Actively Controlled Louver for Human Spacecraft Radiator Ultraviolet (UV), Dust, and Freeze Protection

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This paper examines the use of actively controlled louvers to attenuate UV and dust, as well as mitigate freezing concerns for human spacecraft radiators during Artemis missions. Artemis missions to the lunar orbit or surface will expose the radiators to high energy UV radiation and dust, which will degrade the radiator's coating absorptivity and consequently reduce heat rejection performance. In addition, subfreezing environmental temperatures during transit to lunar orbit and nighttime on lunar south pole can rupture coolant tubes, reduce heat rejection performance, and worst-case scenario result in a Loss of Mission (LOM). Louver technology would be a promising solution to maintaining radiator performance and integrity for Artemis missions, but heritage louvers are passively controlled. This technology needs maturing to active control, or motor actuation, to achieve faster thermal response times. Actively controlled louver design considerations are discussed in this paper. The analysis that follows shows actively controlled louvers can attenuate high energy UV radiation and dust, as well as protect the coolant from freezing.

Nomenclature

ESH	=	Equivalent Solar Hours
I-HAB	=	International Habitat
IR	=	Infrared Radiation
ISS	=	International Space Station
LEO	=	Low Earth Orbit
LOM	=	Loss of Mission
LSH	=	Lunar Surface Habitat
NASA	=	National Aeronautical Space Administration
SOA	=	State of the Art
TRL	=	Technical Readiness Level
UV	=	Ultraviolet

I. Introduction

National Aeronautical Space Administration's (NASA) Artemis missions will return humans to the Moon for the first time in over half a century, and the development of new technologies are necessary to enable a sustained presence. Unlike the Apollo missions, astronauts will live and work near the lunar south pole, and gradually build infrastructure to conduct long duration tests and experiments[1]. NASA also plans to assemble a space station in lunar orbit called Gateway to conduct science, perform technology demonstrations, and be utilized as a pit stop for spacecrafts to deliver cargo to the lunar surface. Conventional human spacecrafts (i.e., ISS and Shuttle) are cooled using mechanically pumped liquid cooling loops to collect, transport, and reject heat using radiators. The radiator's performance is highly dependent on the surrounding environmental, or sink, temperatures, and available surface area.

These radiators can be body mounted, or imbedded, into the spacecraft's structure, or deployable like wings on an aircraft. State of the Art (SOA) body mounted radiators like those on Orion are historically lighter than deployable radiators, but the limited surface area and exposure to cold environmental temperatures offers less heat rejection capability than deployable radiators. SOA deployable radiators like those on the International Space Station (ISS) can have an indefinite number of panels to increase surface area, articulate to optimize thermal environments, and reject heat on both sides of the panel. This advantage is why the initial concepts for Gateway's International Habitat (I-HAB) and the Lunar Surface Habitat[2] (LSH) are derived from the ISS deployable radiators[3].

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II. Problem Statement

The ISS deployable radiators were designed to operate in Low Earth Orbit (LEO) and coated with Z-93 inorganic white paint to maximize heat rejection. Z93 has an emissivity and absorptivity of 0.91 and 0.16, respectively, and studies have shown exposure to high energy UV radiation or lunar dust can significantly degrade the absorptivity. In addition, the environmental temperatures during a spacecraft's transit to lunar orbit and surface are significantly colder and last longer when compared to operating in LEO. These harsher lunar environmental conditions may reduce the radiator's heat rejection capability and jeopardize the success of the mission. This paper investigates the use of actively controlled louvers to attenuate UV and dust, as well as mitigate freezing concerns for human spacecraft radiators such as those on I-HAB and the LSH during Artemis missions.

A. UV Radiation Impacts

Artemis spacecrafts and habitats traveling through and beyond the Van Allen Belts will be exposed to ionized, or high energy, UV radiation, which can significantly degrade the radiator's absorptivity. The Apollo missions mitigated ionized UV concerns by rapidly traveling through the belts and shortening mission durations to less than two weeks [4]. However, Artemis missions can linger in the Belts from minutes to days and can take months to reach the lunar orbit or surface[5]. Experiments[6,7] have shown the Van Allen Belt ionized UV particle densities can vary from $1x10^{13}$ to $1x10^{14}$ particles/cm^2 @ 50 and 200 KeV, respectively, and exposure to more than 500 Equivalent Sun Hours (ESH) under these conditions can degrade the Z-93 absorptivity from 0.16 to 0.24, or 50%, as shown in Figure 2.

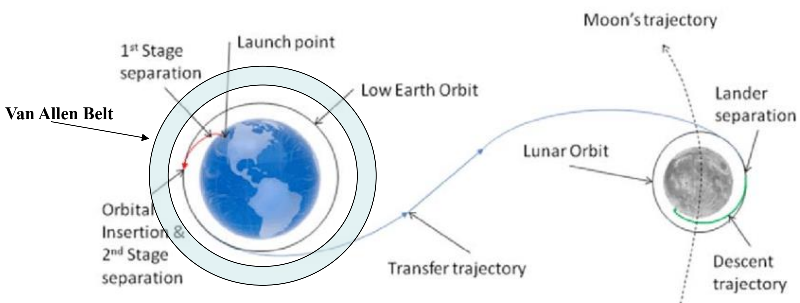

Figure 1. Simplified Artemis Spacecraft Flight Path

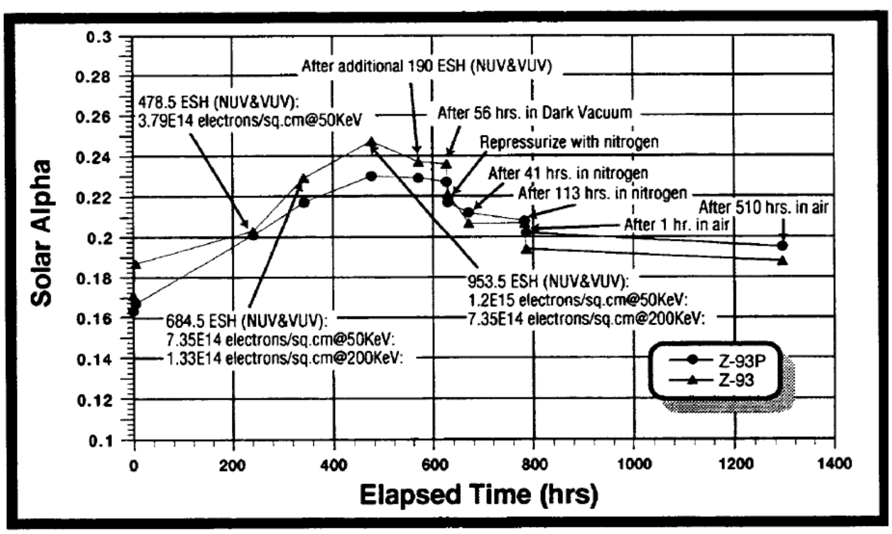

Figure 2. Change to Z-93 Absorptivity Due to UV exposure

A deployable radiator's heat rejection capability is calculated based on the conservation of energy[8] as shown in Equation 1.

$$Q_h = Q_r - Q_e \quad \text{Eq. (1)}$$

Q_h is the spacecraft's internal heat load rate, Q_r is the rejected heat load rate, and Q_e is the external environmental, or sink, heat load rate. Q_r is calculated using Equation 2 where σ is Stephan-Boltzmann constant, ε is the emissivity, η is the radiator fin efficiency, A is the radiator surface area, T_r is the radiator temperature and T_s is the environmental temperature.

$$Q_r = \sigma\varepsilon\eta A(T_r^4 - T_s^4) \qquad \text{Eq. (2)}$$

The environmental heat load is calculated from Equation 3 where α is the absorptivity, A is the radiator surface area, H_s is the solar flux, H_{ir} is the planetary IR flux, and H_a is the planetary albedo flux.

$$Q_e = \alpha A(H_s + H_{ir} + H_a) \qquad \text{Eq. (3)}$$

Heat rejection degradation due to UV traveling through and beyond the Van Allen belt can be calculated by subtracting Q_h with a 0.14 absorptivity from Q_h with an 0.24 absorptivity. Assuming the following conditions, the results show the heat rejection capability will reduce from approximately 9 kW to 3 kW, or 60% reduction, as shown in Figure 3.

<u>Assumptions</u>

1. 90% radiator fin efficiency
2. Constant solar and planetary fluxes[8]
3. LSH total radiator surface area of 48 m^2 (517 ft^2)
4. HFE 7200 coolant, setpoint temperature of 3 Deg C (38 Deg F)

Therefore, it's possible the radiator will operate with reduced capability upon arriving at its destination, and likely violate the spacecraft's temperature requirements during Artemis missions.

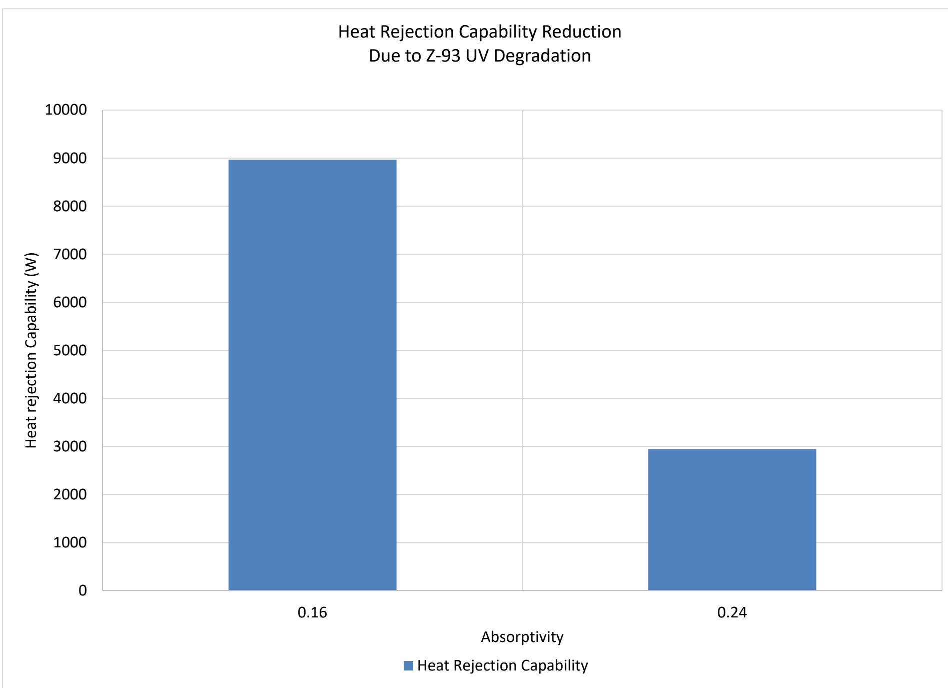

Figure 3. Change to Z-93 Absorptivity and Heat Rejection Capability due to Ionized UV

B. Lunar Dust Impacts

Lunar dust is copious and highly adhesive. Tests have shown Z-93 absorptivity linearly degrades with the amount of dust coverage[9] as shown in equation 4. This is based on the rule of mixtures[9], and the lack of interactions between the dust particles and radiator coating doesn't reduce the absorptivity of the radiator area without dust.

$$\alpha_{final} = (f_{dust}\alpha_{dust} + f_{bare}\alpha_{initial}) \qquad \text{Eq. (4)}$$

In equation 4, f_{dust} and f_{bare} are the fractions of the radiator's surface covered and not covered by dust, respectively, α_{dust} is the 0.76 absorptivity of JSC-1AF lunar dust simulant, $\alpha_{initial}$ is Z-93's absorptivity of 0.12, and α_{final} is the degraded Z-93 absorptivity value. Using equations 2 and 4 for an initial 9 kW heat rejection capability and assuming a constant 30% solar flux to represent the lunar south pole, as little as 20% dust coverage can increase the absorptivity and decrease the heat rejection capability by 75% and 30%, respectively, as shown in Figure 4.

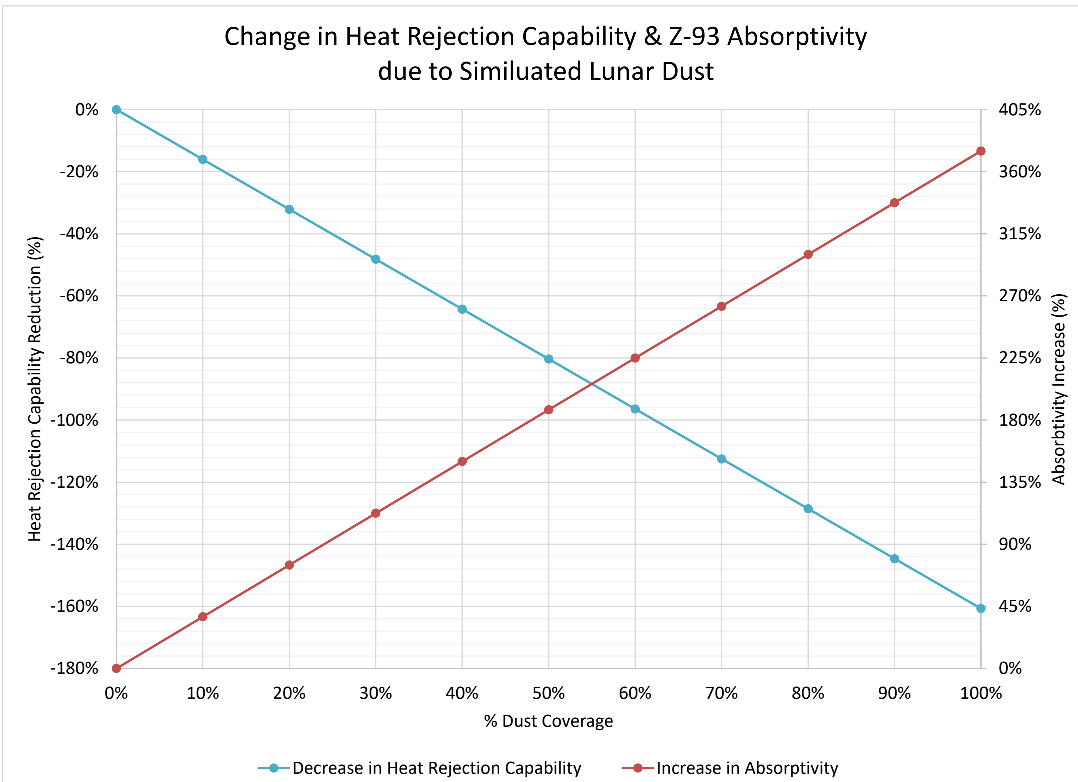

Figure 4. Deployable Radiators Z-93 Absorptivity and Heat Rejection Capability Degradation due to Lunar Dust

C. Radiator Freezing Impacts

The I-HAB and LSH will operate with low heat loads without astronauts onboard for approximately eleven months out of the year. The environmental temperatures during transit to lunar orbit and the fourteen-day lunar nights on the Moon's surface can drop below -213 °C (-351 °F)[10,11]. These temperatures are lower than the HFE 7200 coolant working limit and freezing point of -100 °C (-148 °F) and -137 °C (-215 °F), respectively, and studies have shown approximately 1 to 4 kW heater power is required to keep the coolant flowing and avoid freezing[2]. Heater power availability may be limited during these conditions and the consequence of freezing, thawing, and rupturing of coolant tubes could result in a decrease of heat rejection capability or Loss of Mission (LOM).

III. Solution Using Louvers

A possible solution to reduce Z-93 absorptivity degradation and mitigate coolant freezing concerns is equipping a radiator with louvers. The conventional louver[12] is constructed of aluminum blades, which are passively actuated by a bimetallic spring as shown in Figure 5. Numerous testings and flight histories have shown louvers can vary a radiator's effective emissivity from 0.14 to 0.74. Heat is retained, reducing the emissivity to 0.14 when the louver is closed. Heat is rejected while the louver is open, increasing the emissivity to 0.74. The radiator suffers a slight reduction in capability since the emissivity without louvers is 0.91, which is explored in this paper.

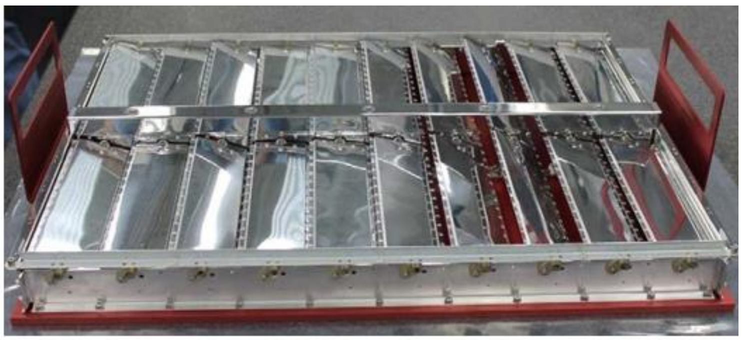

Figure 5. Sierra Nevada Corporation's (SNC) Passive Louver

A. UV Attenuation

The louver blades can attenuate ionized UV from reaching the radiator coating while closed and can limit Z-93 absorptivity degradation depending on the blade thickness. Conventional aluminum louver blades are ~ 1.3 cm thick[8], and the ionized UV attenuation can be calculated using Beer-Lamberts Law as shown in Equation 5.

$$I = I_0 e^{-\left(\frac{\mu}{\rho}\right)\rho l} \qquad \text{Eq. (5)}$$

I_o is the original ionized UV intensity, μ/ρ is the mass attenuation coefficient, and l is the blade thickness. Since the mass attenuation coefficient for aluminum[13] is approximately 3.4 cm^2/g (234 $in^2/lb.$), the UV intensity through and beyond the Van Allen Belts can be reduced from $7x10^{14}$ particles/cm^2 @ 50 KeV to 0 with the standard louver blade thickness as shown in Figure 6, effectively eliminating the Z-93 absorptivity degradation and maintaining heat rejection capability upon arrival to lunar orbit or surface.

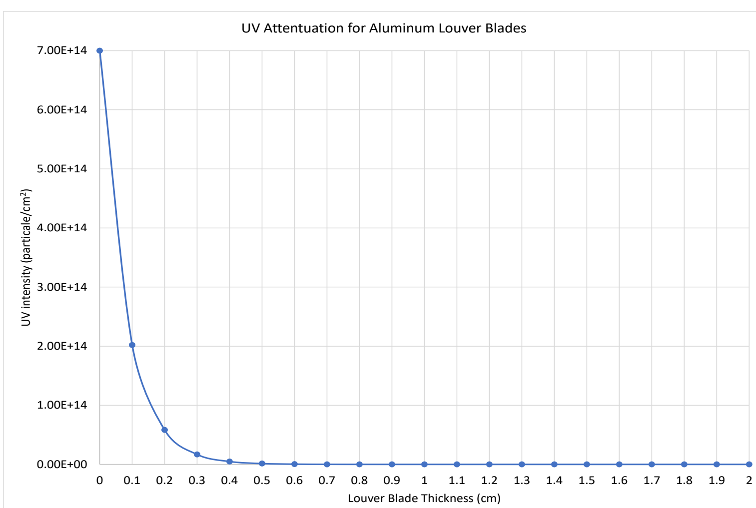

Figure 6. Aluminum Louver Blade Thicknesses Ionized UV Attenuation

B. Dust Protection

Louvers can also block dust from settling on LSH radiators while in the closed position, and limit Z-93 absorptivity and heat rejection capability degradation. Currently, the amount of lunar dust adhering to a bare radiator without a louver for the LSH life cycle is undetermined, but assumptions can be made to assess the feasibility of using louvers for protection. The current LSH concept positions the radiators on top of the habitat to limit dust impacts. Assuming the bulk of the dust originates during landing, then the dust should only impact one side of the stowed deployable radiator assembly. Using Equations 2 and 4 and the same assumptions for Figure 4, then the analysis showed a radiator panel fully covered with dust on one side will degrade the total heat rejection capability of a four-panel radiator assembly by approximately 20% as shown in Figure 7. Adding louvers to the radiator will protect the panel from dust degradation and maintain heat rejection capability.

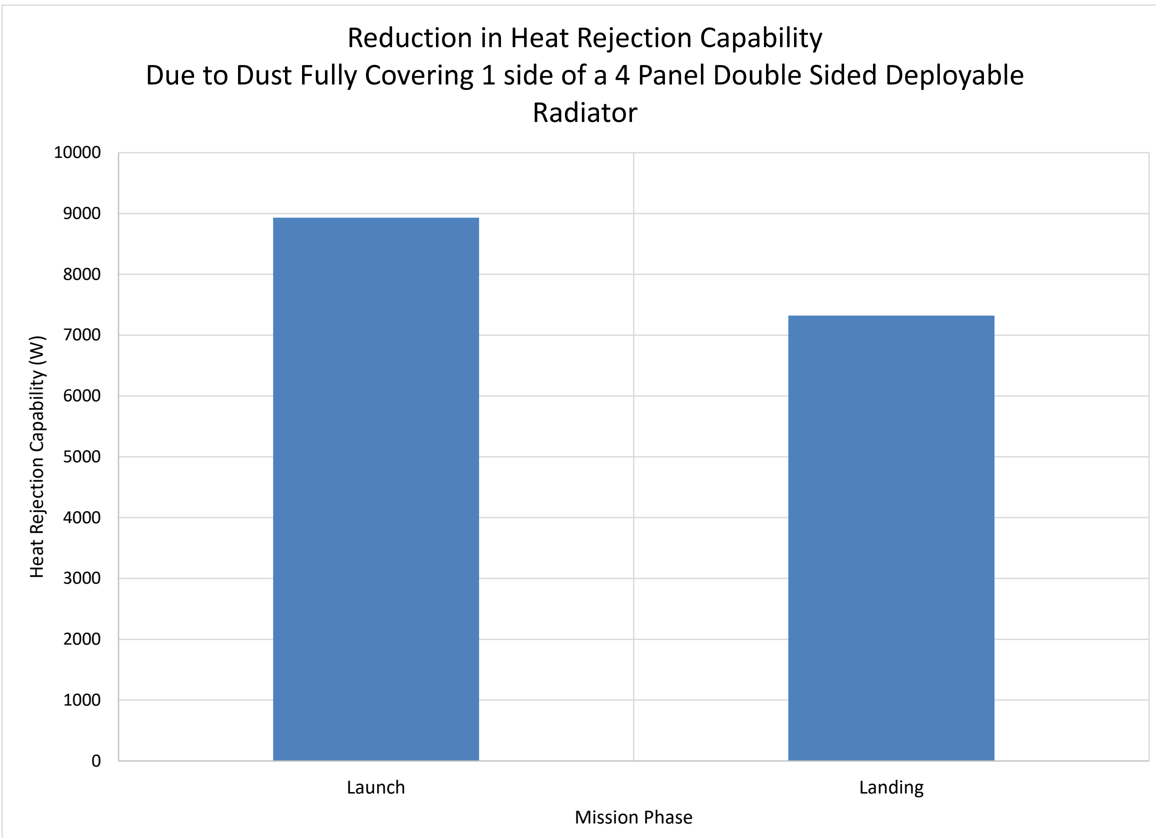

Figure 7. LSH Heat Rejection Capability Due to Dust on 1 Side of 1 Radiator Panel

C. Radiator Freeze Protection

Louvers can reduce the radiator's effective emissivity to 0.14 while in the closed position and keep the radiator outlet temperature above the HFE 7200 working and freezing points. This can be calculated using the first law of thermodynamics as shown in Equation 6, assuming no environmental heat loads to bound the analysis (i.e., worst case cold conditions).

$$Q_h = Q_r \quad \text{Eq. (6)}$$

Q_r is the spacecraft heat load rate and Q_r is the rejected heat rate. Assuming steady state conditions and incompressible liquid, then Q_{in} can be reduced to Equation 7.

$$Q_h = mcp(T_{out} - T_{in}) \quad \text{Eq. (7)}$$

Where *m* is the mass flow through the coolant tubes, *cp* is the HFE 7200 specific heat, and T_{out} and T_{in} are the HFE 7200 temperatures existing and entering the radiator, respectively. Equating Equation 2 to Equation 7 and using the LSH heat power as the loads, results in Figure 8 show that reducing the radiator's emissivity from 0.74 to 0.14 using louvers will keep the outlet temperature above the working and freezing points. This will eliminate the need for heater power during low heat loads and when operating in cold environments.

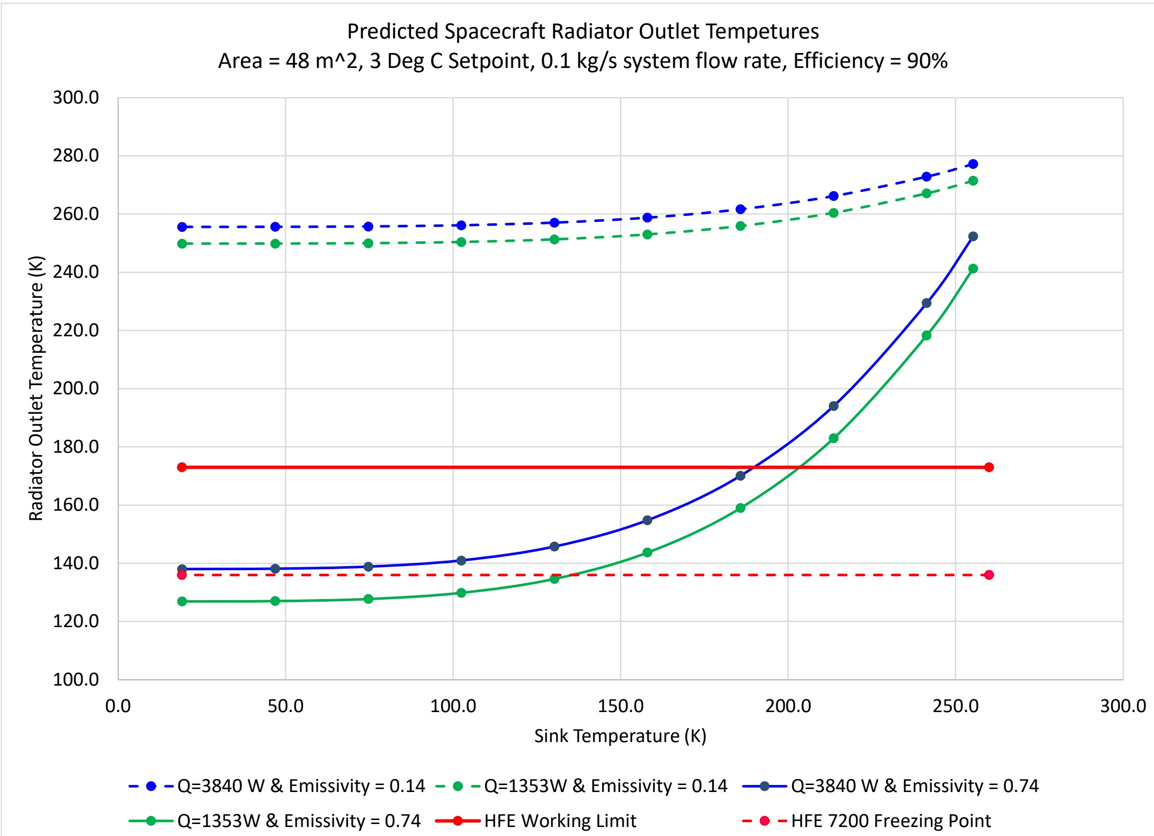

Figure 8 LSH Radiator Outlet Temperatures for 0.14 and 0.74 emissivity and 1300 and 3800 Watts as a Function of Sink Temperature

D. Radiator Heat Rejection Capability with Open Louvers

The louver will shunt some of the heat rejection capacity because the blades will block some of the radiated heat, and this reduction in capability can be calculated by adding a view factor to Equation 2 as shown is Equation 8. Assuming the blades are perpendicular to radiator surface while in the open position, then the view factor can be calculated as a rectangular-to-rectangular plate as shown in equations 9. The view factor will also depend on the number of blades; this paper investigated using 14-blades per panel. The heat rejection capability can be calculated as a function of sink temperature assuming the blade area and radiator surface area are equal.

The results shown in Figure 9 indicate a 13 to 7% reduction in heat rejection capability with the louvers. The slight reduction in capability outweighs the reduction due to ionized UV and dust, which can range from 20 to 120%. The analysis in this paper provides an estimated heat rejection capability for initial design consideration, and testing is required to refine the analysis for detailed designs.

$$Q_r = \sigma \varepsilon \eta F A (T_r^4 - T_s^4) \quad \text{Eq. (8)}$$

$$F = \frac{1}{\pi}\left[2acrtan\left(\frac{1}{h}\right) - \sqrt{2}arctan\left(\frac{1}{\sqrt{2}h}\right) + \frac{1}{2h}ln\left(\frac{h_1 h_2}{4}\right)\right] \quad \text{Eq. (9)}$$

F is the view factor, h is the lengths divided by the widths of the blade, and h_1 and h_2 are calculated from Equations l0 and 11, respectively.

$$h_1 = 2(1 + h^2) \qquad \text{Eq. (10)}$$

$$h_1 = \left(1 + \frac{1}{h_1}\right)^{2h^2-1} \qquad \text{Eq. (11)}$$

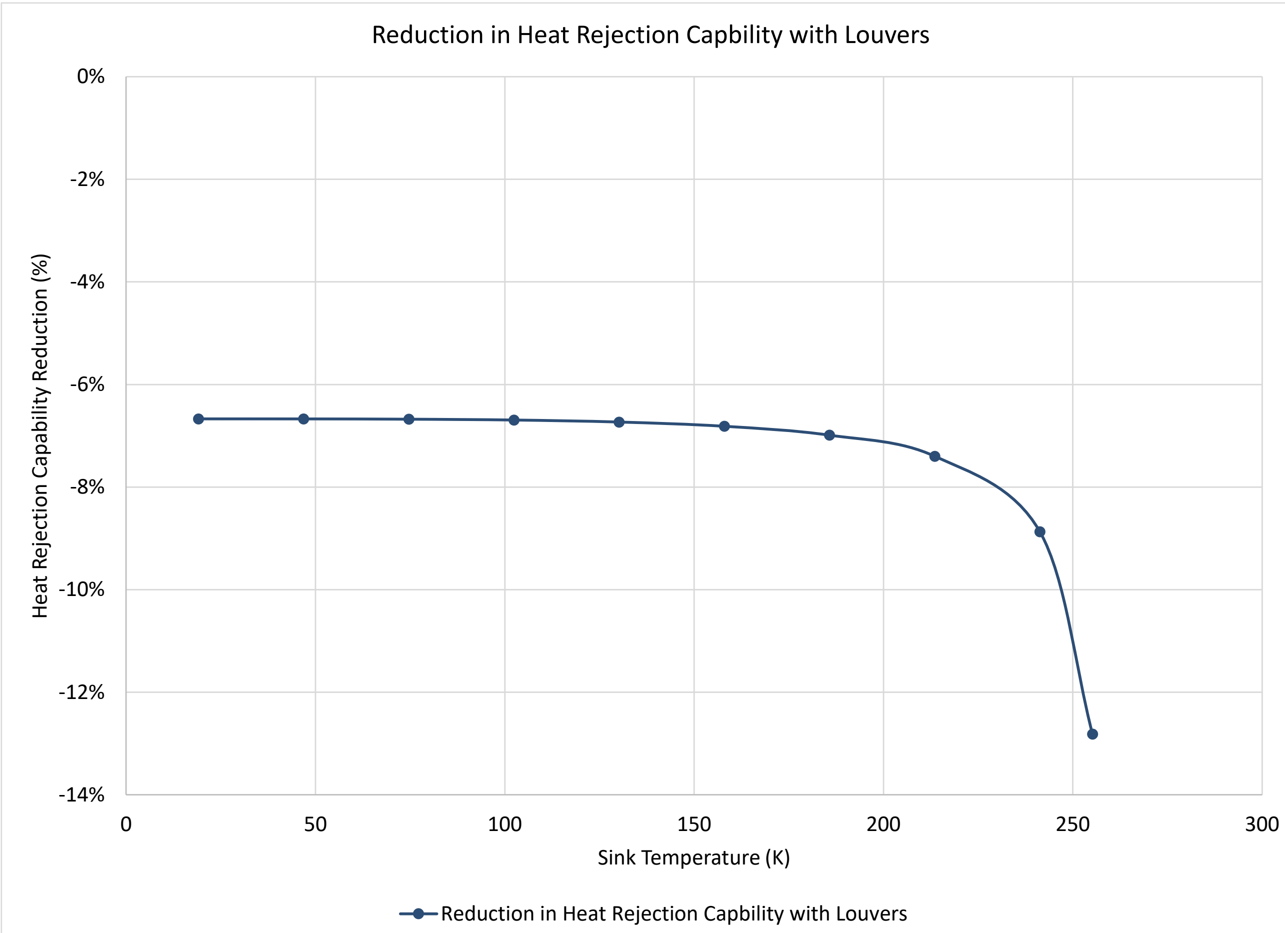

Figure 9. Heat Rejection Capability with a 14 Blade Louver and View Factor

IV. Actively Controlled Louver Design Considerations

Louvers have been used on satellites like New Horizons Pluto and Rosetta[12] for decades, but not on heritage human spacecrafts. Therefore, they have a low Technical Readiness Level[14] (TRL), and advancement in the technology is necessary to make it practical for human spacecraft radiators. For instance, the louver blades will need to be actuated using active control, like a motor, rather than a conventional passive bimetallic spring, to improve thermal response times. Passively controlled louver blades are actuated based on the environmental temperatures and can take hours transitioning from open to closed.

The I-HAB and LSH heat loads[3] can vary between 2 and 15 kW and it may be necessary to reject heat while astronauts are onboard during the nighttime. Passively controlled louvers may prevent heat rejection during nighttime, and temperatures can exceed limits if the transition time is not decreased. Therefore, active control is necessary for operators to control when to open and close the louver and reduce the transition times to minutes.

The total surface area and weight of a 14-blade conventional louver is less than 0.14 m^2 (217 in^2) and 1 kg (2.2 lb.). For the LSH, this will require approximately 85 louvers to cover a 12 m^2 (129 ft^2) radiator and add approximately 85 kg (187 lb.) to the radiator. This is a 50% increase in radiator mass and can impact manifest cost and launch volume. Therefore, a goal is to limit the louver mass to less than 0.5 kg (1 lb.). Though the preferred louver material is aluminum, other materials can be explored but must conform to NASA's Standard Materials and Processes Requirements for Spacecrafts (NASA-STD-6016A). In addition, controls should be in place to minimize or mitigate electromagnetic charging for metallic actively controlled louver designs, and the actuation mechanism should be protected from the lunar environment and dust. Table 1 is a list of design consideration for an actively controlled louver in comparison to a passively controlled louver.

Parameter	Passive Louver	Active Louver
Emissivity Range	0.14 to 0.74	0.14 to 0.74
Heater Power	4 kW	0
Power	0 kW	Less than 350 W
14-Blade Weight	1 kg (2.2 lb.)	0.5 kg (1 lb.)
Blade Thickness	Less than or equal to 1.3 cm (0.5 in)	Less than or equal to 1.3 cm (0.5 in)
Open to Close Response Time	1 to 2 hours	< 15 minutes

Table 1. Human Spacecraft Active Louver Design Considerations Compared to Passive Louvers

V. Conclusions and Recommendations

Equipping human spacecraft radiators with louvers is a feasible solution to limit coating degradation due to ionized UV and lunar dust, as well as mitigate coolant freezing concerns during Artemis Missions. Analysis in this paper showed louver blades with standard ~1.3 cm (0.5 in) thickness can negate ionized UV that can otherwise reduce rejection capability by 60%. In addition, the radiator's heat rejection capability may be reduced up to 120% depending on the amount of dust coverage and can be mitigated by closing the louver during events that will spur up dust. Louvers may naturally reduce the heat rejection capability due to radiative view factors, but the slight reduction in capability (7-13%) outweighs the reduction due to dust and ionized UV.

The analysis also showed that adding louvers to a radiator can keep the coolant above the working and freezing limits during transit to lunar orbit and nighttime on the Moon's surface, therefore eliminating heater power needs and reducing the Loss of Mission (LOM) risk. Technology development is necessary to advance the louver from the conventional passive controlled to active control to reduce the thermal response time from approximately hours to minutes.

References

[1] Kirasich, Mark., Kshatriya, Amit., "Artemis I-IV Mission Overview/Status," NASA Advisory Council (NAC), October 31, 2022.

[2] Schunk, G., "Conceptual Thermal Control System Design for a Lunar Surface Habitat," *Thermal & Fluids Analysis Workshop*, 24-26 August 2021.

[3] IDS Business Support, "Active Thermal Control Systems (ATCS) Overview," URL: https://www.nasa.gov/pdf/473486main_iss_atcs_overview.pdf [cited 15 January 2019].

[4] "Apollo Rocketed Through the Van Allen Belts" URL: https://www.popsci.com/blog-network/vintage-space/apollo-rocketed-through-van-allen-belts/ [Cited 19 September 2014]

[5] McGuire, M.L., McCarty, S. L., et al., "Overview of the Lunar Transfer Trajectory of the Co-Manifested First Elements of NASA's Gateway," *AAS/AIAA Astrodynamics Specialist Conference,* 5 August 2021.

[6] Sawyer, D.M., Vette, J.I.,"AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum," NASA Technical Memorandum TM-X-72605, pg. 87, December 1976.

[7] Edwards, D.L., Zwiener., J,M., "Radiation Induced Degradation of White Thermal Control Paints Z-93 and Z-93P," NASA Technical Memorandum 108518, October 1996.

[8] Gilmore, D., *Spacecraft Thermal Control Handbook*, 2nd ed., The Aerospace Press, California, 2002, Chaps. 6.

[9] Gaier, J.R., Siamidis, J., et al., "The Effect of Simulated Lunar Dust on the Absorptivity, Emissivity, and Operating Temperature on AZ–93 and Ag/FEP Thermal Control Surfaces," NASA Technical Memorandum 215492, December 2008.

[10] Ungar, E.K., "Spacecraft Radiator Freeze Protection Using a Regenerative Heat Exchanger with Bypass Setpoint Temperature Control," *38th International Conference on Environmental Systems (ICES)*, 29 June – 3 July 2008.

[11] Hager, David., Binns., David., "Thermal design challenges of lunar ISRU payloads," *50th International Conference on Environmental Systems (ICES)*, 12-15 July 2021.

[12] Sierra Nevada Corporation (SNC) Product Catalog 2015.

[13] NIST., "Aluminum Attenuation Coefficient," URL: https://physics.nist.gov/PhysRefData/XrayMassCoef/ElemTab/z13.html

[14] NASA., "NASA Technical Readiness Levels" URL: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level [cited 28 October 2012].