48th International Conference on Environmental Systems
8-12 July 2018, Albuquerque, New Mexico

ICES-2018-43

Analysis Approach to Predict Condensation on International Space Station (ISS) Docking Systems

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When thermal analysis showed that interior temperatures of the NASA Docking System Block 1 (NDSB1) that will be used by future visiting vehicles of the International Space Station (ISS) could be lower than the air dewpoint temperature during the initial post-docking phase, a method was developed to evaluate the worst-case impact and design verification approach. This analysis was performed in three phases. In phase 1, the Boeing Passive Thermal Control Systems (PTCS) Team performed a thermal analysis using an integrated ISS model to determine the interior component transient temperatures. Using this data, Phase 2 was executed by the Boeing Environmental Control and Life Support (ECLS) team to determine the amount of water that could condense, its distribution over the various surfaces, and the amount of time required for it to evaporate. Rather than performing a complicated computational fluid dynamic (CFD) analysis that would have impacted design schedules, the problem was simplified by making conservative assumptions, and a spreadsheet was used to perform the calculations. The results, which are intentionally conservative for both the duration and amount of exposure to water, were then evaluated in Phase 3 by the Boeing Materials and Processes (M&P) team to determine if corrosion or other degradation would result, and if so, advise how to address material compatibility issues. The purpose of this paper is to discuss the analysis method for determining the locations, quantity, and durations of condensation exposure on the internal surfaces of NDSB1. A detailed discussion of Phase 3 is beyond the scope of this paper.

Nomenclature

A_i = Area of surface *i* (m^2)
$A_{Exposed}$ = Total surface area exposed to airflow (m^2)
A_{Total} = Total surface area within the vestibule (m^2)
CCV = Commercial Crew Vehicle
CFD = Computational Fluid Dynamics
$\mathrm{D_H}$ = Hydraulic diameter (m)
H_D = Saturation humidity ratio at dewpoint (kg of water per kg of dry air)
H_i = Saturation humidity ratio at surface temperature *i* (kg of water per kg of dry air)
h_{fg} = Heat of vaporization (kJ/kg)
IDA = International Docking Adapter
IMV = Intermodule Ventilation
ISS = International Space Station
m_{Air} = Mass of air at pressurization (kg)
M&P = Materials and Processes

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$\dot{m}_{evap(i)}$ = Rate of evaporation of water from surface *i* (kg/s)

m_i = Total mass of condensation collected on surface *i* (kg)

$\dot{m}_{IMV}$ = Mass flow rate of water vapor entering the vestibule during IMV flow (kg/s)

m_p = Total mass of water in vestibule at pressurization (kg)

m_{p_NDSB1} = Total mass of water accumulated by NDSB1 system after hatch opening (kg)

m_{pc} = Total mass of water accumulated per NDSB1 component after hatch opening (kg)

m_{pi} = Mass of water on surface *i* at pressurization (kg)

MW_{Air} = Molecular weight of air (kg/mol)

μ = Dynamic viscosity of fluid (air) (Pa · s)

NDSB1 = NASA Docking System Block 1

p_a = Saturation vapor pressure at the temperature of the air (kPa)

p_D = Saturation vapor pressure at dewpoint temperature of the ambient air (kPa)

PMA = Pressurized Mating Adapter

P_p = Air pressure after pressurization

PTCS = Passive Thermal Control System

R = Ideal gas constant (J/(mol•K))

ρ = Density of fluid (air) (kg/m^3)

SCS = Soft Capture System

T_{Air} = Air temperature at pressurization (K)

T_D = dewpoint temperature (K)

t_{Di} = Amount of time after the hatch is open that surface *i*’s temperature remains below the dewpoint (minutes)

t_{di} = Amount of time surface *i* was exposed to condensation (s)

t_{dR} = Maximum allowable time of exposure to condensation (s)

T_i = Temperature of surface *I* (K)

v_i = Air speed over surface *i* (m/s)

V = Internal volume of the vestibule (m^3)

$\overline{V}$ = Average velocity of fluid (air) (m/s)

VV = Visiting Vehicle

YPR = Yaw, Pitch, and Roll rotation sequence (°)

I. Introduction

IN the process of designing the NASA Docking System Block 1 (NDSB1), it became apparent that condensation could occur during the initial post-docking phase in the worst-case flight attitude/beta angle combinations. Because this was discovered late in the design cycle, the impacts of this needed to be known quickly and inexpensively. Engineers needed to know how much water would condense, where it would condense, and how long it would be present. A detailed Computational Fluid Dynamics (CFD) analysis would yield the most precise results but would incur large costs and delays. So instead of determining how much condensation would actually occur, the problem was bounded by determining a worst case scenario. This paper discusses the analysis method and results. The analysis was performed in three phases. Phase 1 was to determine the temperature profiles during the initial hours after docking, and was performed by the Passive Thermal Control System (PTCS) team. That data was used in Phase 2 by the Environmental Control and Life Support (ECLS) team to determine the location and quantities of condensation and the amount of time required for the condensation to evaporate. The analysis then entered Phase 3, where the Specialty Engineering team used the results of the ECLS analysis to perform a materials compatibility assessment and determine the maximum allowable wet time.

The NDSB1 is an active docking device that will be installed in future Commercial Crew Vehicles (CCV's), also called Visiting Vehicles (VV's) used for missions to ISS. The International Docking Adapter (IDA) is the passive docking device companion installed on the ISS Pressurized Mating Adapter. NDSB1 mates to the Internal Docking Adapter (IDA), which is attached the Pressurized Mating Adapter (PMA). Together, NDSB1, IDA, and the PMA comprise the vestibule.

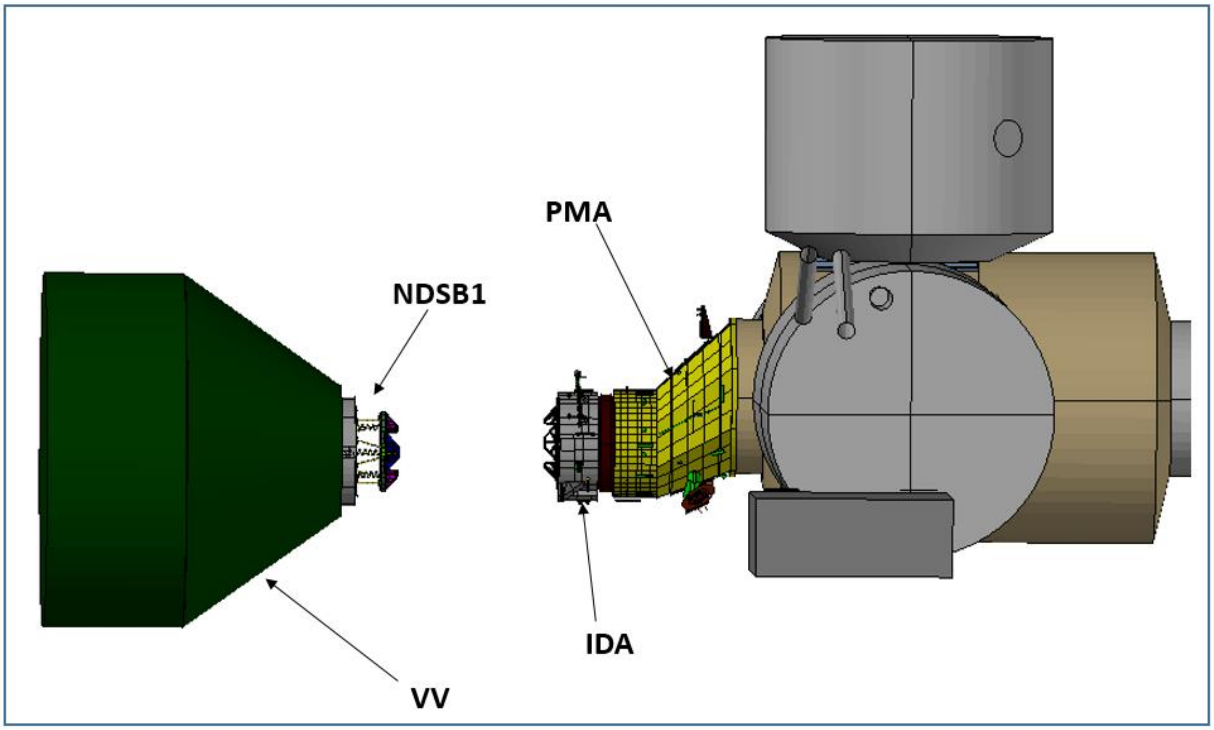


Figure 1. Depiction of Visiting Vehicle, NDSB1, IDA, and PMA prior to Docking

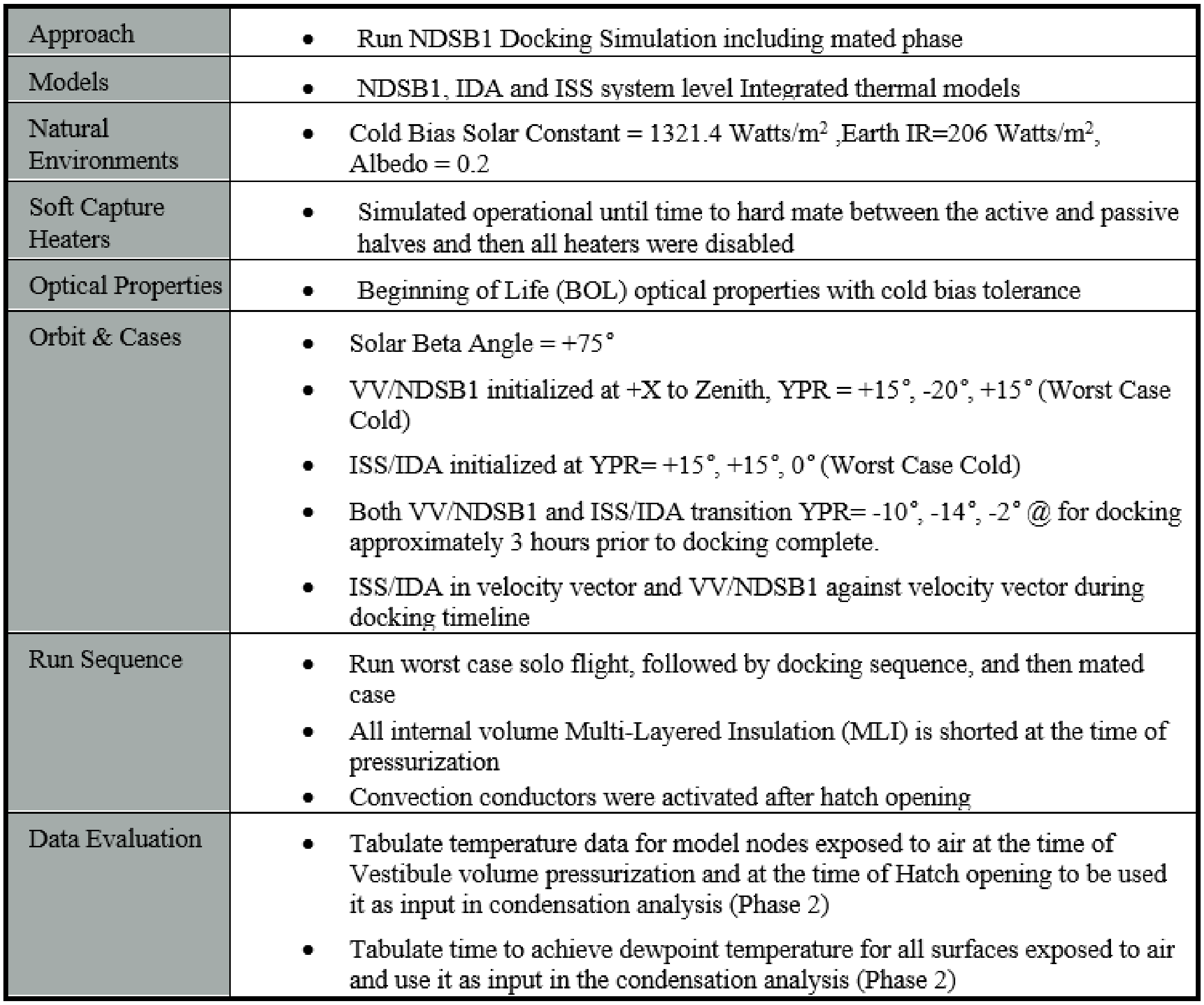
Condensation will occur on NDSB1 during pressurization and ingress on internal surfaces whose temperatures are below the dewpoint temperature prior to pressurization. (Hereafter, the dewpoint temperature will be referred to as the "dewpoint" for brevity, although it is also a function of pressure.) Following the completion of hard mate, the NDSB1 Soft Capture System (SCS) heaters will be turned off while the IDA heaters remain operational. The temperature rise rate will be a function of the internal conditions provided by the ISS/IDA and the VV. Per the IDA Concept of Operations[1], the IDA/NDSB1 vestibule volume will be pressurized within a number of minutes after the completion of docking. At this point, several surface temperatures will remain below the dewpoint, but the amount of condensation possible is limited by the moisture contained in the small volume of conditioned air in the enclosed volume. At ingress, Intermodule Ventilation (IMV) flow begins and provides a continual stream of moisture in the form of water vapor in the vestibule, which increases the amount of condensation collected on surfaces whose temperature is below the dewpoint. The IMV airflow also increases the temperature increase rate of the components because the cabin air is warmer than the component temperatures. Condensation will continue to collect on a surface until the surface's temperature climbs above the dewpoint. Once the dewpoint is exceeded, the liquid water on that surface begins to evaporate. Based on the materials exposed to condensation, the M&P team determined a maximum allowable duration of exposure, t_{dR}, that will not shorten the useful life of NDSB1.

II. Phase 1: Thermal Analysis

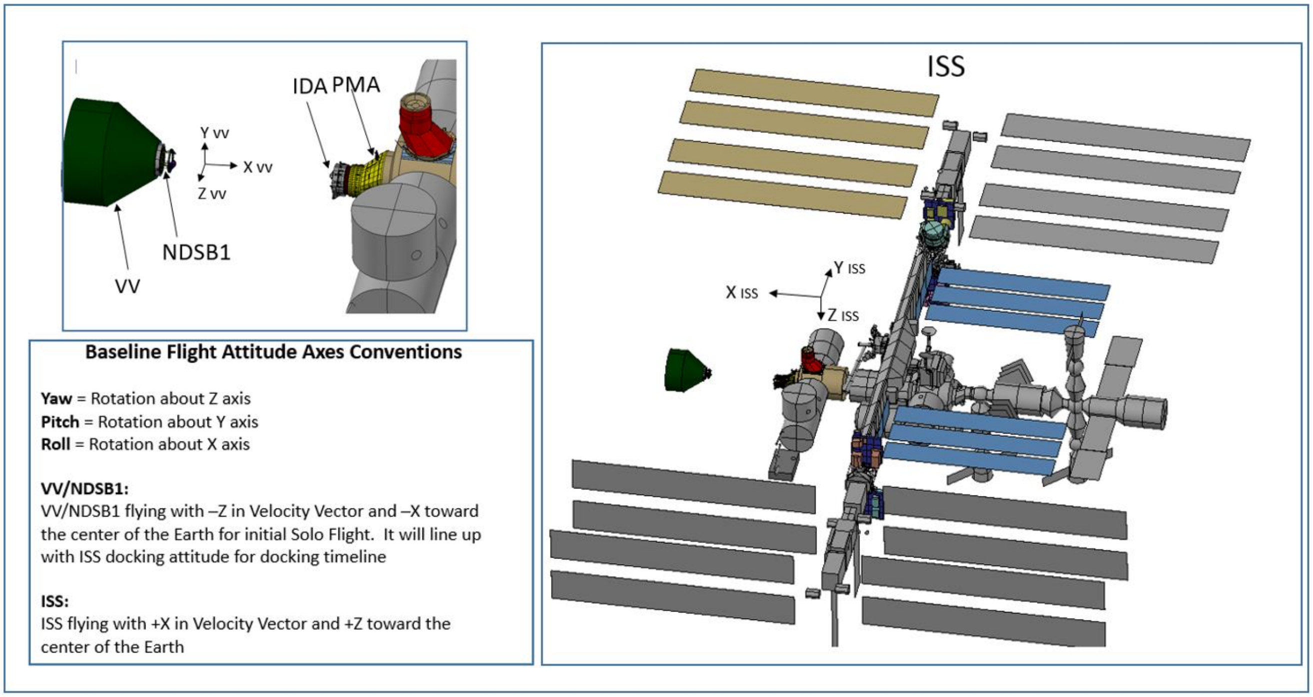
A thermal analysis was performed using the detailed NDSB1 system level thermal model combined with IDA and ISS thermal models. The analysis simulated the docking timeline including NDSB1 heat loads prior to mating to get initial temperatures and followed by the temperature response of the hardware after mating, including determination of the surfaces time to reach dewpoint for worst case cold environmental conditions. Table 1 gives the analysis assumptions. These assumptions were based on worst case previous predictions for both IDA and NDSB1 in support of design and reflect docking parameters in order to achieve conservative cold environmental conditions. However, these assumptions do not necessarily reflect any specific Visiting Vehice (VV) flight orientation assumptions. Thermal Desktop was the software used for the analysis. Figure 2. shows the Thermal Desktop geometric model overview and ISS and NDSB1/VV flight orientation angle of rotation conventions.

Table 1 PTCS Analysis Assumptions and Process

Natural Environments and ISS/VV orientation parameters resulting in conservative cold conditions.



Approach	• Run NDSB1 Docking Simulation including mated phase
Models	• NDSB1, IDA and ISS system level Integrated thermal models
Natural Environments	• Cold Bias Solar Constant = 1321.4 Watts/m^2 ,Earth IR=206 Watts/m^2, Albedo = 0.2
Soft Capture Heaters	• Simulated operational until time to hard mate between the active and passive halves and then all heaters were disabled
Optical Properties	• Beginning of Life (BOL) optical properties with cold bias tolerance
Orbit & Cases	• Solar Beta Angle = +75° • VV/NDSB1 initialized at +X to Zenith, YPR = +15°, -20°, +15° (Worst Case Cold) • ISS/IDA initialized at YPR= +15°, +15°, 0° (Worst Case Cold) • Both VV/NDSB1 and ISS/IDA transition YPR= -10°, -14°, -2° @ for docking approximately 3 hours prior to docking complete. • ISS/IDA in velocity vector and VV/NDSB1 against velocity vector during docking timeline
Run Sequence	• Run worst case solo flight, followed by docking sequence, and then mated case • All internal volume Multi-Layered Insulation (MLI) is shorted at the time of pressurization • Convection conductors were activated after hatch opening
Data Evaluation	• Tabulate temperature data for model nodes exposed to air at the time of Vestibule volume pressurization and at the time of Hatch opening to be used it as input in condensation analysis (Phase 2) • Tabulate time to achieve dewpoint temperature for all surfaces exposed to air and use it as input in the condensation analysis (Phase 2)



Baseline Flight Attitude Axes Conventions

Yaw = Rotation about Z axis
Pitch = Rotation about Y axis
Roll = Rotation about X axis

VV/NDSB1:
VV/NDSB1 flying with –Z in Velocity Vector and –X toward the center of the Earth for initial Solo Flight. It will line up with ISS docking attitude for docking timeline

ISS:
ISS flying with +X in Velocity Vector and +Z toward the center of the Earth

Figure 2 Thermal Model Overview and Flight Orientation Description Conventions

Figure 3 shows the thermal profile of the hardware surfaces at vestibule volume pressurization. The data is presented as the ratio of T_i / T_D with absolute units used for the calculations, where T_i is the temperature of surface "i" and T_D is the dewpoint temperature. A ratio of 100% or greater indicates that the surface reached or exceeded the T_D. Because the ratios are calculated using absolute temperature, the difference in percentages can be misleading. A 1% difference in the temperature ratio could reflect a difference of several °C. At the time of vestibule volume pressurization the petals and ring temperature ratios were as low as 93%of the dewpoint and the linear actuator MLI covers were at 94%. The tunnel wall is equal or greater than 100%, meaning that temperatures are above dewpoint. The time to reach dewpoint for each component depends on the starting temperature, mass and the thermal radiation and convection to the internal environment, plus the interaction with the radiation external environment. Some components may have a relatively warm initial temperature ratio but require longer time to reach the dewpoint due to greater mass and insulation coverage. Figure 4 shows hardware temperature surfaces at the time of vestibule volume hatch opening.

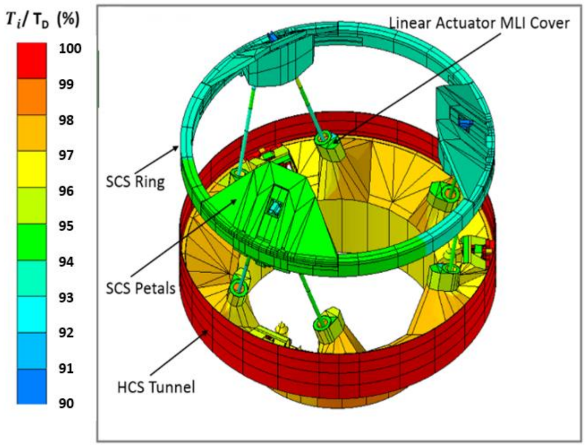


Figure 3. NDSB1 T_i / T_D (%) at Pressurization
Only the HCS Tunnel is at or above the dewpoint.

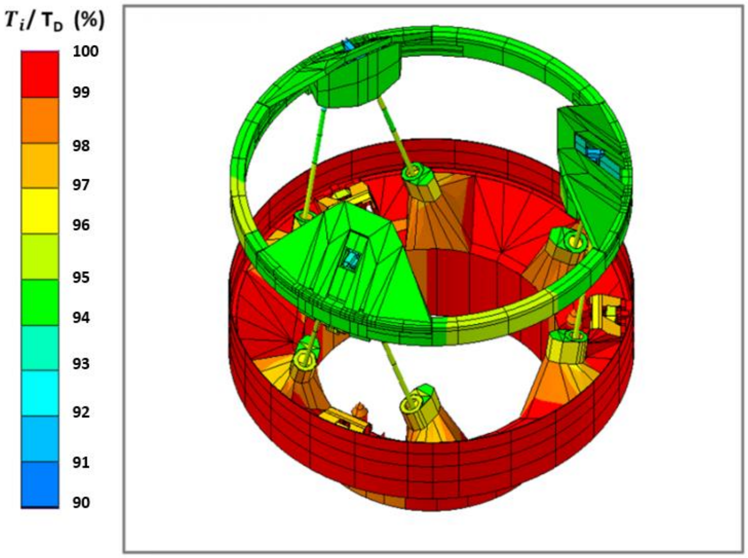


Figure 4. NDSB1 T_i / T_D (%) at Hatch Opening
Surfaces are significantly warmer, but many are still below the dewpoint.

Figure 5 shows selected key NDSB1 surfaces warm-up thermal performance trends as time increases. Data is shown as a ratio of T_i / T_D. A ratio of 100% indicates that the temperature of the surface has reached the dewpoint temperature. The surface with the slowest warm-up performance trend is the Linear Actuator Shaft Ball Screw. Thermal data was used as input for the calculation of surface accumulated condensation and resultant wet times and results are discussed in section III.

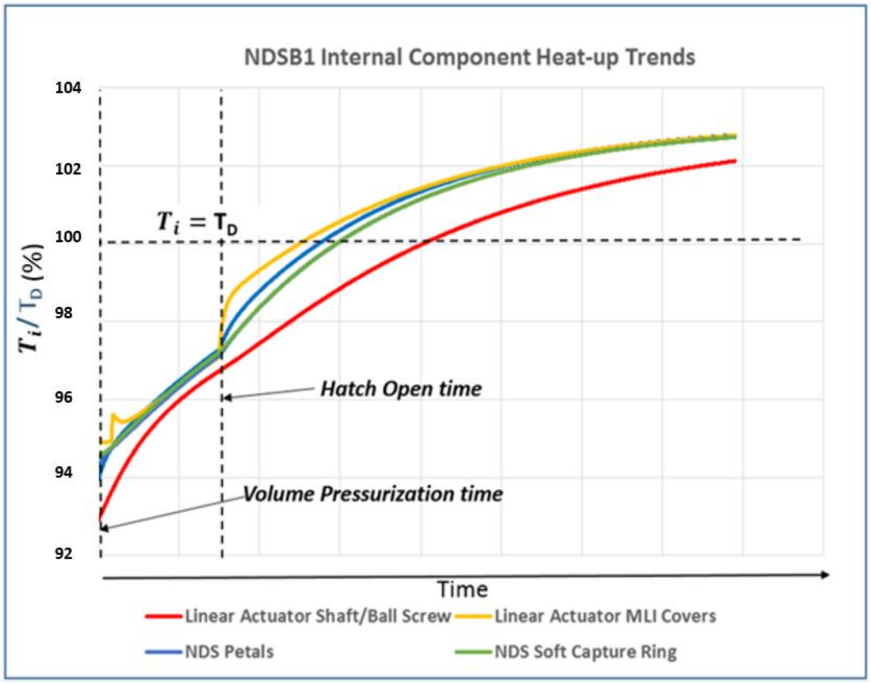


Figure 5. Temperature ratio T_i / T_D as a Function of Time for Key NDSB1 Surfaces.
T_i is the temperature of the surface under consideration, and T_D is the dewpoint temperature. Note that MLI warms quickly due to its low mass and exposure to airflow, whilc the Linear Actuator Shaft is not in contact with the airstream.

III. Phase 2: Calculating Worst-Case Condensation Quantity, Distribution, and Duration

Phase 2 can be split into 3 parts: 1) pressurization 2) Intermodule Ventilation (IMV) flow initiation, and 3) evaporation. Shortly after docking, the vestibule, which includes the International Docking Adapter (IDA), NDSB1, and the Pressurized Mating Adapter (PMA) is pressurized using air from the ISS. The dewpoint of this air is controlled to minimize condensation. For the purpose of explaining the theory, the actual value of the dewpoint is not relevant, and the dewpoint temperature will be referred to as "T_D". Similarly, the volume of the vestibule will be referred to as V, and the amount of water available to become condensation at pressurization, m_p, is limited by V and T_D. The quantity of water each surface (m_{pi}) will acquire is assumed to be proportional to its surface area and to the percent difference between the saturation humidity ratio at T_D and the saturation humidity ratio at the temperature of the surface (H_i), as is shown in Equation 3. Note that m_p was calculated using the ideal gas law, Equation 1, and the saturation humidity ratio as shown in Equation 2.

$$m_{Air} = MW_{Air} \frac{RT_{Air}}{P_p V} \qquad (1)$$

Where:

P_p = Air pressure after pressurization (Pa)

m_{Air} = Mass of air at pressurization (kg)

MW_{Air} = Molecular weight of air (kg/mol)

V = Internal volume of vestibule (m^3)

R = Ideal gas constant (J/(mole • K)))

T_{Air} = Air temperature at pressurization (K)

$$m_p = H_D \ x \ m_{Air} \qquad (2)$$[2]

Where:

H_D = Saturation humidity ratio at dewpoint temperature (kg of water per kg of dry air)

m_p = Total mass of water in vestibule at pressurization (kg)

$$m_{P_i} = m_P \left(\frac{A_i}{A_{Total}}\right)\left(\frac{H_D - H_i}{H_D}\right) \qquad (3)$$

m_{pi} = mass of water on surface *i* at pressurization (kg)

A_i = Area of surface *i* (m^2)

A_{Total} = Total surface area within the vestibule (m^2)

H_i = Saturation humidity ratio at surface temperature *i* (kg of water per kg of dry air)

Prior to hatch opening, the temperatures of many surfaces are below freezing and ice formation is expected. Because the amount of water available is so small, and because the frost has a high surface- area–to-volume ratio[3] allowing fast heat transfer, the time and energy required for the frost to change phase to liquid was not considered in this analysis.

After the hatch is opened and IMV flow begins, the amount of water available to condense is no longer limited by the vestibule volume. To establish IMV flow, the crew drags an air duct from inside the PMA through the visiting vehicle. Conditioned ISS air is supplied through the duct into the visiting vehicle, and the air returns through the open vestibule body as is shown in Figure 6.

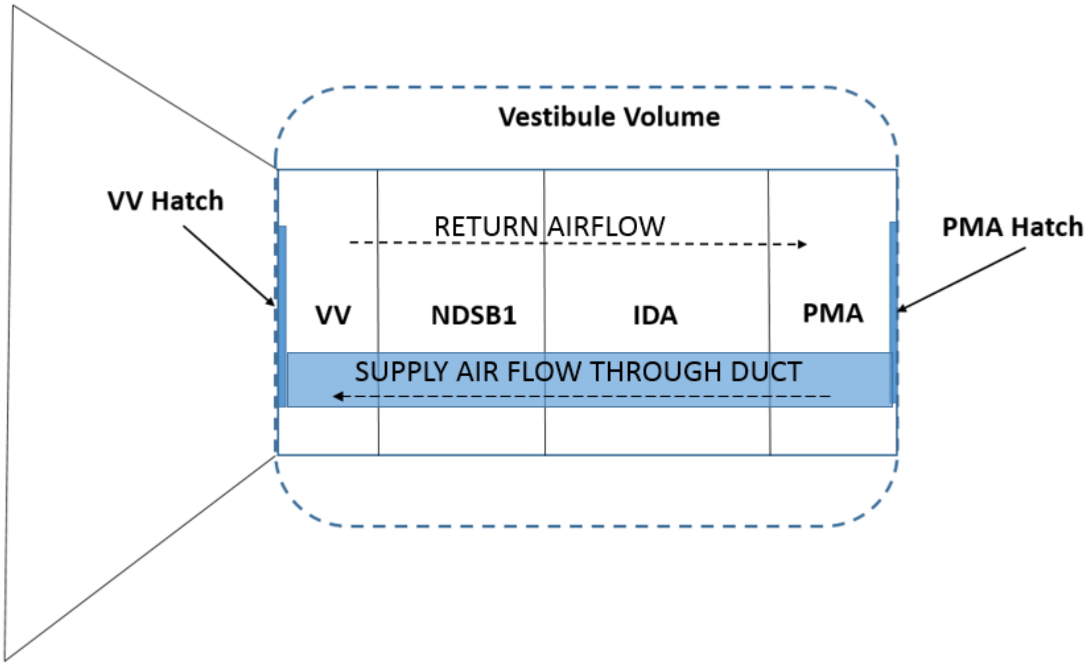


Figure 6. Schematic of Airflow through Vestibule
Air is supplied to the VV via a duct, and returns to the ISS through the open hatches.

Once IMV flow begins, volumetric flow rate replaces volume as a bounding condition, and the rate of water delivery into the vestibule can be calculated by multiplying the volumetric flow rate (m^3/hour) by the density of air at ambient temperature, then multiplied by the saturation humidity ratio. Not all of this water can realistically be assumed to be close enough to a surface to condense. Only the air that touches a surface can deposit its water, and it will only do so if the surface temperature is below T_D. Because the vestibule geometry is similar to an open tunnel with few or no obstacles in the main flow path, the amount of air that could possibly touch the surface depends on the nature of the flow. Laminar flow would only allow a thin layer of air to contact the tunnel structure, while turbulent flow would bring much more air into contact with structure. The air returns to the ISS through open hatches, and to understand the behavior of this flow, the Reynolds number was calculated using equation 4.[4]

$$\mathrm{Re} = \frac{\rho \bar{V} D_H}{\mu} \qquad (4)^4$$

Where:

ρ = Density of fluid (air) (kg/m^3)
$\bar{V}$ = Average velocity of fluid (air) (m/s)
D_H = Hydraulic diameter (m)
μ = Dynamic viscosity of fluid (air) (Pa · s)

For conservatism, since the vestibule volume channel has sections with variable diamaters, the hydraulic diameter was taken to be the largest diameter of the NDS and the smallest diameter was assumed in calculating the average velocity. The resulting Reynolds number was 3.8×10^5, indicating turbulent flow. In turbulent flow, the air velocity profile is chaotic and cannot be assumed to be uniform along the length of the tunnel, and for conservatism, 50% of the air was assumed to contact the structure. Using the specific volume of water vapor at T_D, the mass flow rate of water into the vestibule was calculated to be $\dot{m}_{IMV}$. The total amount of water deposited on a fully exposed surface below T_D was then calculated via equation 5, which conservatively assumes that the surface temperature (T_i) remains constant throughout (t_{di}), the time required for the surface to reach the dewpoint. The temperatures used in this equation are in absolute units.

$$m_i = \dot{m}_{IMV} \left(\frac{A_i}{A_{Exposed}}\right)\left(\frac{H_D - H_i}{H_D}\right) t_{Di} + m_{pi} \qquad (5)$$

Where:

m_i = total mass of condensation collected on surface *i* (kg)

$\dot{m}_{IMV}$ = mass flow rate of water vapor entering the vestibule during IMV flow (kg/s)

A_i = area of surface i (m^2)

$A_{Exposed}$ = Total surface area exposed to airflow (m^2)

H_D = Saturation humidity ratio at dewpoint (kg of water per kg of dry air)

H_i = Saturation humidity ratio at surface temperature *i* (kg of water per kg of dry air)

t_{Di} = amount of time after the hatch is open that surface *i*’s temperature remains below the dewpoint (minutes)

m_{pi} = mass of water on surface *i* at pressurization (kg)

It is important to note that not all surfaces are fully exposed to the airstream. Many are fully or partially concealed behind other surfaces and the assumption that they will collect condensation at the same rate as surfaces directly in the airstream is unrealistic. To address this, each surface was categorized as either fully exposed, partially exposed, or not exposed, and the calculation of their water collection rates was adjusted accordingly. The amount of condensation on unexposed surfaces was assumed not to increase as a result of the IMV flow, and $m_i = m_p$. Partially exposed surfaces were assumed to adsorb condensation at a rate proportional to the percentage of the area that is exposed.

Once a surface temperature reaches the dewpoint, evaporation is assumed to begin. Calculating the evaporation rate was less intuitive and required the use of equation 6, which was empirically derived and taken from the 2012 ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers) Handbook[5]. Note that the units used in the calculation must match the units specified for the equation. Values for p_a and p_D were taken from the Moran and Shapiro text.[2]

$$\dot{m}_{evap(i)} = \frac{A_{i(0.0887+0.07815 v_i)}}{h_{fg}}(p_a - p_D) \qquad (6)^{5}$$

Where:

$\dot{m}_{evap(i)}$ = rate of evaporation of water from surface *i* (kg/s)

A_i = area of surface i (m^2)

h_{fg} = heat of vaporization (kJ/kg)

p_D = saturation vapor pressure at dewpoint temperature of the ambient air (kPa)

p_a = saturation vapor pressure at the temperature of the ambient air (kPa)

v_i = air speed over surface i (m/s)

Note that the air speed was not specifically calculated for each surface, but instead was calculated for each of three types of surfaces: those fully exposed to the airstream, those partially exposed, and those not exposed. The air speed for a fully exposed surface was calculated by dividing the volumetric flow rate by the cross-sectional area at the point where the diameter of the vestibule is largest. Partially exposed surfaces assumed a reduction in air speed equal to the fraction of the area exposed to the airstream , and unexposed surfaces assumed an airspeed of zero.

Dividing the amount of water on a particular surface by the evaporation rate of that surface gives the amount of time for the surface to dry, and the total wet time is the sum of the time between pressurization and IMV flow initiation, the time required for the surface temperature to reach the dewpoint, and the time required for the water to evaporate.

IV. Condensation Analysis Results and Materials Assessment

The water quantities for each surface were mapped onto the model, and the results are shown in the following figures. Figure 7 shows the distribution of condensation on the NDSB1 surfaces shortly after pressurization. Note that the values in the color scale are normalized by dividing the mass of water on each surface by the total mass of water deposited in the NDSB1 surfaces during the entire docking, pressurization, and ingress process, and the scale is in percentage, meaning the ratio has been multiplied by 100. Because the hardware of interest is NDSB1, IDA and the PMA are not shown. Figure 8. shows the distribution of condensation after hatch opening. As in Figure 7, the values in the color scale is normalized.

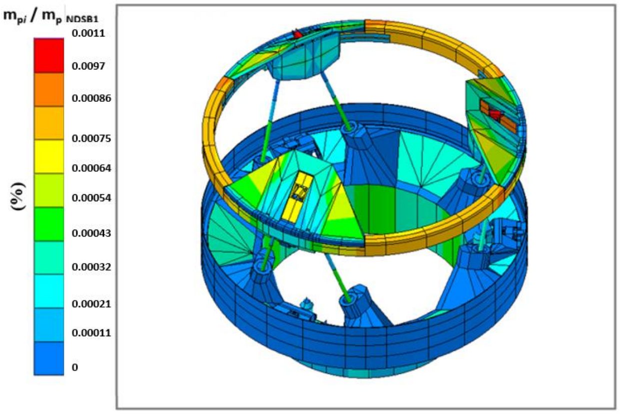


Figure 7. Distribution of condensation ratios (m_{pi} / m_{p_NDSB1}) on NDSB1 surfaces immediately after pressurization

Note that the largest amount of condensation on any one surface is less than .01% of the total amount collected.

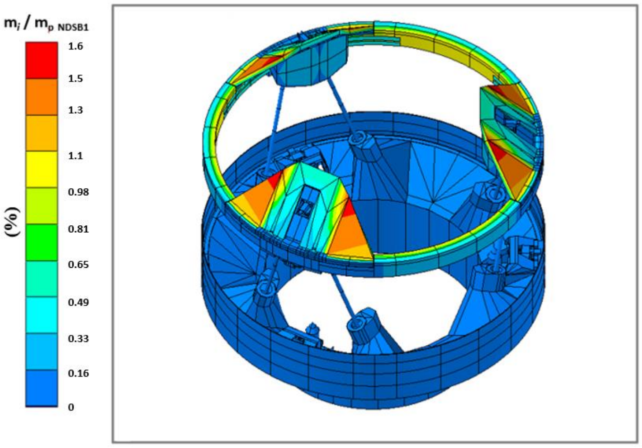


Figure 8. Distribution of condensation ratios (m_{i} / m_{p_NDSB1}) after IMV flow is established

No surface experiences more than 1.6% of the total water collected.

Table 2 shows the distribution of condensation ratios (m_p / m_{p_NDSB1}) per component after hatch opening for the most critical NDSB1 components. The sum of total condensation ratios for components highlighted in orange accounts for approximately 96% of the total condensation deposited on the NDSB1 system. It also shows the individual surface maximum time to dry ratio (t_{di}/t_{dR}) which is the amount of time required for a surface to dry divided by the maximum allowable duration of exposure to condensation. All the surfaces met the time to dry requirement with the maximum predicted time to dry ratio (t_{di}/t_{dR}) being 84% for the Linear Actuator Shaft/Ball Screw. Although the surfaces of the Linear Actuator Shaft/Ball Screw only experience 0.01% of the total condensation, the fact that they are completely sheltered from convective flow results in a slow drying process.

Table 2. NDSB1 Total condensation (m_{pc} / m_{p} _NDSB1) and surface required time to dry (t_{di}/t_{dR}) ratios
NDS Pelats dry out in 62% of the allowable wet time and experienced 50% of the total NDSB1 accumulated condensation mass.

NDSB1 Component	m_{pc} / m_{p} _NDSB1 after Hatch Opening (%)	t_{di} / t_{dR} (%)
NDS Petals	50.39	62
NDS Soft Capture Ring	23.56	59
Capture Latch Shroud	10.94	54
Linear Actuator MLI Covers	5.91	58
Heater on Soft Capture Ring	5.27	62
Linear Actuator Shaft/Ball Screw	0.01	84

Boeing Materials and Processes (M&P) reviewed the water quantities, type of material, and duration of exposure to condensation and determined that NDSB1 would not be adversely affected by this worse-than-worst-case scenario. The M&P team also determined a maximum allowable wet time, and all surfaces were dry within the allowable time. A detailed discussion of M&P's evaluation is outside the scope of this paper.

V. Conclusion

Without performing a CFD analysis, which would impact cost and design schedule, the worst-case impacts of condensation on NDSB1 were evaluated. Transient surface temperatures were determined by the Boeing PTCS team using Thermal Desktop. From the temperature profile, the Boeing ECLS team determined the quantity of condensation on each surface and the amount of time required for the condensation to evaporate. The results were compared to the maximum allowable time of exposure to condensation, which was determined by the Boeing M&P team.

VI. Acknowledgements

Special thanks to William Burt/Boeing PTCS for the assistance in thermal analysis and data post-processing and Kevin Braman/Boeing ECLS who assisted in reviewing the condensation calculation approach and also provided enhancement inputs and oversight.

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