

Investigation of Transient Performance for a Sublimator

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Sublimators have been used as heat rejection devices for a variety of space applications including the Apollo Lunar Module and the Extravehicular Mobility Unit (EMU). Sublimators typically operate with steady-state feedwater utilization at or near 100%. However, sublimators are currently being considered to operate in a cyclical topping mode, which represents a new mode of operation for sublimators. Sublimators can be used as a topper during mission phases such as low lunar or low earth orbit. In these mission phases, the sublimator will be repeatedly started and stopped during each orbit to provide supplemental heat rejection for the portion of the orbit where the radiative sink temperature exceeds the system setpoint temperature. This paper will investigate the effects of these transient starts and stops on the feedwater utilization during various feedwater timing scenarios. The X-38 sublimator and Contamination Insensitive Sublimator (CIS) were tested in a ground vacuum chamber to understand this behavior and to quantify the feedwater performance. Data from various scenarios will be analyzed to investigate feedwater utilization under the cyclical conditions.

Nomenclature

u	=	Utilization
\dot{m}_i	=	Ideal sublimation rate
\dot{m}_a	=	Actual sublimation rate
Q	=	Energy
Δh	=	Heat of Vaporization
$OAFU$	=	Orbit Averaged Feedwater Utilization
t	=	time step
$m_{reservoir}$	=	Amount of Water in Reservoir
T_{set}	=	System Set Point Temperature

INTRODUCTION

Rejecting heat is a critical requirement for any space vehicle or habitat. For certain mission scenarios, a sublimator provides an attractive option for heat rejection. For example, a sublimator can be used to supplement radiators for handling peak heat loads, or a sublimator can be used exclusively for heat rejection in warm thermal environments where the use of radiators is unfeasible. A sublimator rejects heat by using the process of sublimation, which is when a substance, such as water, changes from the solid phase directly to the vapor phase. Sublimators have been used for heat rejection in a variety of space applications, such as the Apollo Lunar Module and the Extravehicular Mobility Unit (EMU).

An example of where a thermal environment can change and reduce the heat rejection capability of a radiator is a Low Lunar Orbit (LLO). Lunar surface temperatures range from 400 Kelvin at the sub solar point to less than 100 Kelvin on the dark side as shown in Figure 1. Due to this large change in Lunar surface temperature, a vehicle's radiator is subjected to a wide variation in incident infrared fluxes. Closer to the sub solar point, the radiator is

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unable to achieve the desired set point temperature of a vehicle, therefore the vehicle must rely on a supplemental heat rejection device (SHReD) such as a sublimator or phase change material heat exchanger (PCMHX). Sublimators are considered to be the most mass efficient for short mission durations when compared to PCMHX. Figure 2 shows the radiator capability, sublimator requirement, and vehicle requirement for an example spacecraft. In this figure, the sublimator requirement is simply the difference between the radiator capability and the vehicle heat rejection requirement. For the majority of the orbit, the sublimator heat rejection requirement drops to zero due to the ability of the vehicle's radiator to reject all of the vehicle waste heat. A sublimator has never been used to provide heat rejection in a cyclic fashion. This report outlines testing performed on the full scale X-38 sublimator designed and fabricated by Hamilton Sundstrand for use on the X-38 vehicle. The sublimator test program also included the Contamination Insensitive Sublimator (CIS), which was designed and fabricated by JSC. Specifically, the sublimator feedwater consumption efficiency for various feedwater controls was investigated and will be described in this report.

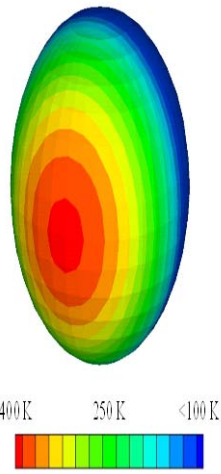


Figure 1. Spatial Temperature Distribution of Lunar Surface

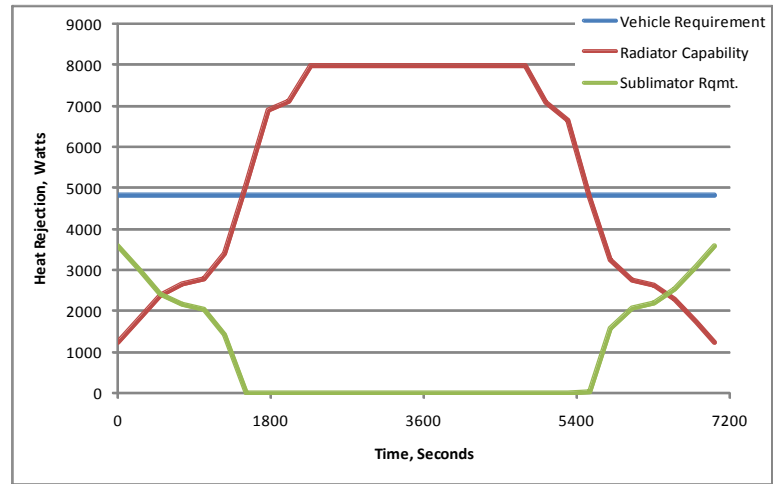


Figure 2 Radiator capability, sublimator requirement, and vehicle heat rejection requirement for an example spacecraft in Low Lunar Orbit.

SUBLIMATOR TESTING REQUIREMENTS

For this study, three architectures were investigated for sublimator implementation into a flight system. Vehicle requirements were derived using an Altair LLO heat rejection requirement of 4.8 kW, while maintaining a system return temperature, or set point temperature, of 10°C during LLO. The analysis was performed for a two-hour orbit with a beta angle of 0°, resulting in a radiative sink temperature varying between -350°F (-213°C) to 62°F (17°C) for an infrared emissivity of 0.85 and solar absorptivity of 0.1. Moreover, the radiators for this analysis were sized for lunar surface operation. Due to the large variation in sink temperatures, the outlet temperature of the coolant from the radiator varies considerably during the two hour orbit. The relatively warm sink temperature near the sub solar point results in loss of the system set point temperature, and supplemental heat rejection is therefore required by the sublimator. The following architectures outline various potential sublimator placements within a vehicle's thermal control system (TCS) to provide this supplemental heat rejection.

The objective of the current testing is to assess the performance of a sublimator when used as a SHReD under cyclical heat loads. There are several system architectures and operational options for using a sublimator in this manner. The first option investigates the sublimator response when the sublimator is installed immediately downstream of the radiator. For this architecture, coolant is constantly flowing through the sublimator during all portions of the mission. A simplified schematic of the system architecture is shown in Figure 3. The heat source is representative of all the energy acquired by the coolant loop from coldplates, cabin air heat exchanger, and other heat acquisition equipment within the vehicle. The green three-way valve is used to proportion the coolant flow so that a constant set point temperature (T_{set}) of 10°C can be maintained entering the cabin. The graph in Figure 3 shows the coolant inlet temperature and flow rate into the sublimator, which is essentially the coolant exit condition from the radiator. This plot shows that supplemental heat rejection is required approximately 50 minutes into the lunar orbit because the radiator cannot maintain the system setpoint. It is important to note that the analysis assumes

that a coolant temperature of 0°C exits the sublimator at all times. A constant bypass flow mixes with the flow exiting the sublimator to provide the aforementioned setpoint temperature.

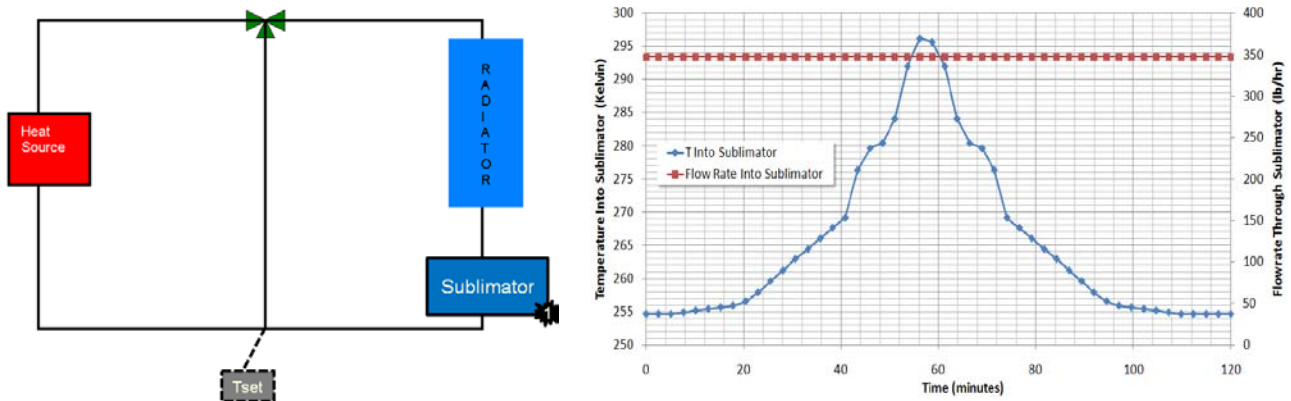


Figure 3. Sublimator Configuration 1 Schematic and Inlet Temperature/Flowrate to Sublimator (Transient Scenario 1)

The second option considered for this study included the sublimator being placed at the same location as configuration 1, but with a bypass valve around it to allow for diverting the coolant flow around the sublimator when supplemental heat rejection is not required. This results in no coolant flow through the sublimator for about 90 minutes of the two-hour orbit during which supplemental heat rejection is not needed. A schematic of this system architecture is shown in Figure 4. The schematic is essentially the same as Figure 3, with the addition of the bypass line around the sublimator. The resulting coolant inlet conditions to the sublimator are shown in the corresponding graph. During the portions where no supplemental heat rejection is needed, zero flow is sent to the sublimator since the bypass valve diverts the flow around the sublimator. During the portions where the sublimator is providing supplemental heat rejection, the flow and inlet temperature profile are the same as in configuration 1.

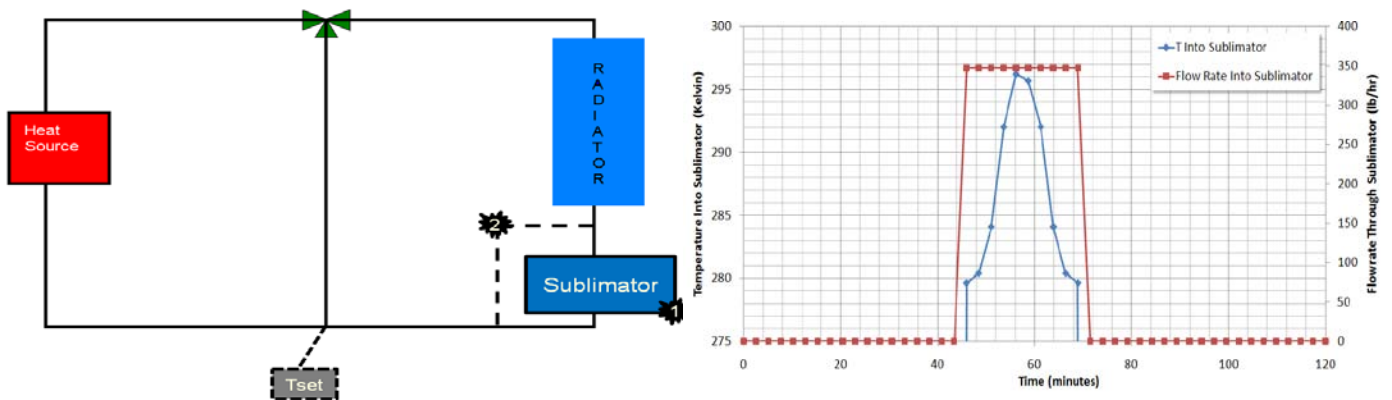


Figure 4. Sublimator Configuration 2 Schematic and Inlet Temperature/Flowrate to Sublimator (Transient Scenario 2)

A final option investigates installation of the sublimator downstream of where the radiator and bypass lines join. This third architecture allows the sublimator to be used after the radiators are detached from the flight vehicle. Scenarios when this would occur include the ascent phase of a Lunar lander, when the ascent module detaches from the descent module where the radiators are located, or when a spacecraft's reentry vehicle separates from the service module when returning to Earth (i.e. Apollo's crew module). During nominal operations, when a radiator can be used as the sole means of heat rejection, the original proportioning valve can be used to control the system set point temperature. Nonetheless, due to the fact that the set point location of the coolant loop is located after the

sublimator when a SHReD is required, another proportioning valve is required to ensure the set point temperature of 10°C is met entering the cabin. The simplified loop architecture for this configuration is shown in Figure 5. Due to the fact that the set point temperature is required to be maintained at 10°C, the flowrate through the sublimator varies with time in order to provide the proper amount of supplemental cooling. This results in a varying coolant flowrate and temperature through the sublimator for the 30 minute duration when a SHReD is needed.

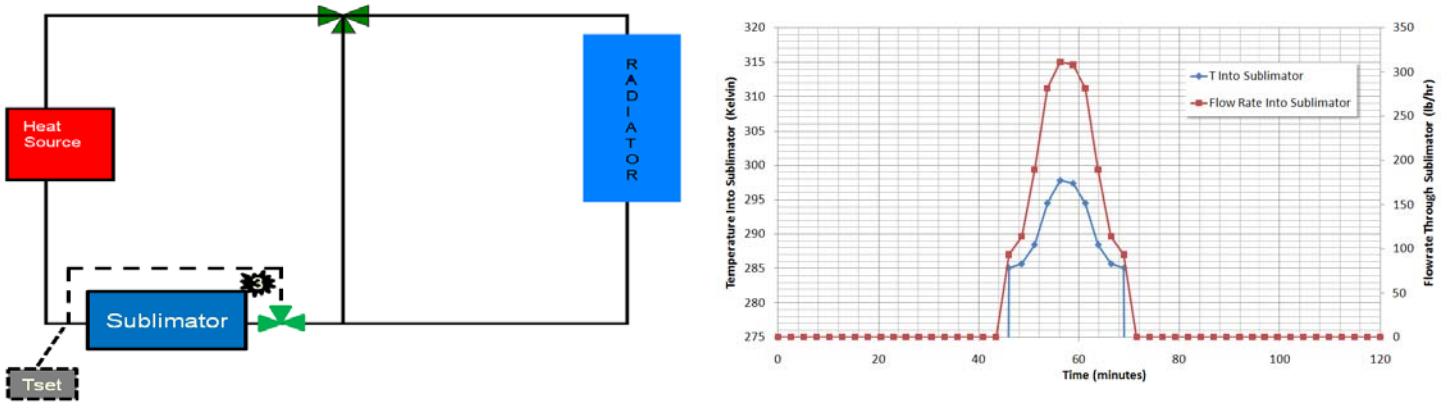


Figure 5. Sublimator Configuration 3 Schematic and Inlet Temperature/Flowrate to Sublimator (Transient Scenario 3)

These three TCS architectures were used to derive the coolant test loop architecture so that all scenarios could be tested as well as several steady state performance tests which were outlined in the test plan.

SUBLIMATOR TEST LOOP ARCHITECTURE

The test loop architecture for transient and steady state sublimator testing was based on the requirements discussed in the previous section. Figure 6 is the schematic used to assemble the coolant side of the test system for the sublimator. While the chiller was used to provide the cold coolant temperatures, the combination of a liquid/liquid heat exchanger and heater cart were used to vary the temperature into the sublimator. Three-way valve 1 and thermocouple 3 in the schematic were used to control the temperature into the sublimator while three-way valve 2 and flow meter 2 were used to control the flowrate into the sublimator. It is important to note that the cold chiller had a lower achievable limit of 263K rather than the required 255K previously discussed.

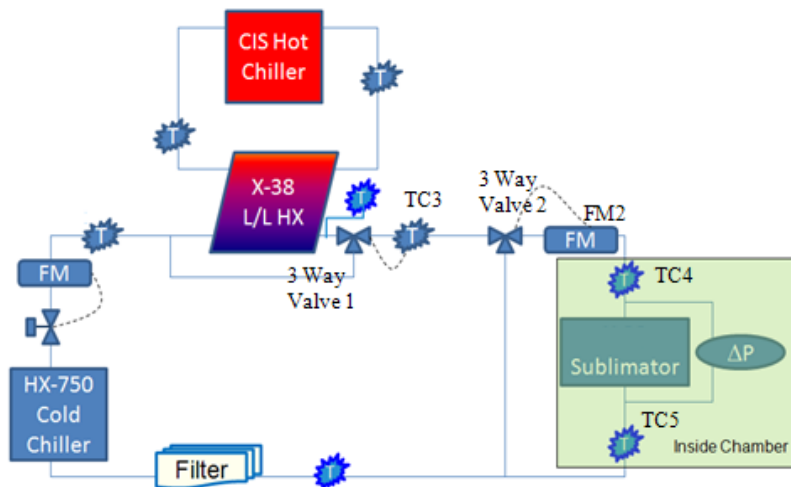


Figure 6. Coolant Test Loop Schematic for Transient and Steady State Sublimator Testing

The feedwater loop for sublimator testing is shown in Figure 7. The loop architecture is a heritage system used in previous sublimator testing. The valve titled *feedwater* in the schematic was used to supply the feedwater into the sublimator as discussed in the previous section (i.e. it was the valve that was open/closed to control the feedwater flow into the sublimator).

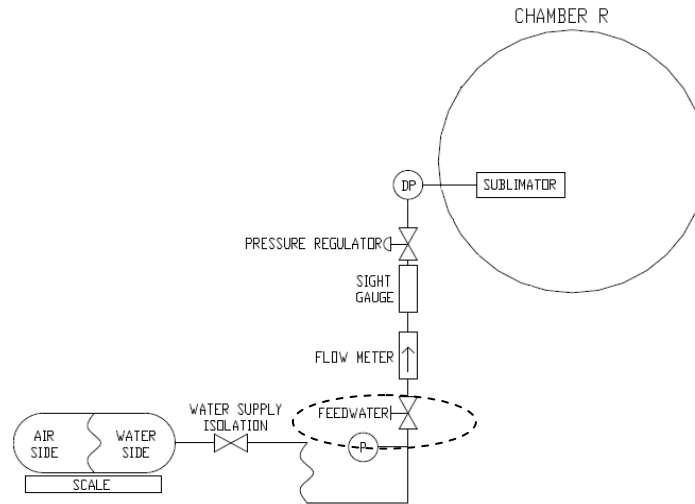


Figure 7. Sublimator feedwater schematic highlighting the isolation valve used to control feedwater flow to the sublimator.

KEY PERFORMANCE PARAMETERS AND RELEVANT INSTRUMENTATION

For the purposes of this report a few components of the test setup were deemed critical for analysis of the test data.

1. Feedwater tank scale—continuously measured and recorded the mass of the feedwater tank.
2. Thermocouples 4 and 5 – to measure the inlet and outlet coolant temperatures of the sublimator
3. Flow meter 2 – to measure the coolant flow rate into the sublimator.

Two key performance parameters were derived for the transient sublimator testing. The first of these parameters is the heat dissipation of the sublimator. Due to the cyclical characteristic of the heat load, an integrated value was calculated of the applied heat load to obtain an overall energy load over a two hour orbit. During the orbit, the sublimator is subjected to a varying heat load for about 30 minutes with the remaining 90 minutes near zero heat load. The energy heat dissipation (Q_{orbit}) was calculated as follows:

$$Q_{orbit} = \int_0^{2hr} [\dot{m}C_p(T_{in} - T_{out})]dt \quad \text{Equation 1}$$

In the preceding equation, the variables were defined as:

\dot{m} : Coolant flow rate into the sublimator

C_p : Specific heat of the coolant used (50/50 Mixture by weight of Propylene Glycol Water)

T_{in} : The coolant temperature into the sublimator

T_{out} : The coolant temperature out of the sublimator

dt : Time interval

The second key performance parameter derived for the sublimator test was feedwater utilization (u). For steady state operation, utilization is simply a ratio of the ideal feedwater usage over the actual feedwater usage. The sublimator utilization is a measurement of how efficiently the sublimator used the feedwater for an applied heat load. Under

ideal operating conditions, all of the feedwater supplied to the sublimator would freeze to solid ice and be sublimated to the ambient vacuum. In this situation, the ideal feedwater mass consumed over the two hour orbit would be expressed as:

$$m_i = \frac{Q_{orbit}}{\Delta h} \quad \text{Equation 2}$$

From Equation 2 Δh represents the change in enthalpy of the feedwater. The enthalpy change is closely approximated by $\Delta h = h_{fg}$, the heat of vaporization for water evaluated at the triple point temperature, 0°C. However, a slightly more accurate representation of Δh which was used for subsequent analysis is shown in Equation 3.

$$\Delta h = h_{fg} - C_{p,feedwater} \cdot (T_{feedwater,in} - 0^\circ C) \quad \text{Equation 3}$$

In order to assess the efficiency of feedwater usage by the sublimator, a parameter referred to as the orbit averaged feedwater utilization (OAFU) was defined. The OAFU is a measurement of how effectively the sublimator uses the consumable feedwater for an applied heat load over a two hour orbit. OAFU is calculated as the following:

$$OAFU = \frac{m_i}{m_a} \quad \text{Equation 4}$$

In Equation 4, m_a represents the actual amount of feedwater used by the sublimator over a single orbit. It is determined using data from the aforementioned feedwater weight scale. If all of the feedwater was being sublimated and contributing to the heat rejection, OAFU would be equal to unity. A value less than unity occurred when more feedwater was being sent to the sublimator than necessary to efficiently dissipate the measured heat load.

QUANTIFICATION OF SUBLIMATOR FEEDWATER PERFORMANCE

Another test objective was to quantify the relationship between the timing of the feedwater (FW) isolation valve and the sublimator's Orbit Averaged Feedwater Utilization (OAFU). OAFU is a parameter used to quantify how efficiently the sublimator consumes feedwater when used as a supplemental heat rejection device. One possibility to consider is to keep the feedwater isolation valve open for the entire orbit. During the periods of zero heat load on the sublimator, just as it does during normal operation, the presence of the ice layer in the sublimator would prevent the feedwater from rushing out into space. However, even without an active heat load applied to the sublimator, the ice layer is still exposed to space vacuum, and would therefore continue to sublimate, possibly wasting feedwater and lowering the OAFU. To avoid this, the feedwater isolation valve could be closed before the transient heat load goes to zero in an attempt to sublimate away all of the feedwater remaining in the sublimator so that the feedwater reservoir is empty during the periods of zero applied heat load. Analysis showed that if the feedwater supply was stopped to the sublimator during a heating cycle, it would take multiple simulated orbits to sublimate the amount of water in the sublimator reservoir. Nonetheless, four different feedwater control scenarios were completed. This was to understand the sublimator's response to feedwater control and to determine whether there was a relationship between feedwater valve timing and the OAFU. Each scenario changed the time interval for which the feedwater supply was sent to the test coupon. The four test scenarios are summarized below. For additional clarity, a graphical representation is shown in Figure 8:

- No Close – Never close the feedwater supply valve during test
- End Close – Open and close feedwater supply valve at the beginning and end of each heating cycle.
- Mid Close – Open the feedwater supply valve at the beginning, and close the feedwater ¾ through a heating cycle
- Peak Close – Open the feedwater supply valve at the beginning, and close the feedwater supply half way through the heating cycle (of the four operating scenarios, this scenario would result in the largest removal of water from the feedwater reservoir)

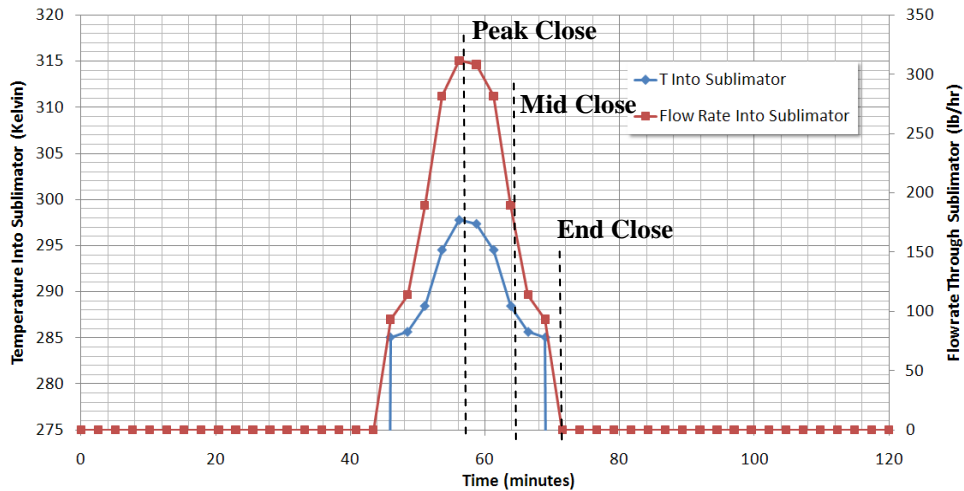


Figure 8. Transient Sublimator Simulated Applied Heat Load denoting the FW valve timing

TEST ARTICLES

The X-38 sublimator was initially chosen to characterize the performance of a sublimator under a transient heat load. This sublimator represents the state of the art in sublimator technology. A picture of the X-38 sublimator is shown in Figure 9.



Figure 9. X-38 Sublimator

Hot coolant enters the sublimator through a manifold, where the flow is divided among five double-sided and two one-sided sublimation plates. Coolant enters the middle flow passage on each sublimator plate, depicted as the red layer in Figure 10. Once the coolant moves through the sublimator, the flow combines in another manifold and exits the opposite side of the sublimator. Another inlet manifold allows feedwater to enter the sublimator and is split into two layers on each sublimator plate, depicted as the blue sections in Figure 10. The feedwater freezes since it is subjected to a vacuum environment and the energy from the hot coolant causes the ice to sublime, carrying away heat from the coolant. The two grey layers sandwiching the coolant and feedwater layers in Figure 10 are the sublimation surfaces.

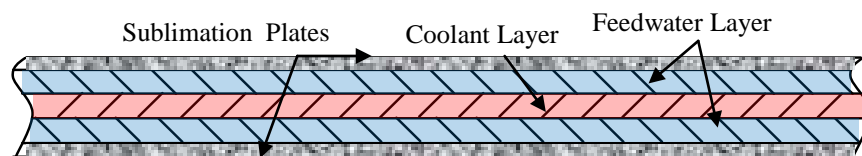


Figure 10. Sublimator Plate Schematic

For reasons discussed later in this paper the Contamination Insensitive Sublimator (CIS) was also used in transient sublimator testing. Figure 11 is a picture of the CIS. The heat rejection requirement for all three transient scenarios exceeded the capability of the CIS. This required the test conditions to be scaled down so that the CIS did not reach a breakthrough heat flux during test. CIS had a heat rejection capability of approximately half of the X-38 sublimator, requiring the scaling of the heat load down to lower levels for the CIS. A scaling factor was derived using the following equation:

$$F = 1 - \frac{Q_{\max,CIS}}{Q_{\max,X-38}} \quad \text{Equation 5}$$

Where:

- F: Scaling factor used for the current test program
- $Q_{\max,CIS}$: Maximum CIS heat rejection capability
- $Q_{\max,X-38}$: Maximum X-38 heat rejection for transient scenario 2

Using the preceding equation, the multiplication factor was determined to be 0.43 and was then multiplied by the coolant flow rate requirement set for the X-38 unit in all the Transient Scenarios. The new coolant flow rate and previously used coolant inlet temperatures to the sublimator were used to test the CIS under the same conditions.

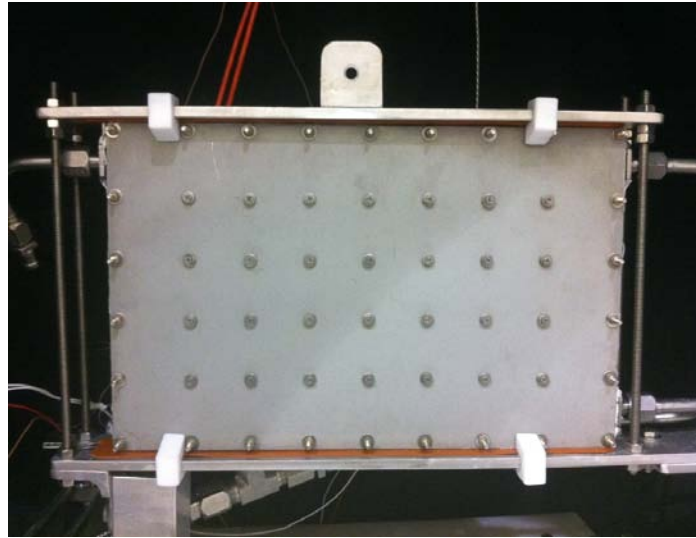


Figure 11. Contamination Insensitive Sublimator (CIS) Test Article

$$\frac{Q_{\text{tested max},X-38}}{q''_{\max,X-38} A_{X-38}} = \frac{Q_{\text{tested max},CIS}}{q''_{\max,CIS} A_{CIS}} \quad \text{Equation 6}$$

Future scaling of the CIS heat load should utilize Equation 6.

In this equation:

- $Q_{\text{tested max},X-38}$: The maximum heat load on the X-38 sublimator during a transient scenario
- $q''_{\max,X-38}$: Maximum heat flux that can be applied to the X-38 sublimator
- $q''_{\max,CIS}$: Maximum heat flux that can be applied to the CIS

Assuming the same maximum fluxes for the two sublimators, Equation 5 simply becomes the ratios of the CIS sublimation area to the X-38 sublimation area.

There were two CIS test articles available for transient sublimator testing. When testing CIS1, it was found that there was a leak on the coolant fitting that was difficult to repair. Therefore CIS2 was used for the remainder of the transient sublimator testing. The following section will review all of the tests completed using the X-38 sublimator and CIS test articles under transient conditions.

TRANSIENT SUBLIMATOR TEST MATRIX AND DATA SUMMARY

Transient Sublimator testing was completed on a total of two test articles. Initially the X-38 Sublimator was used for testing. Although testing will be discussed in further detail later in this report, it is important to note that the first test point run on the sublimator was transient scenario 1 with the feedwater valve kept open for the entire test day. The test plan for this day simulated approximately four orbits. Unfortunately during this first test point, the X-38 sublimator plates were deformed. It was believed that during the portion of transient scenario 1 when sub-freezing (less than 0°C) coolant was sent to the sublimator, the expansion of ice in the feedwater layer caused the deformation of the sublimator plates. For this reason, transient scenario 1 was never again run on any test article. To ensure that the damage did not compromise the structural integrity of the X-38 sublimator, steady state test points were run to compare to past steady state performance data of the same test article. A side-by-side comparison of past sublimator utilization and post-damaged utilization of the sublimator is shown in Table 1 and 2 respectively. It is important to note that previous X-38 sublimator data in Table 1 used a different setup with a slightly higher coolant inlet temperature and a mixture of 60/40 Dowfrost HD and water.

Table 1. Past X-38 Sublimator Data¹

95°F Coolant Inlet		
Flow Rate	Tout	Utilization
lb/hr	°F	
125	33.5	105%
211	36.3	94%
310	40.4	92%
400	42	90%

Table 2. X-38 Sublimator Performance Post Damage

90°F Coolant Inlet		
Flow Rate	Tout	Utilization
lb/hr	°F	(day1,day2)
150	42	82%, 90%
250	45	89%, 89%
400	46	88%, 96%

At first glance, when comparing the utilizations it seemed as if steady state tests showed that the performance of the damaged X-38 sublimator was not compromised due to the deformation of the sublimator plates. But when comparing outlet temperatures of the sublimator, they were considerably higher than previous testing. Furthermore, the outlet temperature of the sublimator in Table 2 should have been cooler than the testing in Table 1 since the coolant inlet temperature was slightly cooler and the mixture of PGW was 50/50, not 60/40 (Dowfrost HD to Water). This gave reason to believe that the sublimator was indeed damaged, but testing was still resumed starting with transient scenario 2 test points. Unfortunately, a few days into testing, coolant began to leak into the feedwater side of the sublimator plates. A picture of this occurrence is shown in Figure 12. Due to the inoperability of the X-38 sublimator, testing was initiated using the Contamination Insensitive Sublimator (CIS). An additional X-38 sublimator is available, but it was not used for any of the testing described in this document.

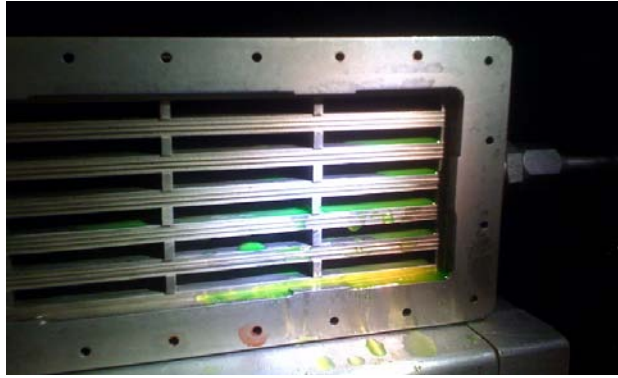


Figure 12. Coolant penetrating and flowing through the sublimator plates on the X-38 Sublimator.

After the X-38 sublimator was damaged, further testing was performed using the aforementioned CIS. During the course of the test schedule, four feedwater valve scenarios were assessed. These valve timings correspond to the ones outlined in Section 2 and Figure 6 of this report. Below, Table 3 is a summary of all transient tests run using both test articles. The test points highlighted in red are repeatability test points. Furthermore, for the purposes of this report, only data from Transient Scenario 2 and 3 will be discussed.

Table 3. Transient Scenario Test Points

Test Article	Transient Scenario 1	Transient Scenario 2	Transient Scenario 3
	<i>Valve Timing Scenario</i>	<i>Valve Timing Scenario</i>	<i>Valve Timing Scenario</i>
Damaged X-38 Sublimator	No Valve Close (Failed)	Valve Always Open	
	Peak Valve Close	Peak Valve Close	
		Mid Valve Close	
		End Valve Close	
CIS		Mid Valve Close	Peak Valve Close
		End Valve Close	Mid Valve Close
		Valve Always Open	End Valve Close
		Peak Valve Close Repeat	Valve Always Open
		Valve Always Open Repeat	Peak Valve Close Repeat
			Valve Always Open Repeat
			Valve Always Open Repeat
			Valve Always Open Repeat

ORBIT AVERAGED FEEDWATER UTILIZATION (OAFU) RESULTS

For each feedwater valve timing, Orbit Averaged Feedwater Utilizations (OAFUs) were calculated for every simulated orbit completed during a day. During a nominal test day, four orbits were completed for each transient scenario and valve timing. Orbit one resembled what a spacecraft would see as start up transient efficiencies associated with the first Lunar orbit (or any orbit that is started with an empty reservoir which would occur for valve scenarios during which the reservoir is completely emptied). Because the feedwater reservoir starts out empty, feedwater is initially required to fill the reservoir, which is why the OAFU is low on the first orbit. Additionally, the thermal mass of the sublimator hardware must be cooled down on the first few orbits, which requires additional sublimation and further reduces OAFU. On later orbits, the hardware thermal mass has achieved a quasi-steady state value, and the feedwater reservoir is no longer empty, so the OAFU improves. The resultant OAFUs are shown in Figure 15, which is a plot of all the compiled OAFUs for Transient Scenario 2. The data represents

OAFUs for CIS for all four valve scenarios over four orbits. Likewise, a plot of compiled OAFUs for Transient Scenario 3 is shown in Figure 16. R1 and R2 in the graph represent data from repeatability tests 1 and 2 for each valve scenario. Repeatability tests for the two transient scenarios never really showed a repeatable OAFU for the various valve timings. Initially it was thought that quasi-steady state had been achieved by orbit 4, but it is not clear from these plots whether that is true. Although it appears that the data is nearing steady state, some of the lines cross from orbit 3 to orbit 4, which may be an indication that quasi-steady state has not yet been achieved. As will be discussed in a later section, one of the forward plans involves longer testing over several simulated orbits. Nonetheless, orbit 4 data was used to assess trends in OAFU with respect to sublimator feedwater control.

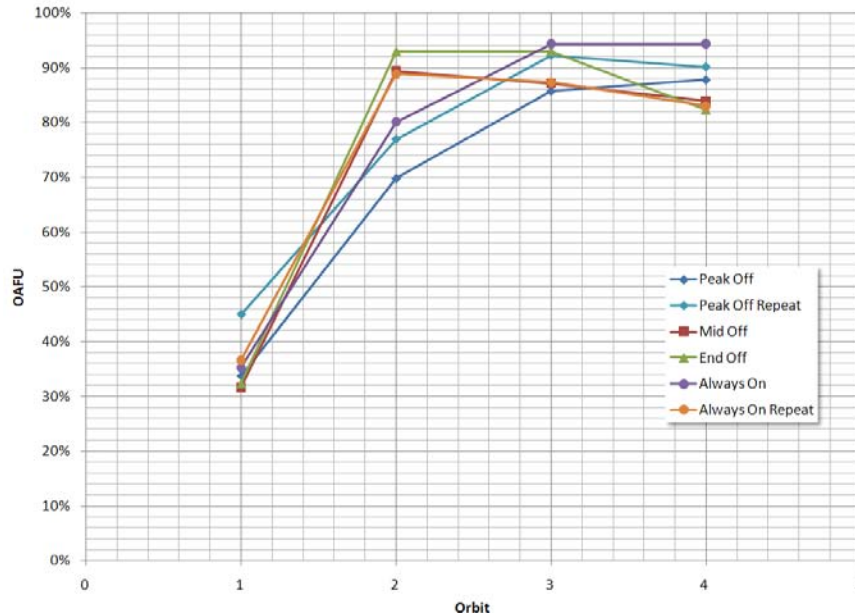


Figure 13. Transient Scenario 2 Compiled OAFUs for Four Orbits

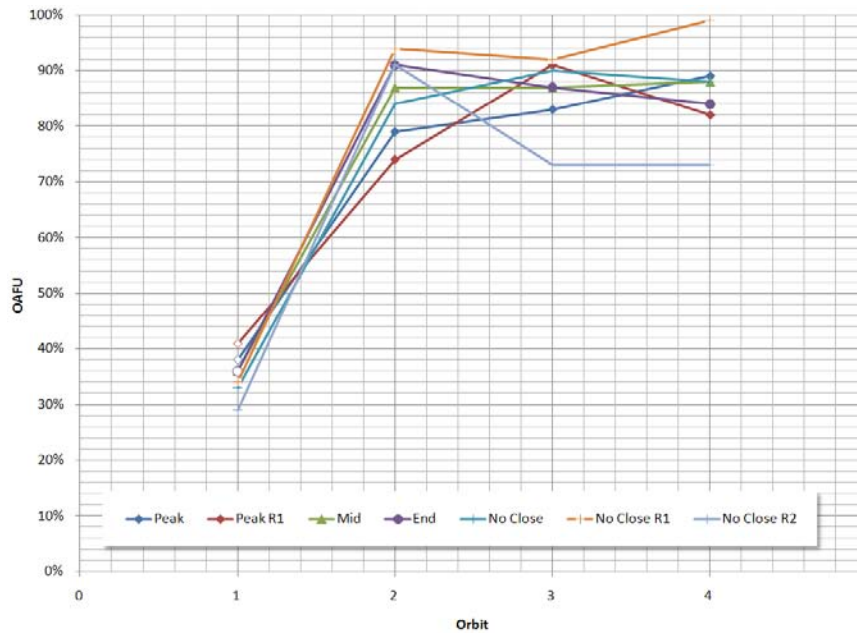


Figure 14. Transient Scenario 3 Compiled OAFUs for Four Orbits

Figures 17 and 18 are plots of Orbit 4 OAFUs for Transient Scenarios 2 and 3, respectively. The OAFUs are plotted with respect to the time at which the feedwater valve was closed. In reviewing Figure 17, one can see how there

does not appear to be an obvious trend between OAFU and the feedwater valve timing for the CIS, but one may exist for the X-38 sublimator. There is clearly a difference in X-38 performance relative to CIS performance. When focusing on the individual data for the two test articles, it seems that the X-38 OAFU increases with an increase of residual water in the feedwater reservoir. This trend would support the theory associated with startup inefficiencies. These are readily apparent in the data shown for the first simulated orbit completed in a test day. Because there is no ice layer present during the first orbit, it is suspected that feedwater rushes through the sublimator and is not impeded by a well-defined ice layer. While Figure 17 seems to show a trend in OAFU for the X-38 sublimator, Figures 17 and 18 also show that there is no apparent trend in OAFU for the CIS. This begs the question whether both sublimators react the same to transient heat loads in varying feedwater valve timings. A theory generated due to the design differences between the two sublimators suggests that the CIS has a different feedwater flow path within the sublimator than the X-38 sublimator. The CIS requires the feedwater to pass through an orifice and a porous disk before entering the porous plate. This path may prevent the initial feedwater from rushing out into space as quickly even though an ice layer may not be established within the porous plate.

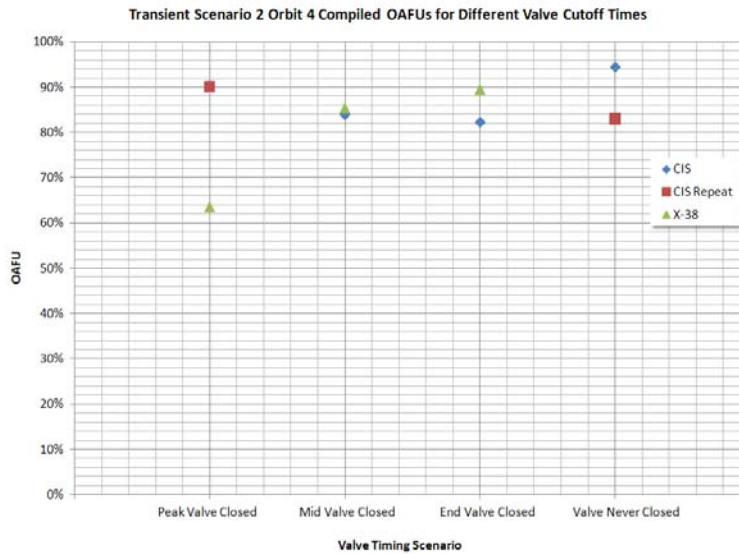


Figure 15. Transient Scenario 2 OAFU Compilation for Orbit 4 and Various FW Valve Timings (data is shown for both the X-38 and the CIS)

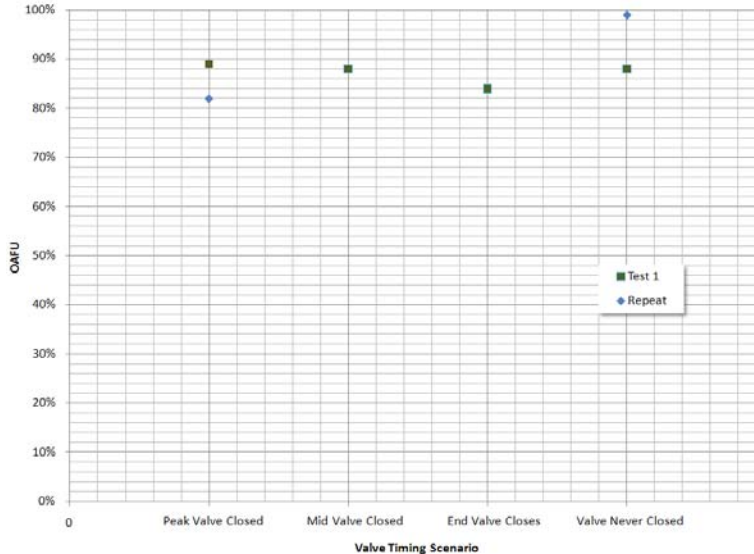


Figure 16. Transient Scenario 3 OAFU Compilation for Orbit 4 and Various FW Valve Timings (this transient scenario was only performed using CIS)

It was believed that the sublimator would show some type of trend in feedwater utilization with respect to feedwater control to the sublimator. The thought was, for operational scenarios where feedwater is allowed to flow to the sublimator during periods of no heat load, the feedwater would continue to sublimate since it is still exposed to vacuum thereby reducing the OAFU. The argument against this hypothesis is based on conservation of energy. The water that is sublimating during periods of no heat load would remove energy which would reduce the temperature of the sublimator and the ice located within the reservoir. This reduction in temperature would tend to increase the sublimator OAFU during the next simulated orbit because of the sensible energy exchange upon start-up.

Alternatively, it was also theorized that if the feedwater valve was closed at some period of time during the simulated orbit, the feedwater required for sublimation would be removed from the reservoir creating a void space in the reservoir. During the next simulated orbit, this void space would have to be filled. It is also possible that the lack of a well-defined ice layer would allow liquid feedwater to “escape” the sublimator plate without freezing which would tend to decrease the sublimator’s feedwater efficiency. Previous testing has shown that the initial filling of an empty reservoir results in reduced feedwater consumption efficiency (see the first orbits in Figures 15 and 16). Figures 17 and 18 seem to provide data that disproves both of these hypotheses as the CIS appears to show no apparent trend between feedwater valve timing and OAFU. The X -38 data though in Figure 17 does show to have some trend with an increase in OAFU for scenarios during which the reservoir is not emptied as much as the other scenarios. The following sections describe additional tests that were performed to better understand the observations made during the OAFU calculations and subsequent analysis.

STARTUP UTILIZATION TESTING

Previous testing (refer to orbit 1 data in Figures 15 and 16) has shown poor utilization at startup. These inefficiencies at startup are theorized to be due to a combination of (1) initial feedwater escaping through the porous plate before an adequate ice layer is established, and (2) sublimation to initially cool the hardware in addition to rejecting heat from the coolant. For this reason, it is believed that scenarios when the feedwater is supplied for an interval of time to the sublimator for optimal water usage, there is degradation in utilization in the following orbits due to inefficiencies associated with startup. These inefficiencies are due to the fact that the feedwater reservoir is not completely filled and/or the ice layer is not fully formed. Figures 17 and 18, though, show no apparent degradation in performance. To better understand any inefficiencies of the sublimator due to startups, “startup utilization” tests were run on CIS. These tests were thought to help understand how the sublimator reacts to various intervals of feedwater deprivation. All tests run to characterize startup utilization were run before analyzing any data from this set of testing. Furthermore, with increasing “valve off” (where the feedwater is prevented from flowing into the sublimator) time intervals, it was theorized that the sublimator utilization would degrade. The test plan called for the sublimator to be run at coolant inlet conditions of 27°C (80°F) and 100 lb/hr. Once it was determined that the sublimator was at coolant steady state operation, the feedwater supply to the sublimator was stopped for a predetermined time while the coolant was kept flowing through the sublimator. The test day was started off with a hot start (the coolant was allowed to flow through the sublimator until the outlet temperature matched the inlet temperature at which time the feedwater was supplied to the hardware) while feedwater stoppage times of 1, 3, 5, 10, 15, 20, and 25 minutes were run during the course of the test day. These intervals of feedwater depletion in the sublimator should correspond to different percentages of the feedwater reservoir that are depleted. When water is depleted from the sublimator, an increased amount of water is sent to the sublimator upon restart to reach coolant steady state operation. For time durations when the feedwater valve is off long enough such that all of the reservoir feedwater is sublimated, the subsequent startup is essentially a hot start. Figure 20 is a graph of the inlet conditions to the sublimator during one day of startup utilization testing. Two days of test were run to verify experimental repeatability.

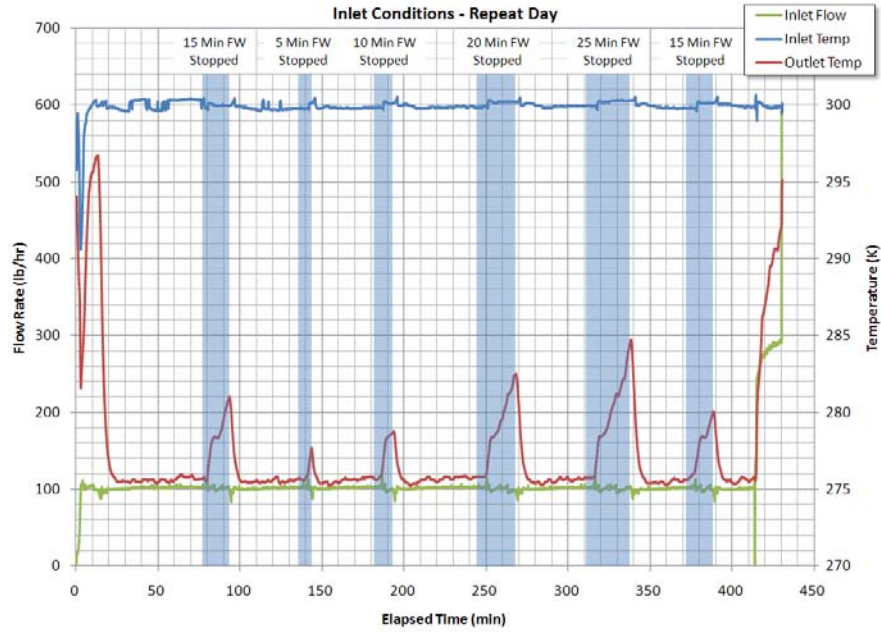


Figure 17. Inlet Conditions for Startup Utilization Testing

Initially utilization was calculated for an interval that included 10 minutes of coolant steady state operation, the period for which the feedwater was stopped to the sublimator, and until coolant steady state operation was again achieved. A representation of this interval is shown in Figure 21 (from 0 to 50 minutes). The shaded region in the figure is the time interval for which the feedwater valve was closed. This Startup Utilization (SU) was calculated for the various times the feedwater supply was stopped to the sublimator using Equations 1 through 4 with the following modifications. A difference between OAFU and SU calculations is the time interval for which the calculation was performed. While OAFU was for a fixed two hour duration, the SU calculation time interval changed in accordance with the time interval for which the feedwater valve was off. The time interval used to calculate each heat rejection for utilization was ten minutes prior to the close of the feedwater valve to a point at which steady state operation was resumed on the coolant side, as shown in Figure 21 (time 0 to 50 minutes). This time span varied with the amount of time the feedwater supply was cutoff to the sublimator. Figure 22 below is a graph of all the SU's calculated in this manner for each feedwater cutoff time interval.

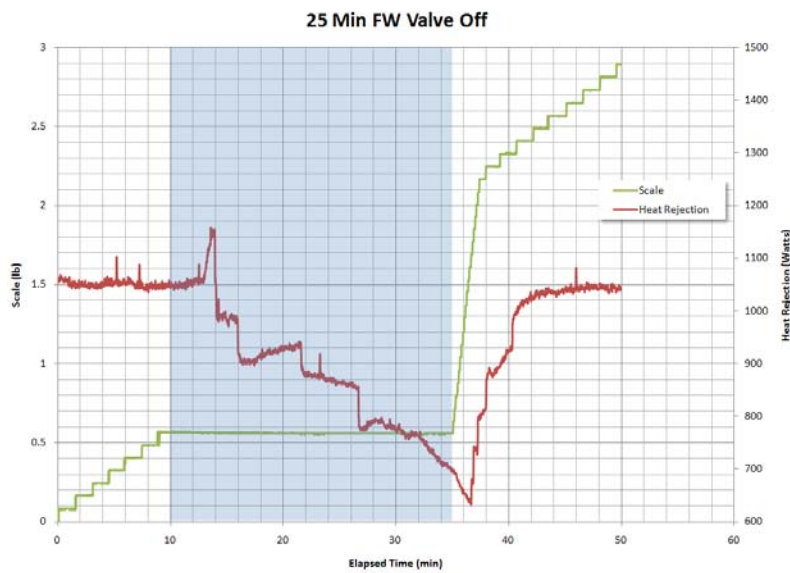


Figure 18. Graph of Feedwater Usage and Sublimator Heat Rejection for 25 Minutes of Feedwater Cutoff to the Sublimator

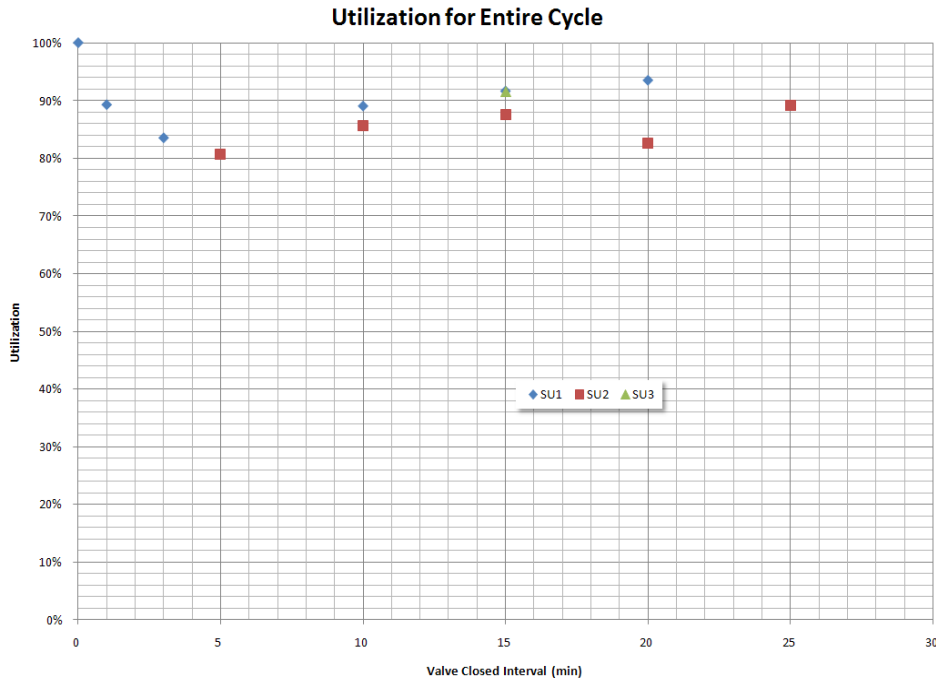


Figure 19. Full Cycle Startup Utilization

The data in Figure 22 is a representation of how the sublimator efficiency is affected by various intervals of feedwater deprivation. A thing to note here is for time interval 0 in the graph 100% utilization represents steady state results. SU1 and SU2 represent the two separate days of startup utilization testing. The experimental repeatability is very good for all of the test points with the exception of “valve closed interval” of 20 minutes. The data labeled “SU3” is another repeatability point run for the 15 minute time interval on the second day. Along with good repeatability, the test data shows how the feedwater consumption efficiency does not appear to be affected by prolonged intervals of feedwater deprivation. In studying Figure 22, it appears that a relationship can be taken away between SU and feedwater valve timing for transient tests. The SU starts at unity and asymptotically approaches a constant value between 80% and 90% with longer durations of feedwater deprivation. This relationship is consistent with the OAFU data shown earlier in this paper. With increased feedwater control to the sublimator, the OAFU did not drastically decrease. This was again counter intuitive since, as discussed previously, it was theorized that for longer periods of feedwater cutoff, the feedwater consumption would be less efficient. The test team originally assumed that the process of filling the reservoir would drive the sublimator utilization down due to water escaping before forming an adequate ice layer. To further investigate this theory, another analysis was performed for each of the completed tests.

Previous startup utilizations were calculated for an interval that included a brief period of coolant steady state operation, time when zero feedwater was sent to the sublimator, and finally to a point where an apparent steady state operation was met again (once the feedwater supply was restarted) on the coolant side. It was determined that a closer look was needed on the portion when feedwater was restarted to when it was deemed steady state operation was resumed on the coolant side. The new form of startup utilization was calculated the same way as previously stated but for a different time interval. Figure 23 is a graph of startup utilizations for all feedwater cutoff times calculated in this new manner. Taking the 25 minute feedwater cutoff interval for example, as shown in Figure 21, this new form of startup utilization was calculated between 35 minutes and 50 minutes. This time frame represented the instant the feedwater valve was re-opened for supply to the sublimator up to the time when it was deemed the sublimator was at coolant steady state operation. Furthermore, hot start utilization was calculated for when a hot start was performed at the beginning of the test day. Hot start utilization was calculated between the time when the feedwater supply was started to the sublimator until it was deemed steady state operation was met by the sublimator. A hot start utilization of 40% was calculated (but is not shown in Figure 23). Neglecting the data points for one and three minute, Figure 23 shows how the startup utilizations never went above the hot start utilization of 40%. The graph also shows the progressive degradation in sublimator start up utilization between 1 and 5 minutes to a steady

40% for the rest of the feedwater cutoff time intervals. Future test plans should run the same test points for longer “valve closed intervals” (valve timings up until a hot start is completed). In addition, the future test points should ensure that steady state operation is achieved on the feedwater side before running the next test point. Previous tests indicated that steady state operation on the feedwater side takes longer to achieve than steady state operation on the coolant side.

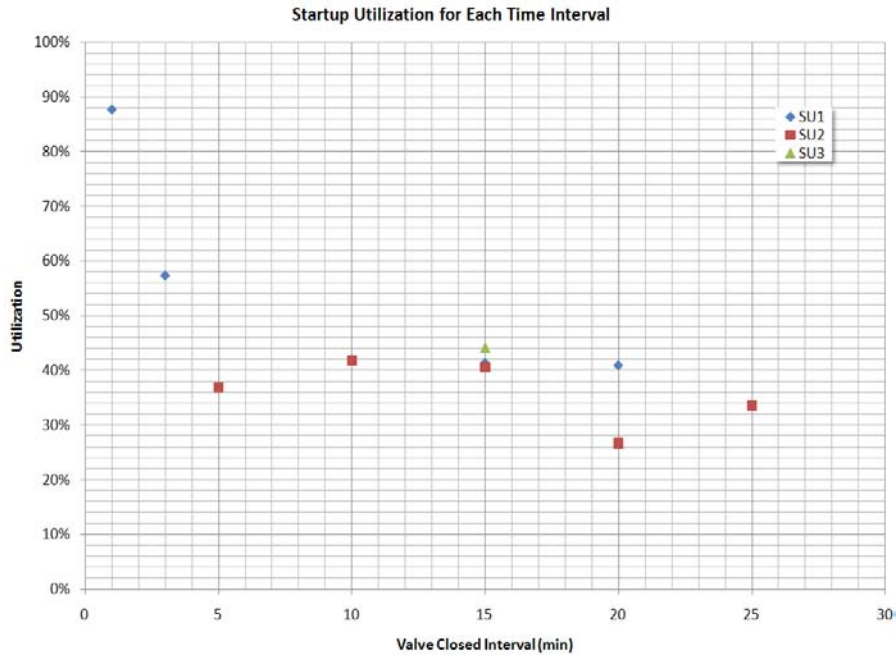


Figure 20. Startup Utilizations for all Feedwater Cutoff Times

Figures 22 and 23 show a steady utilization for increased cutoff time intervals of feedwater supply. This may shed light onto why the OAFU shown in Figures 17 and 18 stay steady with changes in feedwater valve timing during transient heat rejections despite the theory that startup inefficiencies would decrease OAFU for increasing “valve off” times. It appears from this data that the degree to which the reservoir is “empty” is irrelevant as it relates to feedwater efficiency. For example, the feedwater consumption efficiency is degraded (and doesn’t seem to worsen with increased emptiness of the reservoir) regardless of how much water is removed from the reservoir. The interval chosen for the analysis of startup utilizations was chosen by the available data. Future tests and sublimator analysis for the startup utilizations should consider a more rigorous definition of the time interval.

A projection was made of the ideal feedwater usage using the steady state utilization and the actual heat rejection. Equation 7 was used to calculate the ideal feedwater usage.

$$\Delta m = \frac{\int_{t_1}^{t_2} Q dt}{\Delta h \cdot u} \tag{Equation 7}$$

In Equation 7:

- Δm: The ideal feedwater consumption
- Q: The time-varying actual heat rejection (calculated performing energy balance on the coolant)
- dt: The time step between each data point
- Δh: The enthalpy change of the feedwater
- u: The steady state utilization of the sublimator

The steady state utilization was calculated by using the last 10 minutes of coolant steady state operation by the sublimator for each time interval. It was suspected that the feedwater utilization had not reached steady state. An

example of this is shown for the 25 minute feedwater cutoff test point. Figure 24 shows how once the feedwater supply was stopped for 25 minutes, starting at time 10 minutes, it took the sublimator 60 minutes to reach steady state operation, time 70 minutes in the figure. After the 70 minute mark, the valve was closed again for another test point. Steady state utilization was calculated for the time interval between 60 to 70 minutes, referencing Figure 24. This utilization was then used to project the ideal feedwater usage by the sublimator with respect to the heat rejection from the point at which the feedwater valve was turned to the off position. For calculated utilizations above 100%, 100% was used in Equation 7. This process was carried through for every feedwater valve cutoff duration.

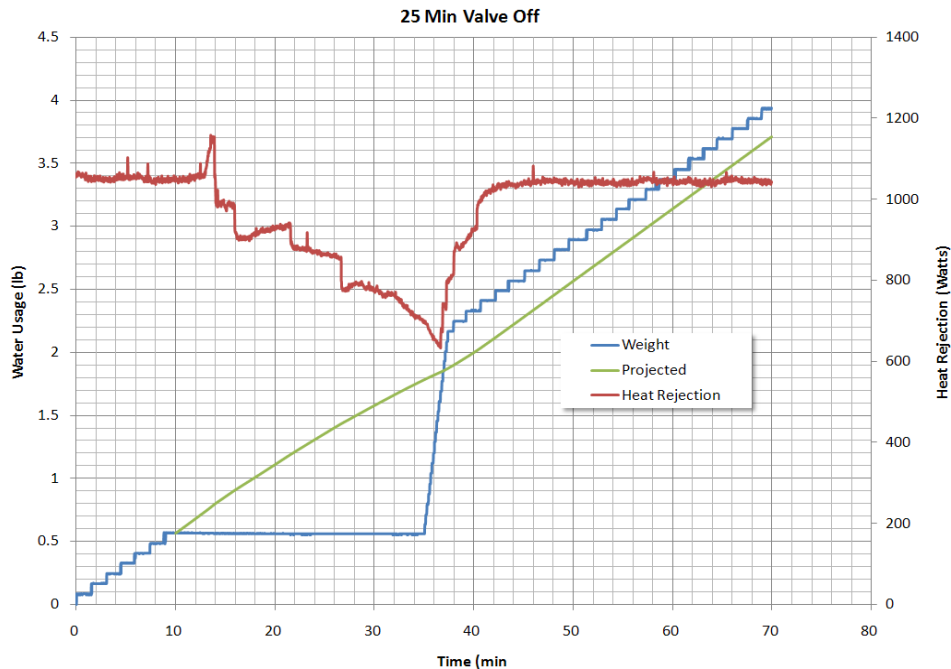


Figure 21. Ideal Feedwater Usage and Actual Feedwater Usage for 25 minutes of Feedwater Cutoff

Initial thoughts suggested that the actual amount of feedwater used would be more than the ideal feedwater usage. This would occur due to the presumed inefficiencies associated with sublimator startups. As shown in Figure 25, this is the case for all times after the feedwater valve has been reopened. However, the ideal feedwater curve (green curve titled *projected*) has a different slope than the actual feedwater usage. After the feedwater valve is re-opened, feedwater rushes in to fill the feedwater reservoir that had been partially depleted while the feedwater valve was closed. It took more water to fill the reservoir than should have been sublimated by the heat rejection during that interval, as shown by the blue line (actual) being above the green line (projected ideal) beyond a time of 25 minutes. However, the blue line appears to be converging closer to the green line, indicating an actual utilization greater than 100%. The data suggests there is another heat rejection source such as sensible heat from the unit. Unfortunately, the external surfaces of the sublimator were never instrumented to record temperature and the surfaces were not insulated because convection losses/gains were negligible due to the fact that the tests were performed in vacuum. In addition, using the assumptions described for the radiation calculations in Section 7.3 the maximum possible heat transfer via radiation was calculated to be 26 Watts which is negligible compared to the coolant heat transfer of nearly 1 kW. Furthermore, a test was never run where the sublimator was allowed to run at steady state operation for more than 30 to 45 minutes after the feedwater valve was reopened. Nonetheless, there is data that suggests the sublimator was not cooler, which would have allowed for heat rejection due to sensible heat. Figure 26 shows sublimator outlet temperature increasing as the sublimator sits without a source of feedwater for heat rejection. This suggests the sublimator structure temperature is also increasing, and therefore does not contribute as an additional heat sink.

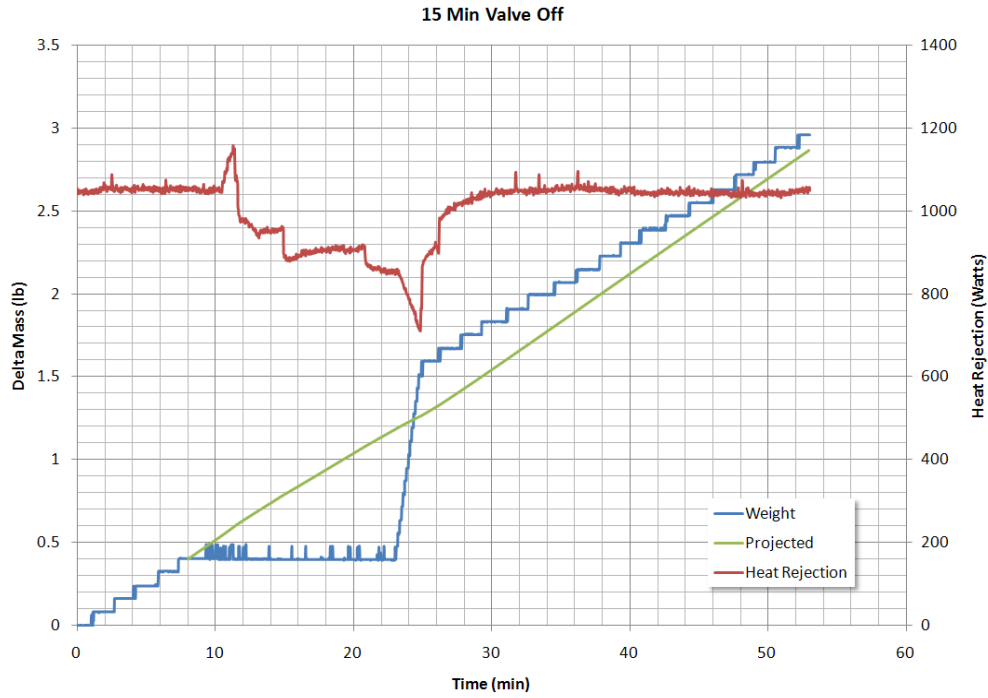


Figure 22. Ideal and Actual Feedwater Usage of Sublimator for a 15 minute Feedwater Cutoff Time

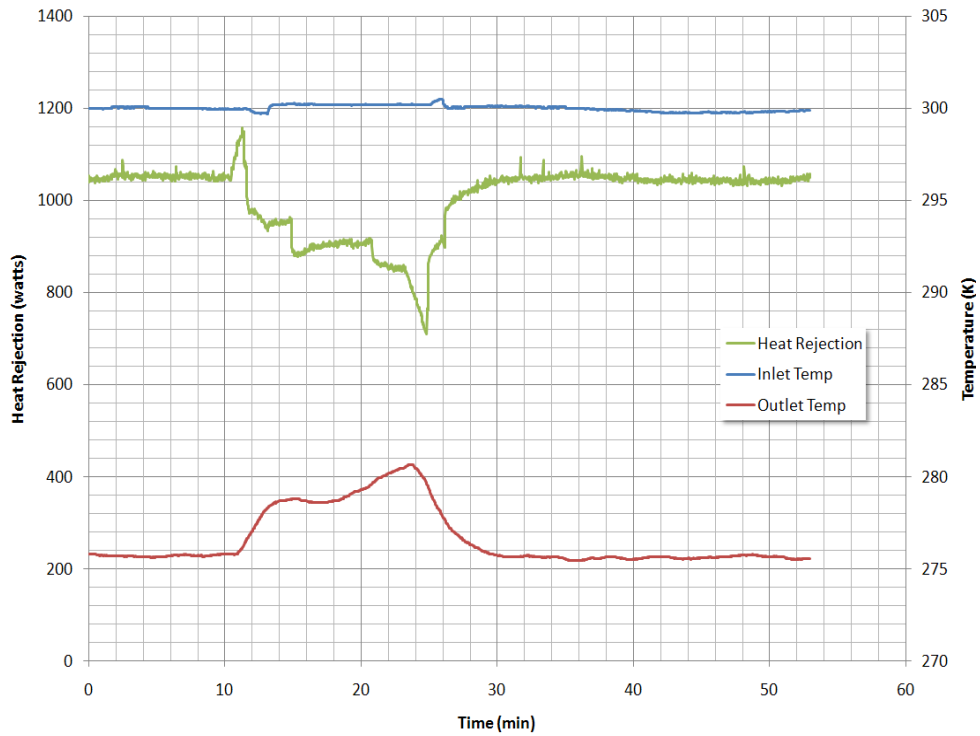


Figure 23. Inlet and Outlet Conditions to Sublimator for 15 Minute Feedwater Cutoff Timing