissipation and/or critical thermal limits were included. The remaining power dissipation (for components not modeled) was distributed evenly across the appropriate board. Measured surface properties (emissivity and absorptivity) were included where possible, and in other cases properties were obtained from standard sources such as the Spacecraft Thermal Control Handbook[11]. Where power

Figure 19: NVP Thermal Model.

dissipation varies significantly over an orbit, such as within the SA, transient power profiles were included in the model using logic blocks that are enabled based on the case definition. In other cases, worst-case constant power dissipations for hot and cold cases are used, again depending upon the case definition.

An overall comparison of the actual and modeled masses for the IP and NVP us shown in Table 5. In general, mass for items such as cabling and MLI is not included in the thermal model, as it will not materially affect the temperatures of the components. The mass of the overall IP is 15% low, which is conservative since it would mean components tend to change temperature more quickly in the model than in the actual hardware. The overall mass of the NVP is 12% low, which is again believed by the SAGE III thermal team to be within acceptable levels, and conservative with regard to thermal predictions.

Table 5: Actual vs. Model Mass Comparison

Subsystem	Actual Mass (lb)	Mass in Thermal Model (lb)	Percentage Difference
IP	730.3	618.8	-15%
NVP	419.3	368.5	-12%

IV. Reduced Thermal Model Development

Reduced versions of the SAGE III IP and NVP models were created, documented, and delivered to the ISS Program and to SpaceX for inclusion in their high-fidelity ISS and Dragon models, respectively. The reduced model, shown in Figure 20 (HMA removed from image on the right so the DMP can be seen), was delivered in August of 2013, around the time of the SAGE III project CDR. At that time, the launch of SAGE III was planned for late 2014; the reduced model delivery due date was no later than launch minus 16 months (a discussion of the evolution of the SAGE III launch manifest and reasons for the actual launch occurring in February 2017 is out of the scope of this report). Along with the models, a report was provided which described the model in detail, including information such as units, submodels, symbols, critical node limits, heaters, logic block descriptions, instructions for running the models, and results from check cases. Providing clear and concise documentation is critical to ensure that the next-level integrator clearly understands how the model works, particularly with respect to analyzing different mission phases. The model deliveries and accompanying report satisfied several ISS requirements for SAGE III. Periodic updates were provided to the reduced IP model and its accompanying documentation, mostly following model correlations completed by the SAGE III team. A final update was provided 2 months prior to launch. Communication between the SAGE III thermal team and the ISS PTCS team was critical throughout this process.

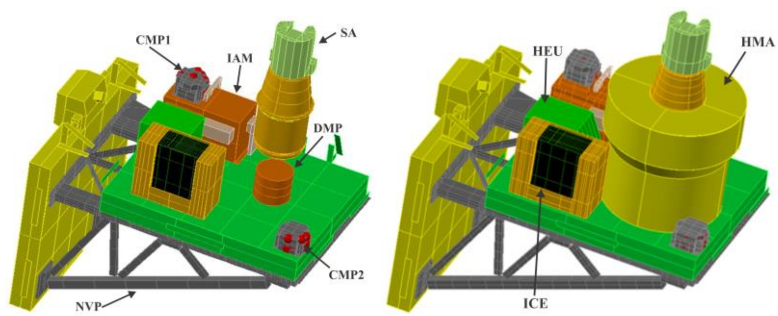


Figure 20: Reduced SAGE III System-Level Thermal Model.

Table 6: Node Counts in Reduced Model.

Submodel	High-Fidelity Node Count	Reduced Node Count
SAGCM1 (CMP1)	367	113
SAGCM2 (CMP2)	360	104
SAGDMP (DMP)	9	6
SAGETC (Thermocouples)	49	15
SAGHEX (HEU & HMA)	1058	104
SAGIAM (IAM)	1887	75
SAGICE (ICE) (2 submodels in high-fidelity version)	2099	108
SAGIEX (IP ExPA)	92	92
SAGINS (SA)	1081	264
SAGITC (SA thermocouples)	26	24
IP Total	7028	**905**
SAGNEX (NVP ExPA)	92	92
SAGNVP (NVP)	1233	554
NVP Total	1325	**646**

The reduced models were developed based on ISS thermal requirements, which provided guidelines for node counts, types of nodes, and model format. Table 6 provides the node count comparison between the high-fidelity and reduced models. At the time that the reduced model was created, the high-fidelity SAGE III model included a total of 7028 nodes for the IP and 1325 nodes for the NVP. The reduced models contained 905 and 646 nodes, respectively. These node counts are above the ISS requirement of 500 nodes per model, so it was necessary for SAGE III to process an exception. The exception was granted because the ISS Program agreed with the SAGE III team's assessment that due to the complexity of the high-fidelity model, it was not possible to meet the required number of nodes while maintaining the capability to produce results that would reasonably approximate the high-fidelity predictions. Specifically, making additional cuts would have resulted in a loss of fidelity on the heaters and active SA parts, and would likely have required modification to external shapes of some of the hardware. The node reduction was primarily achieved by removing the internal details on the electronics box models, such that a single lumped-mass node was used in place off all internal components for the CMPs, HEU, IAM, and ICE. External nodalization was also simplified for these parts where it was possible to do so. For the SA, parts were re-meshed with a coarser mesh, and where possible the geometry of the internal parts was simplified; however, as previously stated there was a limit to the simplification that could be done while retaining the accuracy of the results.

Requirements also stated that the model must be in TD format with a Thermal Radiation Analyzer System (TRASYS)-compatible Geometric Math Model (GMM) and Systems Improved Numerical Differencing Analyzer/Fluid Integrator (SINDA/FLUINT)-compatible Thermal Math Model (TMM). Since PTCS would be converting the models to TRASYS format from TD, it was necessary to work with the PTCS team to determine what changes were necessary to facilitate the conversion. There were ellipses in the high-fidelity model of the SA that were removed and replaced with TRASYS-compatible surfaces. Submodel names were defined such that they had a maximum of 6 characters and only contained A-Z or 0-9. A radiation conductor was used to simulate the radiation in the gap between the CMP1 and the IAM. In addition to format and node requirements, the documentation provided with the reduced thermal models was required to include sufficient detail such that the ISS program could discern that proper consideration was given for hot and cold case parameters such as beginning-of-life (BOL) and end-of-life (EOL) optical properties and ranges of power dissipation values. These considerations were already addressed in the SAGE III high-fidelity model so no additional work was needed during the model reduction process in order to meet these requirements.

The primary purpose of the reduced models was for the SpaceX and ISS PTCS teams to perform mission analysis for the Dragon (solo and berthed) and robotic transfer (from Dragon to ELC-4) portions of the mission. As such, it was critical to ensure that the reduced models were accurate or conservative for survival heater-only and transient cool-down cases. The masses of the IP and NVP reduced models were 613.7 lb and 368.5 lb, respectively. Referencing Table 5 for the as-built IP and NVP masses, it can be seen that the masses in the reduced models were conservative.

Table 7: Comparison between High-Fidelity and Reduced Model, Dragon Cold Case.

Component	Heater Duty Cycle		Temperature Difference (Reduced – High Fidelity), °F
	High Fidelity v41	Reduced v41_r25	
CMP1	0%	0%	+2
CMP2	0%	0%	+3
DMP	86%	87%	+1
HEU	97%	97%	+3
HMA	88% actuators, 0% upper platform	88% actuators, 0% upper platform	0
IAM	77%	71%	0
ICE	67%	61%	+2
SA Elevation Motor	N/A	N/A	+9
SA Azimuth Motor	40% (Zone 3)	14% (Zone 3)	-14
SA Spectrometer Assy	73% (Zone 1)	93% (Zone 1)	+1

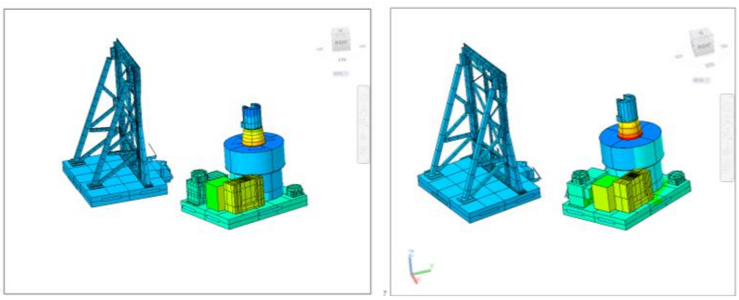


Figure 22: Comparison of High-Fidelity (left) and Reduced (right) Model Results – Dragon Cold Case.

Table 8: Comparison of High-Fidelity and Reduced Model Results – Cold Unpowered EOTP Case.

Component	Difference in Temperature Decrease after 6-hour Unpowered Transient (Reduced – High Fidelity), °F
CMP1	-1
CMP2	0
DMP	0
HEU	-2
HMA	-2
IAM	-1
ICE	+5
SA Elevation Motor	-2
SA Azimuth Motor	+9
SA Spectrometer Assy	-3

Comparisons of temperature predictions to the high-fidelity model are provided in Table 7 through Table 9 and Figure 21 through Figure 23. For each figure, temperature maps are shown from the high-fidelity and reduced models for the same anlaysis case. Temperature scales are not shown but they are equal for any given figure, so a direct comparison can be made. Results are shown as a difference between the reduced and high fidelity models (in °F as required by ISS). A positive number indicates that the reduced model over-predicts when compared to the high-fidelity model. For the Dragon case, the results are shown for the end of a 72-hour transient run. For the EOTP case, the results are shown as the temperature change at the end of 6-hours with no operational or survival power. For the hot operational case, results shown are the maximum temperatures at quasi-steady-state.

Direct comparisons were made where possible; however, there are some approximations. The temperatures shown for the high fidelity model results are generally chassis averages. For the SA, the spectrometer assembly temperatures shown are the CCD shield temperatures (the elevation motor and azimuth motor nodes are the same as in the reduced model). The SA Zone 3 heaters are listed along with the azimuth motor because those heaters are located in the azimuth assembly. Likewise, the scan mirror heater duty cycle (op case only) is shown with the elevation motor since that heater is in the scan head assembly.

In general, the results show good agreement, with temperatures being mostly within 5°F and heater duty cycles being mostly within 6%. The exceptions were considered to be acceptable to the SAGE III thermal team. The SA elevation motor temperature predictions are within 9°F. The SA is the most complex of the SAGE III subsystems, and as such it was difficult to achieve better matching in the reduced version. The SA azimuth motor temperature predictions are 14°F colder in the reduced model than in the high-fidelity model in the cold survival cases (Dragon ATT01 and EOTP) and 6°F warmer than the high-fidelity model in the hot operational case. Although these differences may be larger than desired, they are not of great concern since they are conservative. The transient cool-down in the EOTP unpowered case shows very good agreement for all nodes except for the azimuth motor, for which there is a 9°F difference in the change in temperature during the 6-hour run. Although the cool-down is somewhat slower in the reduced model, the absolute temperature prediction after the 6-hour run matches very well with the high-fidelity model. The discrepancy is also not of major concern because the azimuth motor is not the limiting component when it comes to the transient cool-down case (other components reach limits first). In the hot operational case, some of the electronics box temperature predictions are considerably warmer in the reduced model than in the high-fidelity model; however, it is important to remember that the temperatures shown for the high-fidelity model are chassis temperatures, while the reduced model temperatures represent lumped mass nodes to which the operational power is applied. The SA zone 1 heater duty cycles and the HMA upper platform heater duty cycles are high in some cases; however, this is considered to be acceptable since it will lead to conservative power consumption estimates for the SAGE III payload. The SA zone 3 heater duty cycles are lower in the reduced model than in the high fidelity model; however, this will have a negligible impact on the total power consumption estimates for the SAGE III payload because the zone 3 heaters are low-powered heaters in comparison with the others (6W nominal).

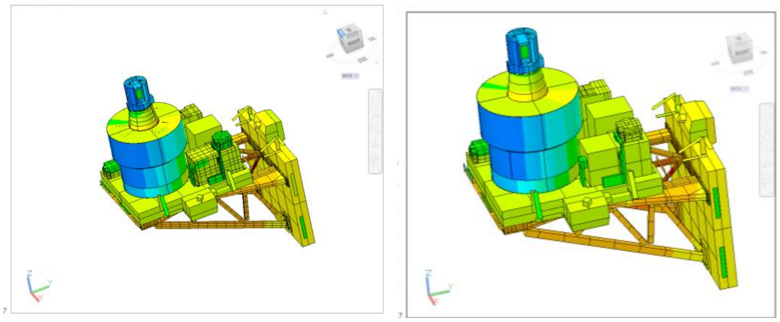


Figure 23: Comparison of High-Fidelity and Reduced Model Results – Cold Unpowered EOTP Case.

Table 9: Comparison of High-Fidelity and Reduced Model Results – Hot Operational Case.

Component	Heater Duty Cycle		Temperature Difference (Reduced – High Fidelity), °F
	High Fidelity v41	Reduced v41_r25	
CMP1	0%	0%	+21
CMP2	0%	0%	+17
DMP	0%	0%	+4
HEU	0%	0%	-1
HMA	0%	0%	+1
IAM	0%	0%	+5
ICE	0%	0%	+21
SA Elevation Motor	100% (scan mirror)	100% (scan mirror)	-2
SA Azimuth Motor	0% (Zone 3)	0% (Zone 3)	+6
SA Spectrometer Assy	0% (Zone 1)	19% (Zone 1)	+5

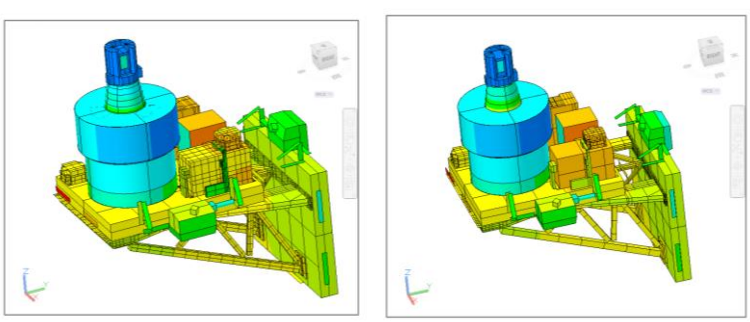


Figure 24: Comparison of High-Fidelity (left) and Reduced Model (right) Results – Hot Operational Case.

Although the reduced models were specifically requested for the scenarios previously mentioned, it is important for ISS payloads to be aware that the models could be used for other analysis cases in the on-orbit configuration as needed. Shortly before the SAGE III launch, it became necessary for the ISS PTCS team to evaluate the impacts to ELC-4 payloads of a previously unplanned Extravehicular Activity (EVA) during which survival power would not be available. When the analysis results were presented, they were not consistent with SAGE III analysis for the same case. Upon further investigation, it was discovered that the reason for the discrepancy was due to a change that was made to the high-fidelity IP model that was not also made to the reduced IP model. This change (the stow angle for the scan head of the SA) did not apply to Dragon or robotic transfer operations, and as such it was not believed (by

SAGE III or ISS PTCS) to be a necessary adjustment to the reduced model. The lesson from this experience is that it is important to keep the reduced model in mind, and to stay in good communication with ISS PTCS, throughout the duration of mission preparation and ops. Working together, the SAGE III and PTCS teams came to agreement with respect to predicted time-to-limit for the EVA scenario.

V. Analysis Case Definition

Many types of thermal analyses were required to ensure that the SAGE III payload would remain within acceptable limits during all phases of the mission. Configurations included those with the payload mounted in the Dragon capsule, on the EOTP during transfer from Dragon to ELC-4, and at the payload's final location on ELC-4. Analysis runs were performed to determine the worst-case orbital parameters for this payload and this location on ISS, standard runs to evaluate the payload thermal behavior during test and in all operational phases, and mapping of thermal results to a structural model to evaluate thermally-induced stress and deflection.

A summary of all of the flight analysis cases for SAGE III on ISS is provided in Table 10. Those cases shown in highlighted rows are the only ones which were run routinely when model updates were made; others were performed for specific requirements and did not need to be repeated throughout the design process. Approximately 90 analysis cases were run routinely to predict SAGE III temperatures throughout the different phases of the flight mission. Analysis cases performed in support of ground testing are not included in the table, though extensive pre-test and post-test analysis was performed for subsystem and system-level TVAC testing. The table also does not include analysis performed by PTCS for the transfer of SAGE III from Dragon to ELC-4 (to be discussed later in this section). Also not shown are cases that were run specifically to map thermal results to structural models for verification of thermal stress requirements. Finally, the table does not include cases that were run to simulate specific operational scenarios during payload commissioning (initial 3 months after SAGE III is installed on ELC-4 and powered on), which were performed in the months leading up to launch. In these cases, the focus shifted from attempting to make worst-case predictions to determining a more narrow range of expected temperatures during initial power on and science event operations.

Table 10: SAGE III on ISS Analysis Cases.

SAGE III Location	Description	Environment	Power	Number of Cases
Dragon Trunk	Solo	Cold	Survival Power	6
			Unpowered	6
		Hot	Survival Power	15
	Solo, Off-Nominal Flight Scenarios	Cold	Survival Power	3
	Berthed to ISS	Cold	Survival Power	7
			Unpowered	7
		Hot	Survival Power	7
			Dragon Trunk Total	***51***
EOTP (Transfer from Dragon to ELC-4)	DOE Runs for Worst-Case Environment Definition	ISS Extreme Cold	Unpowered	59
		ISS Extreme Hot	Unpowered	69
		SAGE Mission Success Cold	Unpowered	77
		SAGE Mission Success Hot	Unpowered	66
			EOTP DOE Total	*271*
	Worst-Case EOTP	ISS Extreme Cold	Survival Power	2
			Unpowered	2
		ISS Extreme Hot	Survival Power	1
		SAGE Mission Success Cold	Survival Power	2
			Unpowered	1
		SAGE Mission Success Hot	Survival Power	1
			Worst-Case EOTP Total	*9*
	ROBO Analysis for Time-To-Limit	Nominal	Survival Power	6
			Unpowered	7
			ROBO Total (SAGE III only, not PTCS)	*13*

SAGE III Location	Description	Environment	Power	Number of Cases
			EOTP Total	***293***
ELC-4	YVV	ISS Extreme Cold	Survival Power	18
		ISS Extreme Hot	Survival Power	18
	ZVV	ISS Extreme Cold	Survival Power	14
		ISS Extreme Hot	Survival Power	14
	Plume Impingement	ISS Extreme Hot	Survival Power	1
			Operational Power	1
			ELC-4 Off-Nominal Total	*66*
	DOE Runs for Worst-Case Environment Definition	ISS Extreme Hot	Unpowered	76
		SAGE Mission Success Hot	Unpowered	92
			ELC-4 DOE Total	*168*
	ELC-4 Survival	ISS Extreme Cold	Survival Power	1
			Unpowered	1
		ISS Extreme Hot	Survival Power	2
		SAGE Mission Success Cold	Survival Power	2
			Unpowered	1
		SAGE Mission Success Hot	Survival Power	1
		SAGE Mission Success Nominal	Survival Power	1
			Unpowered	1
			ELC-4 Survival Total	*10*
	ELC-4 Operational	ISS Extreme Cold	Operational Power	1
		ISS Extreme Hot	Operational Power	1
		SAGE Mission Success Cold	Operational Power	6
		SAGE Mission Success Hot	Operational Power	12
		SAGE Mission Success Nominal	Operational Power	3
			ELC-4 Operational Total	*23*
			ELC-4 Total	***267***

All of the analysis cases required for Dragon solo flight and Dragon berthed to ISS prior to removal of SAGE III were defined by SpaceX. Spacecraft attitude, initial conditions, and durations were specified in the guidelines documentation. There were 6 different spacecraft attitudes to assess, each with their own set of assumptions with respect to hot or cold environments, beta angle, and availability of survival heater power. A total of 48 analysis cases were required in the standard set of cases, with 3 off-nominal scenarios specific to the SpX-10 mission added to the list as the launch date approached. A high-level summary is provided in Table 10 and further details cannot be provided here since the information is considered proprietary by SpaceX. These cases, particularly those for the Dragon solo portion of the mission, were designed to be conservative and provide information on worst-case time-to-limit for Dragon payloads. They were not intended to represent expected temperatures and as such, the usual amount of thermal margin was not applied to these; ±5°C was applied rather than ±15°C which was the typical margin used in SAGE III analysis cases. SAGE III completed the analysis for each of these cases and provided the results to ISS PTCS in a report at various intervals, the last of which was late in 2014, approximately one year before the SAGE III payload was delivered to Kennedy Space Center in November of 2015 in preparation for a launch in February 2016 (later postponed to February 2017).

In addition to the analyses completed by the SAGE III team, SpaceX used the reduced SAGE III models along with their high-fidelity Dragon model to produce predictions to support their Mission Resource Allocation Document (MRAD) cycles. The SAGE III thermal team reviewed these documents and had the opportunity to provide feedback. In a couple of cases where discrepancies were found, the SAGE III team worked with the SpaceX thermal engineers to find the root cause and make the necessary adjustments.

Analysis cases on the ISS included hot operational, cold operational, survival (heater power only), and transient cases with no power which begins from the end of the survival case. The unpowered case was necessary in order to satisfy an ISS requirement that payloads must survive at least 6 hours without survival heater power; however, the SAGE III team typically ran these cases out to 24 hours in order to obtain predictions for when limits may begin to be reached. While mounted on EOTP (after being removed from Dragon, before being installed at ELC-4), the payloads are moved using the Mobile Servicing System (MSS) which includes the Space Station Remote

Manipulator System (SSRMS), Special Purpose Dexterous Manipulator (SPDM), and the Mobile Base System (MBS). SAGE III was not operational on the EOTP; therefore, only the survival and 6-hour no-power transient cases were included for the EOTP location.

Assumptions that are common to all ISS analysis cases are as follows: beginning of life (BOL) optical properties were used for cold cases and end of life (EOL) properties were used for hot cases, minimum voltage was used to determine worst-case heater power (except in nominal cases) and nominal voltage was used to define heater duty cycles used in the Power Equipment List (PEL). Per direction from ISS, radiator wings were parked at specific angles and the solar arrays were articulating (sun-tracking). Several special cases were also analyzed, including plume impingement from visiting vehicles, locked solar arrays, and alternate ISS attitudes.

In the analysis performed for configurations following the removal of SAGE III from the Dragon trunk, both during transfer on the EOTP and during operations on ELC-4, environments were defined based on ISS requirements. In those requirements, two sets of thermal environments were defined; one set of environments was used to verify that ISS program requirements are met (i.e. that SAGE III does not damage ISS or its payloads, that interface temperatures will remain within defined ranges) and one set of environments was used to assure SAGE III mission success. These are referred to as ISS Extreme and SAGE Mission Success environments, respectively, and are shown in Table 11. Albedo and Earth infrared (IR) heat flux values are provided for varying orbit times; these have been implemented as such in the SAGE III system model. Two sets of hot and cold environments, labeled A and B, were defined in the ISS requirements document. Case A is based on the worst-case Earth IR and case B is based on the worst-case albedo. After running both sets of cases, it was determined that the SAGE III hardware is more sensitive to changes in Earth IR and as such, the albedo and Earth IR values from the A cases were used in all future SAGE III analysis and only those parameters are shown below.

Table 11: Thermal Environments on ISS.

Case	Orbit Altitude (km)	Solar (W/m^2)	Albedo*	Earth IR* (W/m^2)
ISS Extreme Cold	500	1321	0-0.27	153-206
ISS Extreme Hot	278	1423	0.25-0.3	286-349
SAGE Mission Success Hot	460	1321	0-0.27	177-217
SAGE Mission Success Cold	360	1423	0.20-0.27	273-307
SAGE Mission Success Nominal	410	1372	0.27	241

*Implemented as time-varying parameters

The full list of ISS attitudes is shown in Table 12. Since +/- XVV are generally considered symmetric, it was not necessary to consider –XVV. Although on-orbit data is not generally covered by this report, it is worth noting that when the ISS transitioned to –XVV with SAGE III installed, temperature fluctuations of approximately 10°C were observed. An analysis was performed to determine whether or not the model would predict this fluctuation and the results were very similar to what was observed on-orbit. For +XVV, two sets of yaw, pitch, and roll (YPR) values are shown. The first is the more extreme range which corresponds to the range used for ISS requirements verification, while the ranges in parentheses are the more realistic values provided in ISS requirements documents and as such these were used in the SAGE Mission Success cases. For the XVV cases, analyses were conducted over a beta angle range of -75° to +75° and over the attitude range shown in Table 12. To determine the worst-case beta angle and attitude combinations for hot and cold cases, Design of Experiments (DOE) methods were used to conduct sets of parametric runs for both the ELC-4 and EOTP locations[12]. A summary of the worst-case beta angle and attitude combinations that were determined based on the results of the DOE analysis is provided in Table 13. It is important to note that there were cases where a certain subsystem was found to have a different worst-case combination of beta angle and attitude than the rest of the payload; these cases were added to the matrix of cases that were routinely run to evaluate SAGE III payload temperatures, but are not shown in this report for the sake of simplicity. Additionally, while four locations in the transfer path between Dragon and ELC-4 were analyzed as part of the EOTP DOE study, locations are not shown here. YVV and ZVV attitudes were only considered for ISS Extreme cases, not SAGE Mission Success cases. YVV is a temporary attitude (likely less than 24 hours) to be used infrequently for certain EVA scenarios and is heavily constrained in current flight rules. For YVV, two reduced case matrices were defined by the ISS PTCS team. For YVV cases with all ISS joints articulating normally, the reduced matrix includes beta angles of 0, ±30, ±55, ±75. The positive beta angles were analyzed for the +YVV configuration (YPR of 90°, 0°, 0°) and the negative beta angles were analyzed for the –YVV configuration (YPR of 270°, 0°, 0°). The beta angle of 0° was evaluated for ±YVV. A second matrix of YVV cases was required with the Solar Array Rotary Joints (SARJs) locked: in +YVV, port and starboard SARJs are locked at 0 for beta angles of 0 and -30, and locked at 270 and 90 respectively for beta angles of -30, -60 and -75. ZVV is a potential short-term attitude only for vehicle docking/undocking. The reduced matrix of ZVV cases was ZVV orientation (ISS pitch 90°), beta angles 0, ±30, ±60, ±75°, with port and starboard Thermal Radiator Rotary Joints (TRRJs) locked at 90°, port SARJs locked at 270° and starboard SARJs locked at 90°.

Table 12: Full ISS Attitude Matrix.

ISS Attitude Name	Solar Beta Range (β)	Yaw	Pitch	Roll	Time in Attitude
+XVV +Z Nadir	-75° ≤ β ≤ +75°	-15° to +15° (-9° to +3°)	-20° to +15° (-12° to -2°)	-15° to +15° (+0.5° to +1°)	No Limit
-XVV +Z Nadir	-75° ≤ β ≤ +75°	+165° to +195°	-20° to +15°	-15° to +15°	No Limit
+YVV +Z Nadir	-75° ≤ β ≤ +10°	-110° to -80°	-20° to +15°	-15° to +15°	No Limit
-YVV +Z Nadir	-10° ≤ β ≤ +75°	+75° to +105°	-20° to +15°	-15° to +15°	No Limit
+ZVV –X Nadir	-75° ≤ β ≤ +75°	-15° to +15°	+75° to +105°	-15° to +15°	3 Hours
-ZVV –X Nadir	-75° ≤ β ≤ +75°	+165° to +195°	+75° to +105°	-15° to +15°	3 Hours

Table 13: Worst-Case Orbital Parameters Determined by DOE Analysis.

	EOTP				ELC-4			
Parameter	**ISS Extreme Cold**	**ISS Extreme Hot**	**SAGE Mission Success Cold**	**SAGE Mission Success Hot**	**ISS Extreme Cold**	**ISS Extreme Hot**	**SAGE Mission Success Cold**	**SAGE Mission Success Hot**
Beta Angle	-75°	+75°	-3.3°	+75°	-75°	75°	-58.9°	47.5°
Yaw	-15°	15°	-5.8°	-8.3°	-15°	-15°	-8.4°	-8.4°
Pitch	+15°	-20°	-12°	-12°	+15°	+15°	-2°	-3.7°
Roll	-15°	15°	+0.5°	+0.7°	+15°	+15°	+0.6°	+0.5°

The approach to defining the analysis cases to determine SAGE III temperature predictions for the transfer from Dragon to ELC-4 on the EOTP evolved over time. For all of the analyses that were run prior to final model correlation, the SAGE III team defined the cases by performing a set of parametric runs in order to determine the worst-case hot and cold locations as well as beta angle/attitude combinations for the SAGE III payload while it is mounted on the EOTP. Four EOTP locations were defined in the model, with assistance from ISS PTCS, to represent specific times in the transfer timeline. These included just outside of the Dragon trunk, just prior to mating the IP to the NVP at ELC-4, and two Mobile Translator (MT) worksite locations in between. The worst-case locations and environments were defined using the DOE approach previously mentioned[12]. Once the worst-case locations and environments were defined, survival and unpowered runs were completed at only the worst-cast hot and cold locations, to determine the bounding predictions.

As launch approached, it became necessary to refine the analysis. Along with assistance from the robotic operations (ROBO) and PTCS teams at JSC, a set of cases was defined which gave a more accurate representation of discrete points along the transfer and installation timeline, and nominal environments were used in lieu of worst-case environments so that realistic thermal clocks could be defined. The SAGE III payload transfer from Dragon to ELC-4 occurs over a period of 5 days. Analyses were run at 6 locations at 3 beta angles (defined based on expected launch window). Each case was initiated from the end of the previous case, so that time-to-limit and required warm-up time could be determined for each scenario. These results were delivered to ISS PTCS in April 2016, with an expected launch date of November 2016. The ISS PTCS team performed an independent analysis using the detailed ISS model and reduced SAGE payload models. This analysis included 9 locations at 7 beta angles. The results of this analysis were used to determine thermal clocks that would be used during transfer operations, since the work completed by PTCS was more detailed than the work completed by SAGE III. The SAGE III thermal team worked informally with PTCS to compare results and confirm that there was good agreement, as well as to come to agreement on the margin approach and finalized thermal clocks. Note that the primary responsibility for this analysis resides with the PTCS team. In many cases, project thermal analysts are no longer assigned to the project by the time the details of the robotic transfer become clear. In this situation, it is critical for the project thermal analysts to communicate with the PTCS team prior to departing the project to convey any concerns they may have (such as requests for additional margin or concerns about a particular component).

For the operational cases once SAGE III is mounted to the ELC-4, multiple cases were defined in order to capture different operational scenarios for SAGE III; specifically, in order to bound the worst-case temperature predictions, hot cases were defined with the maximum number and expected duration of each science event (solar, lunar, and limb) and cold cases were defined with the minimum number and duration.

VI. Conclusion

This paper has presented details related to the design and analysis of the SAGE III on ISS payload, with the intention of providing future ISS payloads with relevant information to support early thermal design and analysis planning efforts. ISS requirements and constraints were taken into account throughout the design process. A detailed thermal model was developed that provided capability to perform analyses for all ground and on-orbit configurations within a single model. A reduced thermal model was created for inclusion in detailed Dragon and ISS thermal models so that SpaceX and the JSC/Boeing PTCS team could perform independent analyses for mission planning purposes. A large number of analyses cases were required to determine the worst-case environments for each phase of the SAGE III on ISS mission, to ensure that the payload would remain within acceptable thermal limits, to verify ISS requirements, to prepare for and correlate to ground testing, and to predict expected temperatures during the early operations phase of the mission.

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