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Determining Thermal Capabilities for External Transfer Operations on the International Space Station

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External transfers on the International Space Station have a degree of difficulty caused by the severity of the radiative thermal environment and the complexity of the operational choreography to perform the installation and activation of the hardware. These transfers can be performed robotically, by astronauts during an Extra Vehicular Activity (spacewalk), or combination of robotic/crew operations. Robotic transfers may include capability to intermittently power the hardware; while the hardware remains unpowered for EVA operations. Robotic transfers can be staged to occur in a favorable thermal environment, though typically take longer than a transfer by crew during an EVA where the hardware may not be robotically compatible. The hardware is under passive thermal control, use of optics/ multi-layer insulation/ heaters, while being transferred from/to a visiting vehicle, airlock, stowage platform, or external ISS structure and may include additional design components, such as removable protective blankets, to meet the transfer requirements. Thermal analysis must be performed to determine the capability of the hardware being transferred to provide the Mission Control team the products necessary to plan and execute the operation while establishing an awareness for any contingency response. An overview of the thermal aspects in planning these types of transfer operations, the analytical approaches and assumptions, and examples of results are provided in this paper.

Nomenclature

<u>Not ordered for draft:</u>

EVA	=	Extravehicular Activity (spacewalk)
EVR	=	Extravehicular Robotics
ISS	=	International Space Station
ORU	=	Orbital Replacement Unit
R&R	=	Remove and Replace (or Return and Replace)
CSA	=	Canadian Space Agency
MT	=	Mobile Transporter
MLI	=	Multi-Layer Insulation
MBS	=	Mobile Base System
SSRMS	=	Space Station Remote Manipulator System
POA	=	Payload/ORU Accommodation
EOTP	=	Enhanced ORU Temporary Platform
ESA	=	European Space Agency
SPDM	=	Special Purpose Dexterous Manipulator (Dextre)
YPE	=	Yaw, Pitch, Roll
LEO	=	Low Earth Orbit
XVV	=	+X-Axis into the Velocity Vector
ZLV	=	Z Local Vertical

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LVLH = Local Vertical/Local Horizontal
JEM = Japanese Experiment Module
USOS = United States On-orbit Segment

α = absorptance or absorptivity (in solar spectrum), dimensionless
ε = emittance or emissivity (in IR spectrum), dimensionless
β = solar beta angle, °
τ = thermal time constant, R·C, seconds
C = thermal capacitance, J/K
h_R = radiation heat transfer coefficient, W/m^2 K
R = thermal resistance, K/W
t = time, seconds
T = temperature, °C
$\bar{T}$ = absolute temperature, K

I. Introduction

THE International Space Station (ISS) has experienced over 100 external transfers of hardware during the build sequence, for required operational maintenance or for increase in system capabilities, along with approximately 25 deployments of external Payloads for scientific/technological advancements[3][1]. A key component in the planning of these operations is the thermal role since the transfers are typically unpowered and subject to the severe thermal environment of space. The question raised to the thermal engineer is, in effect, "Will temperatures remain within limits over the timeline? And if not, are there any recommended modifications?" These modifications may include timing of the event, modification to the hardware, and/or the re-sequencing of events. Thermal analysis must be performed to determine the capability of the hardware being transferred to provide the Mission Control team the products necessary to plan and execute the operation while establishing an awareness for any contingency response. The analytical problem is a basic thermal resistor-capacitor solution complicated with the radiative interaction of ISS structure and the orbital mechanics for determining the absorbed heating on the hardware throughout the orbit. Detailed geometric and thermal math models are typically utilized to solve for the temperature response to insure the successful deployment of the hardware. This paper provides an overview of the thermal aspects in planning these types of transfer operations, the analytical approaches and assumptions, along with examples of results. The techniques outlined in this paper are still in use for planning and execution of hardware transfers on ISS and these techniques are applicable to future space exploration for both robotic and crew based missions.

"The International Space Station serves as a blueprint for global cooperation and scientific advancements, a destination for growing a commercial marketplace in low-Earth orbit, and a test bed for demonstrating new technologies."[2] This massive and complex space structure, Figure 1, requires hardware change-out from expected and unexpected wear-and-tear caused in part by the severity of the space environment. These Orbital Replacement Units (ORUs) undergo a Remove and Replace (R&R) operation by astronauts during a spacewalk (Extravehicular Activity, EVA) or robotically (Extravehicular Robotics, EVR), or by a combination of EVA and EVR operations. Robotic transfers can be staged to occur in a favorable thermal environment, though typically take longer than a transfer by the EVA crew where the hardware may not be robotically compatible, e.g., cameras, lights, upgraded computers. ORU sizes range from 20 to 800 kg, comparative size from a lunch box to a refrigerator. External Payloads are similar to the size of ORUs, more in the small to midsize range, also having similar thermal characteristics. This paper considers the External Payload being synonymous with the ORU pertaining to the thermal aspects of the transfer operations on ISS, henceforth the ORU is only mentioned.

The ORU temperature response throughout the orbit at a given solar beta angle is established by the interrelationship of the hardware thermal design, the vehicle flight attitude, altitude, orbit position, surrounding structure, and position of solar arrays and thermal radiators which in turn establish the orbital heating from Solar, Albedo, and Earth Infrared (IR) on the exterior of the hardware. The ISS encounters a solar beta angle ranging from -75 to +75° based on the orbit inclination 51.6° and a solar flux in Low Earth Orbit (LEO) ranging from 1321 to 1423 W/m^2. The ORU design for nominal on-orbit operations generally cold biases the hardware, i.e., low solar absorptance and high thermal emittance surface coatings/finishes ($\alpha/\varepsilon < 1$), since the hardware must sustain the

[3] Approximated number of transfers to/from United States On-orbit Segment (USOS) via astronauts or Canadian Space Agency (CSA) Robotics

addition of electronics heating which in turn establishes cold concerns during dormant transfer operations. Hot concerns may arise from design of low thermal emittance surfaces ($\alpha/\varepsilon > 1$) or from relatively low upper temperature limits, e.g., upper limit near room temperature. These hot concerns typically occur for mechanisms, e.g., clamps, brackets, grapple fixtures, and rarely seen in ORU designs. Certain ORUs fall into the mechanism category as they are comprised of mechanical components, e.g., motors, pumps, accumulators, but also contain electronics and subject to similar temperature limits of an electronic ORU. For this paper, the ORU cold problems will be highlighted.

Figure 1
https://spaceflight.nasa.gov/gallery/images/station/crew-27/hires/iss027e036656.jpg

II. Planning

Transfer operations are generically planned during the hardware design phase. At this point, the transfer may show acceptable response time to protect thermal limits without contingencies applied to the installation timeline. As the actual event approaches, a more in-depth timeline becomes available and the thermal assumptions are revisited to indicate acceptability of the timeline, to provide contingency capabilities, and/or relief of restrictive constraints identified during the design phase. For example, restrictions in the exposure time of the hardware at the installation/worksite may be relaxed based on a more favorable thermal environment, i.e., not at worst-case conditions.

The majority of the information required for transfer operations is provided by the Mission Control team including a timeline of events. During the design phase, the timeline is evaluated for temperature response under worst-case conditions, which may include solar beta angle, solar flux, assumptions for positioning of solar arrays and central thermal radiators, positioning of intermediate transfer locations, and/or extreme flight attitude/orientation, i.e., corner of the Yaw-Pitch-Roll (YPR) envelope. As the specific date of the event approaches, these parameters become better established, and the updates in the analysis typically provide an improvement in the temperature response, thus the Mission Control team can better plan the transfer, and the updated thermal capability provides an awareness to contingency responses. There are instances of changes to the plan causing a critical decrease in thermal capabilities where the ORU temperatures fall below limits within the timeframe of the installation. In these cases, an iterative process between NASA engineering and the Mission Control teams is performed to seek a solution. An example includes locking of solar arrays/central thermal radiators that cause shadowing of the ORU, where an alternative angle is sought to improve the overall thermal environment for the transfer operation.

Additionally, the ORU transfer may impact other systems on ISS upon removal/power-down of the hardware. These include impacts by stopping of active thermal control flow to systems during a pump shutdown, and/or the power feed to adjacent/downstream loads during change-out of electrical equipment. Power is generally removed just prior to egress for an EVA or just prior to grappling the ORU for an EVR operation. The thermal response for these power-downs are separately determined from the transfer analyses and integrated as part of the operational timeline. Additional specifics for EVA and EVR planning for transfers are included in the following paragraphs.

A. EVA Operations

EVA operations are initialized from the ISS Airlock where the crew may egress with the ORU being activated or may retrieve the ORU from a specific location on ISS or from a visiting vehicle. Present-day aboard the ISS, EVA retrieval from a visiting vehicle is rarely performed, though in the assembly sequence of ISS was regularly executed from the Space Shuttle Payload Bay. For typical operations, the Replacement or "new" ORU is taken to the installation or worksite, stowed temporarily while the existing ORU is removed, and the new ORU is replaced at the worksite. The R&R may take as little as 1 hour and up to 6 hours for small to midsize ORUs. Thermal protection is generally required for the transfer in the form of uniquely designed thermal cover or a beta cloth with multi-layer insulation (MLI) transfer bag. The thermal protection doubles as a guard to mitigate scratching or unwanted contact of the hardware during the transfer. For smaller ORUs, the astronaut may perform other tasks prior to the R&R and the translational route needs to be well defined for determining thermal impacts. For larger ORUs where the EVA may span over several days, the R&R may require temporary stowage (temp-stow) of the Return ORU prior to retrieval of the Replacement ORU. Figure 2 shows the transfer of a camera and light ORU by astronaut Robert L. Curbeam Jr. (red stripe on suit leg). The large transfer bag is visible on the back of European Space Agency's (ESA) astronaut Christer Fuglesang on the right.

For EVA operations, thermal capability is defined with transfer clocks, to/from the installation/extraction location and in the vicinity of the worksite. At the worksite the ORU may become uncovered by removing it from a transfer bag or removal of a design cover for the transfer, thus causing a change in the thermal environment and increase in the temperature decay rate for the hardware. In the same manner the ORU removed from the operational location may require protection for the return, e.g., to the ISS Airlock. The Return ORU is removed near the time of Airlock egress by the astronaut or as the thermal capability allows, and similarly, for the Replacement ORU when retrieved from an external location. The thermal clocks are stopped when the ORU is thermally protected, typically via heaters, operational power, or returned to the ISS Airlock.

Figure 2
https://spaceflight.nasa.gov/gallery/images/shuttle/sts-116/hires/s116e05983.jpg

Contingencies are typically covered by the thermal analysis results in the calculation of a thermal clock or time-to-limit (TTL). The difference between the time-to-limit and the planned task timeline establishes the margin for contingency. Contingencies may include difficulties in removal or installation of the ORU, restart of systems to enable heaters and/or operational power, and/or delays during loss of signal between the ISS and ground controllers.

In the event the predicted temperatures exceed limits over the nominal timeline, then modification to hardware, ISS system controls, and/or timeline must be made to ensure proper installation and activation of the hardware. For the hardware, this could include a protective blanket/transfer bag. ISS system controls may include alternate positions of solar arrays and/or central thermal radiators. The timeline may require adjustments to when the ORU is removed, the translation path, orbital timing of the event, i.e., sun-pass, and/or perform the operation in a favorable solar beta regime. Generally, the translation path is set, the orbital timing and awaiting a favorable solar beta is avoided due to the time constraints and scheduling of EVA tasks. Orbital timing is not a preference since the transfer operation can take several orbits. Therefore, the preferred options typically pursued are design of or use of existing transfer bags, modifications to array plans, and/or reducing the timeframe when the ORU can be removed.

B. EVR Operations

Similarly, for EVR operations, the Replacement ORU is retrieved, taken to the worksite, the existing Return ORU is removed, and swapped at the installation site with the Replacement ORU. The Return ORU is transferred back to the retrieval or an alternative location, e.g., Japanese Experiment Module (JEM) Airlock. Due to the implicit nature of the hardware design, thermal protection is purely passive and rarely reliant on removable protective thermal covers. The details of robotic joint angles are typically unavailable during the design phase and intermediate locations are selected using a worst-case orientation or known stop-points during the transfer. The worst-case orientation is based on engineering judgment, e.g., space-pointed, and the stop-points may be selected to capture an arbitrary orientation along the translation path, again using engineering judgment to discern the capabilities of the hardware against the timeline. Heaters may be designed and operable using the Space Station robotic arm (SSRMS), via EVR compatible power feeds.

For certain EVR procedures where the ORU is placed at the outermost locations on the truss or dealing with multiple ORUs, the transfer operations can occur over the course of days, and an overnight park (ONP) location is established, see Figure 3. Power may or may not be available at the ONP position(s) dependent on the design features of the ORU. The ONP is a benign thermal environment which may be determined during the design phase, and/or confirmed at the time of the event with details of robotic joint angles. The ORU is located by Earth-pointing critical areas of the hardware and not pursuing a sun-pointed orientation as a function of solar beta which adds complications to the flight products. The Earth-pointed approach allows for a single operational solution across the solar beta range with the vehicle being in LVLH attitude.

Figure 3
https://spaceflight.nasa.gov/gallery/images/station/crew-27/hires/iss027e016182.jpg

Similar to EVA operations, thermal capability for EVR operations are defined with transfer clocks, to/from the installation/extraction location and in the vicinity of the worksite. The thermal clocks are stopped when the ORU is thermally protected, typically via heaters, operational power, or option to return in the JEM Airlock. A recovery time is required for heater operation to attain an elevated temperature level and readied for the next transfer phase. A recovery time may also be required for the ONP location if heaters are unavailable. Determination and types of contingency capabilities are similar between EVA and EVR.

Where temperatures exceed limits over the nominal timeline, then modification to hardware, ISS system controls, and/or timeline must be made to ensure proper installation and activation of the hardware. Any modification to the hardware would occur during the design phase. Robotically removed covers/MLI are generally not pursued. Heaters may be incorporated in the design of External Payloads to maintain temperatures above lower temperature limits at the ONP location and/or for preheating prior to transfer operations. Similar to EVA operations, the modifications to ISS system controls include positions of solar arrays and/or central thermal radiators, and the re-examination of robotic joint angles for the translation path / intermediate locations. Timelines are somewhat set for EVR operations, though scheduling the event to occur in a favorable solar beta regime is sometimes an option.

C. Combined EVA & EVR Operations

Typically, the ORU is prepositioned via EVR operations, then the EVA crew swaps the ORUs, followed by EVR operations of the removed ORU back to the primary location or an alternative location such as the Japanese Airlock for maintenance/disposal purposes. As of writing this paper, a pump swap is planned for the spring of 2018 between the outermost port location and a central pallet at the module cluster. The pump is EVR compatible at the port truss and not at the pallet, therefore the dual operation plan is to save EVA time by not having to "walk" to an extreme point on the ISS truss, 40 meters (one way).

III. Analytical Approaches and Assumptions

Key parameters in the thermal analysis include the timeline of events, the position of solar arrays and thermal radiators, location of the MT/MBS, and intermediate/ONP transfer positions. Other parameters fallout from the date specifics of the event which include solar beta angle, flight attitude, altitude, and solar flux. During the design phase these inputs are generalized by specific assumptions, e.g. MT/MBS at Worksite 4 (truss center), while others are parameterized, e.g. solar beta angle. As the event approaches, the differences in the assumed vs. the actual plan for these variables can be identified and impacts, if any, to the timeline assessed at this point. A general listing of parameters used during the design phase and the updated values available at the time of the event are provided in Table 1. A clear understanding by the thermal engineer of the hardware design is required for use of engineering judgment to narrow down the case matrix, e.g. solar beta angle at 10-20° increments, number of intermediate transfer points.

Table 1. Differences in Design and Event Specific Parameters as Applied to Detailed Thermal Analysis

Parameter	Design	Time of Event
ISS Configuration	Assembly Complete	Current Stage with associated Visiting Vehicles
Timeline	6 hours	Detailed timeline
Solar Arrays[1]	Articulating (or worst-case lock position)	Articulating or locked
Central Thermal Radiators[2]	Articulating (or worst-case lock position)	Articulating or locked
MT/MBS	Worksite 4	Worksite 1-8
Transfer Positions	Worst-case or ONP	Translation path, temp-stow and/or ONP
Solar Beta Range	-75 to +75°	Near-term range
Flight Attitude	XVV/ZLV YPR±15° (worst-case)	Actual YPR
Altitude	350 to 500 km	400 km
Solar Flux	Minimum (1321 W/m^2)	Day of event or narrow range

[1] Solar Arrays are sun-pointed / Lock position: 0 to 360° with 2 degrees of freedom
[2] Central Thermal Radiators are edge-to-sun pointed / Lock position: -90 to +90° (single axis)

A. Engineering Judgment

Engineering judgment may be used to clear the transfer of large ORUs over the timeframe of an EVA. The larger ORUs range from 400 to 800 kg with the thermal time constants for these ORUs being in excess of 24 hours, thus the capability of the hardware far exceeds the time required for the EVA, 6 to 8 hours. Detailed analysis is performed for long-term stowage, e.g., temp-stow on MT/MBS.

B. Simplified RC Computation

The simplified resistance-capacitance (RC) computation is utilized for ORUs where an extreme thermal sink is selected and the resultant value well exceeds the requirements of the timeline. Small and midsize ORUs fall into this category, with a small ORU mass being as low as 20 kg.

The calculated decay of the ORU is determined by the lumped capacitance method as follows:

$$\Delta T(t) = \Delta T_0 e^{-t/\tau} \tag{1}$$

Where: ΔT = *temperature difference,* $T(t) - T_f$ *or* $T_0 - T_f$
T = *temperature, at t, initial time (0), or final (f)*
t = *time*
τ = *thermal time constant (thermal resistance x thermal capacitance, R·C)*

The thermal resistance (R) is based on the linearized radiation term (h_R) using the temperature difference at time "t" and the final temperature (T_f), along with the heat transfer area and emissivity of the device. For a transfer bag, the emissivity used to compute h_R becomes the effective radiative emissivity (ε^*) of the insulation based on the number of layers and outer optics of the bag. The above equation is solved incrementally over time as the temperature decays causing the value of h_R to change as a function of the temperature at the next time step ($t + \Delta t$).

The final temperature, a radiative sink temperature, is based on detailed analysis results and/or use of engineering judgment from previous case sets. Flux coupons may be used within the ISS system level model to compute the orbital sink temperatures based on the ORU optical properties, with the final result calculated as an orbital averaged value. To correctly compute the orbital average temperature, the flux must be computed which is directly proportional to the absolute temperature to the fourth power, as follows:

$$\overline{T}_{average} = \sqrt[4]{\int_{x=0.0}^{1.0} \overline{T}_x{}^4} \tag{2}$$

Where: $\overline{T}$ = *absolute temperature, K*
x = *orbit position (fraction of orbit)*

The sink temperature may be based on extreme cold results from existing analysis. An orbital average value can be 60°C below the limit of the hardware, an improvement to the worst-case value in excess of 200°C below the limit. A more precise method is to determine temperatures using the ISS system level model to improve the overall capabilities for the hardware during the transfer and potentially beta regimes where the sink/ORU temperatures are above limits.

C. Detailed System Level Modeling

Detailed math modeling provides the best predictor of the thermal environment for determining capabilities during the transfer operation. This becomes much more involved to establish specific parameters necessary to execute the model case runs. For the design phase, the ISS system level model, Figure 4, may initially require certain assumptions in determining the dependents to the thermal environment, primarily where shading may occur. This could include a solar beta sweep to identify trends and noting the root cause of the minimum orbital temperatures, e.g., higher solar beta regimes causing shadowing by the module cluster with an articulating solar array. Additional studies of variables can be performed as a next step by keeping a variable fixed, e.g., locking solar array at a fixed solar beta. This reduces the number of case sets since each parameter becomes a multiplier in Table 1 with the potential of an all-encompassing matrix exceeding 10,000 computer runs. The system level model can also be used for graphical depiction of

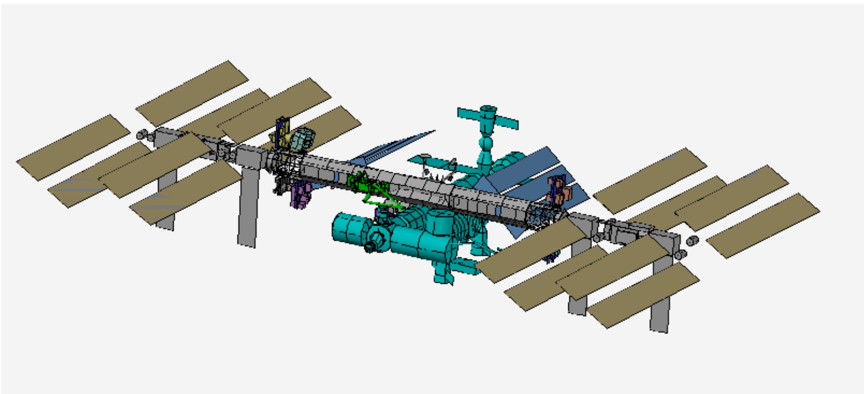

Figure 4. ISS System Level Math Model

orbital sun views and the impact of the sun exposure (or lack of sun) on the ORU over the orbit. This approach is also used to reduce the case matrix and gain understanding of impacts from structure, both fixed and rotating elements.

The intermediate transfer locations are dependent on the operational timeline, along with the design of the ORU and the resultant capabilities to sustain short-term changes in environmental temperatures, i.e., the sink temperatures. Graphic views of the transfer from the Mission Control team can align the hardware in intermediate positions without having detailed model of robotic joint angles. A direct transfer may account for investigation of a midpoint where the ORU thermal clock is relatively low, approximately 2 hours for a small ORU. Where the transfer clock exceeds the timeline, the temperatures of the ORU are initialized at point "A" and driven by the thermal environment at point "B", e.g., transfer from Dragon trunk to Columbus External Payload Facility, a distance of approximately 15 meters. Whether or not an intermediate position will need to be investigated is somewhat of an iterative process since the thermal capability is unknown at the start of the analysis efforts. The ONP locations establish a preferred location thermally and run to quasi-steady state in the analysis. Typically, the critical areas of the ORU are Earth-pointed to allow a single operational solution across the solar beta range versus a sun-pointed area which would require a solar beta dependent solution.

IV. Examples

A. Simplified RC Computation

The simplified resistor-capacitor or lump sum computation can be utilized as an initial screening approach and in some cases to compute a conservative thermal clock, i.e., the time-to-limit far exceeds the timeframe of the operation. Figure 5 provides an example of the results for a small ORU transfer operation where the thermal clocks for the Replacement ORU in the transfer bag and out of the transfer bag are combined on the graph. An example using a 2 hour in-bag thermal clock would discount the initial temperature by approximately 10°C resulting in a 15 minute decrease in the out-of-bag clock, with a final computed clock of 2 hours to install and activate the ORU. The total clock is 4 hours in this example, though there is not 4 hours of capability to transfer the ORU without the bag. Similarly the Return ORU thermal clocks can be obtained from the graph where the out-of-bag clock would be determined followed by the in-bag time. The Return ORU ΔT is more constraining than the Replacement ΔT due to initial temperature based on the environmental (install) location and associated power configuration of the hardware, e.g., only heaters enabled due to a nonfunctional (powered) unit. The Return ORU thermal limits are protected in order to refurbish the unit. There are infinite options in combination of in-bag followed by out-of-bag clocks to provide to the Mission Control team, and the data are reduced to tabular form in 30 minute to 1 hour increments, see Table 2 and Table 3. Additional data are provided in Table 3 to provide trade space in determining impacts of allowable DT to improve transfer capability.

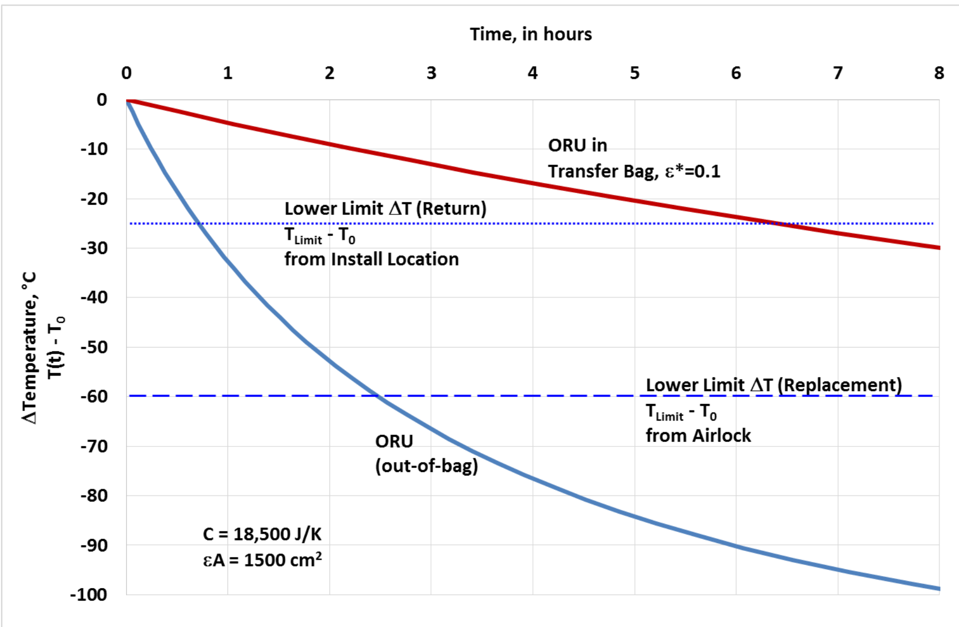

Figure 5. RC Example - Thermal Response for small ORU

Table 2. RC Example - Replacement ORU Thermal Capability

In-Bag (hrs)	Out-of-Bag (hrs)
0	2.5
1	2.4
2	2.3
3	2.1
4	2.0

Table 3. RC Example - Return ORU Thermal Capability v. Allowable Temperature Difference, ΔT from Limit

Allowable ΔT (°C)	Out-of-Bag (hrs)	In-Bag (hrs)
-25	0.75	0
-25	0.5	1
-30		2
-35		3
-40	1	1
-45		2
-50		3

B. Detailed System Level Modeling

Detailed level modeling is utilized to better predict temperatures during the transfer operation. Figure 6 depicts the geometric math model of an unpowered midsize ORU transfer from a central located pallet to the central truss location where the ORU (in red) is positioned in an intermediate transfer and ONP location. Table 4 provides the temperatures across the analyzed solar beta range from -60 to +60° (β > 60°, absolute, was not considered for this operation between engineering and Mission Control planners). The data indicate the ONP position thermally acceptable, and temperatures below the hardware limit by 7°C (ΔT) at the intermediate locations. The intermediate location is somewhat arbitrary since the ORU is in a fixed location relative to the vehicle, and conversely, the ORU could also see the maximum temperature in the Table 4. The likelihood of the ORU being at the worst-case or the best-case thermal environment is considered low based on engineering judgment, therefore, the location of the ORU in the selected location provides a means to establish a thermal clock for the transfer applied across the solar beta range. Figure 7 shows the decay curve for the ORU, establishing a time-to-limit of 8.25 hours and is within the nominal timeline of approximately 2 orbits (3 hours) for this phase of the transfer operation.

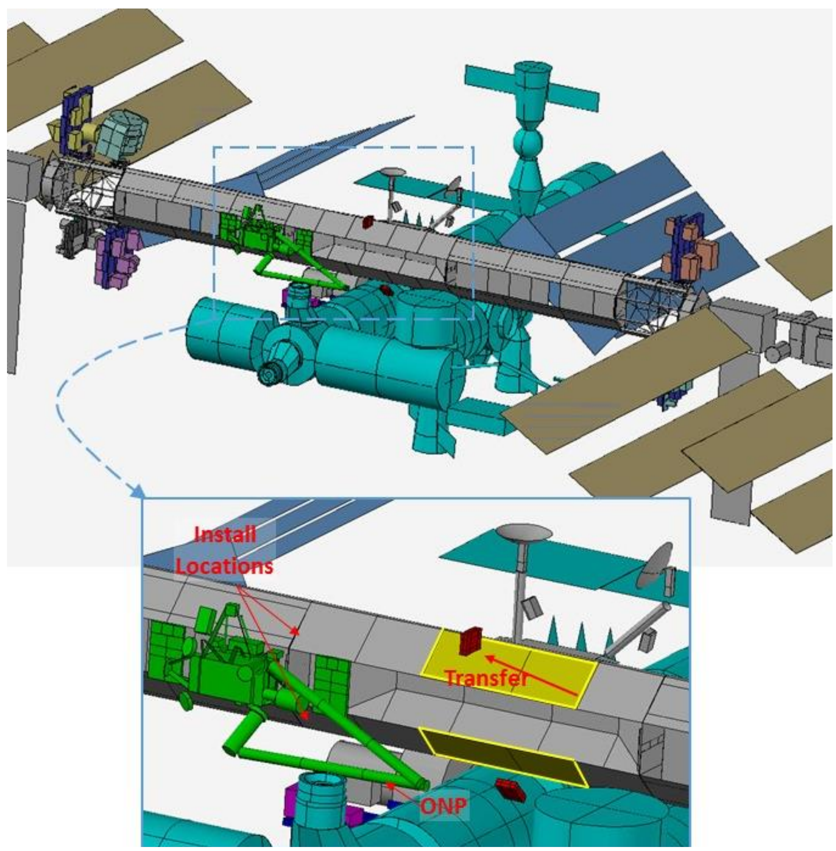

Figure 6. Detailed Modeling Example - Integrated ORU Model for Transfer Analysis

Table 4. Detailed Model Results Example - Minimum Orbital Temperature Margin, ΔT from Limit

Solar Beta Angle (degrees)	ONP (°C)	Transfer (Intermediate, °C)
-60	16	-7
-45	19	-4
-30	22	-3
-15	27	-4
0	32	-2
15	36	29
30	35	46
45	25	56
60	34	71

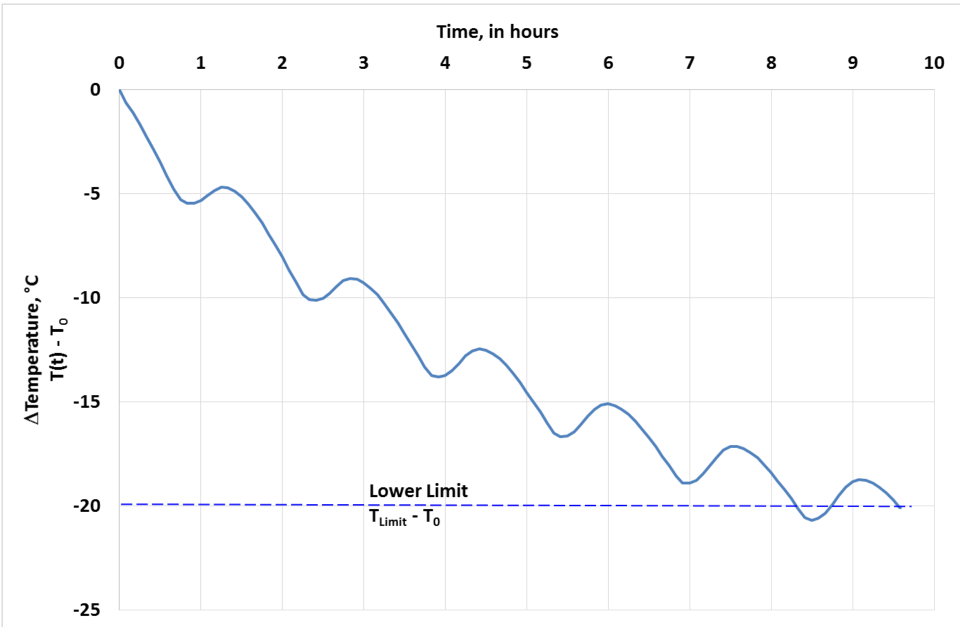

Figure 7. Detailed Model Results Example - Transfer Capability at Intermediate Location

V. Conclusion

An overview of the thermal aspects in planning EVA and EVR transfer operations are provided in this report. Options to improve thermal capabilities are outlined which include event specific details, changes to ISS system controls, and/or addition of protection via thermal insulation for EVA or heaters for EVR operations. Also, included are descriptions of the analytical approaches and assumptions, along with examples of results. The techniques outlined in this paper are still in use for planning and execution of hardware transfers on ISS, and these techniques are applicable to future space exploration for both robotic and crew based missions.

References

[1]TBD