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# Thermal Performance of *Orion* Active Thermal Control System With Seven-Panel Reduced-Curvature Radiator

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## Summary

The active thermal control system (ATCS) of the crew exploration vehicle (*Orion*) uses radiator panels with fluid loops as the primary system to reject heat from spacecraft. The Lockheed Martin (LM) baseline Orion ATCS uses eight-panel radiator coated with silver Teflon coating (STC) for International Space Station (ISS) missions, and uses seven-panel radiator coated with AZ–93 white paint for lunar missions. As an option to increase the radiator area with minimal impact on other component locations and interfaces, the reduced-curvature (RC) radiator concept was introduced and investigated here for the thermal perspective. Each RC radiator panel has 15 percent more area than each Lockheed Martin (LM) baseline radiator panel. The objective was to determine if the RC seven-panel radiator concept could be used in the ATCS for both ISS and lunar missions. Three radiator configurations—the LM baseline, an RC seven-panel radiator with STC, and an RC seven-panel radiator with AZ–93 coating—were considered in the ATCS for ISS missions. Two radiator configurations—the LM baseline and an RC seven-panel radiator with AZ–93 coating were considered in the ATCS for lunar missions. A Simulink/MATLAB model of the ATCS was used to compute the ATCS performance. Some major hot phases on the thermal timeline were selected because of concern about the large amount of water sublimated for thermal topping. It was concluded that an ATCS with an RC seven-panel radiator could be used for both ISS and lunar missions, but with two different coatings—STC for ISS missions and AZ–93 for lunar missions—to provide performance similar to or better than that of the LM baseline ATCS.

## Introduction

The Orion project is under the Constellation Program for the space exploration vision initiated by President Bush in 2004. The Constellation Program is responsible for providing the elements that will transport humans and cargo to both the International Space Station (ISS) and the Moon. These elements are the crew exploration vehicle (*Orion*), the crew launch vehicle (Ares I), the lunar surface access module (Altair), and the cargo launch vehicle (Ares V). *Orion*, with a crew of up to four astronauts, will launch on Ares I and then use its main engine to insert itself into a safe orbit to either dock with the ISS or with Altair. For ISS missions, *Orion* will be responsible for separation, entry, descent, and landing. For lunar missions, *Orion* also will have to maintain itself in low lunar orbit and perform a trans-Earth injection maneuver to return from the Moon. *Orion* consists of the Launch Abort System (LAS), Crew Module (CM), Service Module (SM), and Spacecraft Adapter (SA). The CM is a capsule design that provides the primary structure for crew support, incorporates the bulk of the avionics systems, and provides the capability for entry and parachute landing. The LAS will safely extract the CM from the launch configuration in the event of an early launch abort. The SM is the structure on which the CM rests and interfaces with Ares I launch vehicle. It will perform in-space flight propulsion operations and power generation and provide the heat rejection for the *Orion* active thermal control system (ATCS).

This study focuses on *Orion*'s ATCS. The purpose of the ATCS is to control the crew environment inside the CM, while maintaining the temperature of all avionics under their temperature limits. As shown in Figure 1, two CM fluid loops will pass through the CM, take heat generated inside the CM and from all electronics, then pass the heat to the SM fluid loops through two interface heat exchangers. On the CM side, there will be a phase-change material (PCM) heat exchanger (HX) and a sublimator for thermal

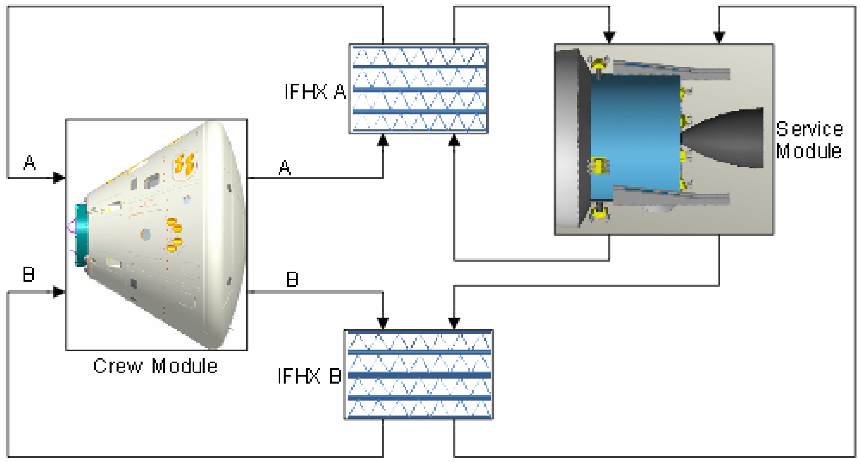

Figure 1.—Active thermal control system for *Orion*. IFHX, interface heat exchanger.

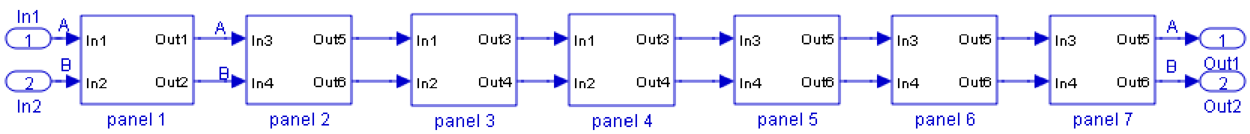

Figure 2.—Seven-panel radiator with two fluid loops.

topping during high heat load phases of the mission. The PCM HX is used only for lunar missions and the sublimator is used for both ISS and lunar missions. The SM fluid loops will carry the heat to the radiator panels and radiate the heat to space.

The radiator panel has a thin surface with fluid channels attached at its interior surface. The interior surface is covered by multilayer insulation blankets. The exterior surface is coated with material that has high emissivity. The fluid loop will come into the header and split the flow through a number of channels along the panel. For the two-loop (A and B) flow configuration, the channel will flow alternately along fluid loops A and B, and the flow condition in the two loops can be different.

The Lockheed Martin (LM) baseline design has an eight-panel radiator with flow going through two loops in series for ISS missions and a seven-panel radiator for lunar missions as shown in Figure 2. The coating on the radiator is different for ISS missions and lunar missions. The LM baseline ISS radiator uses silver Teflon coating (STC) that has a solar absorptivity and emissivity of 0.11 and 0.88, respectively. For lunar missions, the *Orion* radiator will use AZ–93, which has a solar absorptivity and emissivity of 0.2 and 0.90, respectively.

The RC radiator concept is introduced in Reference 1 and is shown in Figure 3. The major difference between the LM baseline radiator and the RC radiator is that each RC radiator panel has 15 percent more area and a reduced curvature. Two coatings, STC and AZ–93, were considered for the RC radiator concept. Three radiator configurations are evaluated for ISS missions: an LM baseline eight-panel radiator with STC, an RC seven-panel radiator with STC, and an RC seven-panel radiator with AZ–93 coating. Two radiator configurations are evaluated for the lunar missions: an LM baseline seven-panel radiator with AZ–93 coating and an RC seven-panel radiator with AZ–93 coating. The performance of the ATCS with RC radiator was evaluated for both ISS and lunar missions and compared with that of the LM baseline ATCS.

A dynamic model of the ATCS built using Simulink/MATLAB was used to compute the performance. The model includes all major components in the ATCS: the cabin HX, cold plates on the CM and SM sides, the interface heat exchanger, the regenerative HX, the PCM HX, and the radiator with its fluid loops on the SM side. The control system also was modeled to meet the thermal requirements for

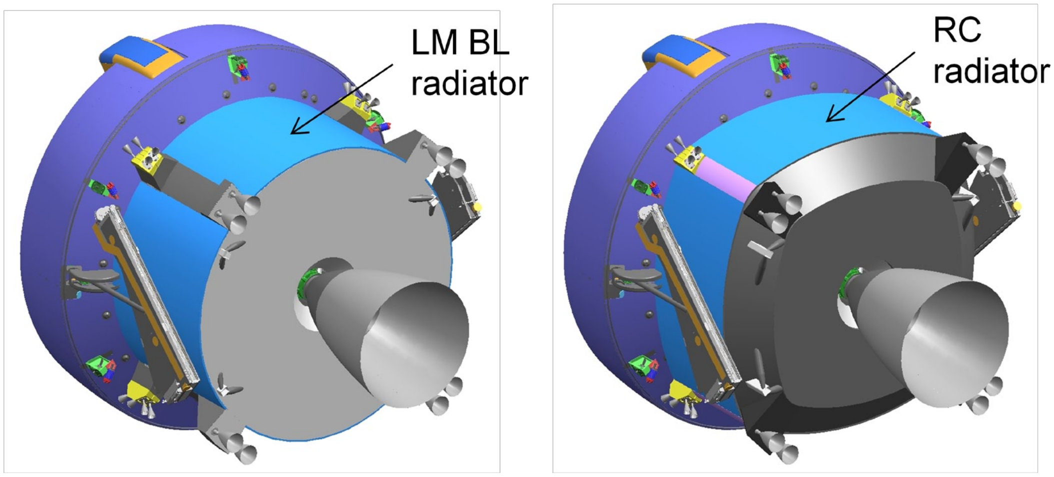

Figure 3.—Reduced-curvature (RC) radiator configuration compared with a Lockheed Martin (LM) baseline (BL) radiator.

the ATCS. The initial conditions and the ambient radiation sink temperature for the radiators must be provided for the model. Reference 2 describes the model in detail.

The following sections describe the ATCS thermal performance of each configuration for both the ISS and lunar missions and present the results. Then the conclusions are given.

## Thermal Performance of the Active Thermal Control System With a Reduced-Curvature Radiator for International Space Station Missions

Each RC radiator panel has 15 percent more area than the LM baseline. The LM baseline ATCS for ISS missions uses an eight-panel radiator. The RC seven-panel radiator has the same total area as the LM baseline eight-panel radiator. The RC seven-panel radiator concept was studied with two different optical coatings. The study's goals were to determine if the seven-panel RC radiator could replace the LM baseline eight-panel radiator design, (1) providing similar performance, (2) allowing cargo to be installed in the bay where the eighth panel is located, and (3) reducing the amount of water sublimated and total mass of the vehicle. An additional goal was to determine if the STC used for the LM baseline radiator for ISS missions could be replaced with AZ–93 coating (the same coating used for lunar missions) to simplify the design and qualification test articles.

Four major on-orbit hot cases, one ISS docked case on node 3, and two on-orbit cold cases on the thermal timeline were selected for the study. The four hot cases were two low Earth orbit (LEO) aft to Sun, LEO nose forward, and LEO tail nadir. The two cold cases were LEO nose forward and LEO aft to Sun. Table 1 lists the thermal beta angle; altitude; attitude; pitch, yaw, and roll angles; ATCS heat load; phase duration; and the orbit time for each case. The LEO aft to Sun case with a power load of 3728 W and the docked case were the dominant hot cases that required the most sublimator water usage.

The ATCS performance results were computed using the NASA Glenn Research Center's Simulink/MATLAB model with the sink temperature version 13 provided by LM. Table 2 lists the results for the three configurations.

During the four hot on-orbit cases and the one ISS docked case in the thermal timeline, the ATCS total water usages were

- LM eight-panel radiator with STC: 11.2 lb (baseline)
- RC seven-panel radiator with STC: 1.7 lb
- RC seven-panel radiator with AZ–93 coating: 20.0 lb

For the cold cases, the RC radiator with STC needed to have 2 to 3 percent more flow going through the regenerative HX than for the LM baseline radiator to keep the system as warm as required.

TABLE 1.—CASE DESCRIPTIONS FOR INTERNATIONAL SPACE STATION (ISS) MISSIONS

| Cases[a] | β | Altitude, km | Attitude[a] | Pitch | Yaw | Roll | ATCS[b] load, W | Phase duration, hr | Orbit time, hr |
|---|---|---|---|---|---|---|---|---|---|
| LEO AtS hot | 75 | 230 | AtS | 5 | –5 | 0 | 4683 | 1.27 | 1.485 |
| LEO NF hot | 75 | 230 | NF | 0 | 0 | 315 | 4429 | 3.62 | 1.485 |
| LEO TN hot | 75 | 230 | TN | 0 | 0 | 270 | 4429 | 3.3 | 1.485 |
| LEO AtS hot | 75 | 230 | AtS | 5 | –5 | 0 | 3728 | 15.65 | 1.485 |
| ISS node 3 docked | 75 | 350 | | –20 | –15 | 15 | 2329 | 5054 | 1.529 |
| LEO NF cold | 40 | 460 | NF | 0 | 0 | 315 | 2406 | | 1.5632 |
| LEO AtS cold | 0 | 460 | AtS | 0 | 0 | 0 | 1870 | | 1.5632 |

[a]LEO, low Earth orbit; AtS, aft to Sun; NF, nose forward; TN, tail nadir.
[b]ATCS, active thermal control system.

TABLE 2.—ACTIVE THERMAL CONTROL SYSTEM (ATCS) PERFORMANCE FOR INTERNATIONAL SPACE STATION (ISS) MISSIONS

| Cases[a] | Lockheed Martin baseline eight-panel radiator with silver Teflon coating (STC) | | Reduced-curvature seven-panel radiator with STC | | Reduced-curvature seven-panel radiator with AZ–93 coating | |
|---|---|---|---|---|---|---|
| | ATCS water usage per orbit, lb | Flow to regenerative heat exchanger | ATCS water usage per orbit, lb | Flow to regenerative heat exchanger | ATCS water usage per orbit, lb | Flow to regenerative heat exchanger |
| LEO AtS hot | 1.68 | 0 | 0.73 | 0 | 2.4 | 0 |
| LEO NF hot | 1.63 | 0 | .44 | 0 | 5.1 | 0 |
| LEO TN hot | 2.6 | 0 | .0 | 0 | 2.46 | 0 |
| LEO AtS hot | 0 | 0 | 0 | 0 | 0.0 | 0 |
| ISS node 3 docked | 0 | 0 | 0 | 0 | 0 | 0 |
| LEO NF cold | 0 | 62 | 0 | 65 | 0 | 62 |
| LEO AtS cold | 0 | 80 | 0 | 82 | 0 | 80 |

[a]LEO, low Earth orbit; AtS, aft to Sun; NF, nose forward; TN, tail nadir.

It can be concluded that the ATCS with RC seven-panel radiator with STC would have better performance than would the LM baseline ATCS and that less water would sublimate. However, the ATCS with RC seven-panel radiator with AZ–93 coating would sublimate more water than the LM baseline ATCS would.

## Thermal Performance of an Active Thermal Control System With a Reduced-Curvature Radiator for Lunar Missions

The LM baseline ATCS for lunar missions uses a seven-panel radiator. The RC seven-panel radiator has 15 percent more total radiator surface area than the LM baseline seven-panel radiator since each RC radiator panel has 15 percent more area than the LM baseline.

A larger radiator area will increase heat rejection and reduce the amount of water sublimated for the hot case: when the heat load on the ATCS is high and the environment is hot. For cold cases when the heat load is low and the environment is cold, a larger radiator area will make the system colder. Thus, a larger radiator area will result in increasing flow to the regenerative HX, which is used to keep the fluid temperature from going below a defined set point of 20 °F. We needed to find out how much the amount of sublimated water could be reduced and how cold the system would get when all the control requirements were met for the different configurations.

The study's goals for lunar missions were to determine if the seven-panel RC radiator could replace the LM seven-panel radiator with the same coating (AZ–93). Seven hot cases and two cold cases on the timeline were used. The hot cases were LEO aft to Sun, LEO nose forward, LEO tail nadir, LEO nose nadir, lower lunar orbit (LLO) aft to Sun, LLO nose forward, and LLO nose nadir. The cold cases were LLO aft to Sun and lunar transit aft to Sun. The details of each case are listed in Table 3, and the results are listed in Table 4.

TABLE 3.—CASE DESCRIPTIONS FOR LUNAR MISSIONS

| Cases[a] | β angle | Altitude, km | Attitude[a] | Pitch | Yaw | Roll | ATCS[b] load, W | ATCS[b] load duration | Orbit time, hr |
|---|---|---|---|---|---|---|---|---|---|
| LEO AtS hot | 56 | 172 | AtS | 20 | –20 | 0 | 4500 | 23 min | 1.466 |
| LEO NF hot | 56 | 172 | NF | 0 | 0 | 315 | 4134 | 2.3 hr | 1.466 |
| LEO TN hot | 56 | 172 | TN | 0 | 0 | 270 | 4246 | 45 min | 1.466 |
| LEO NN hot | 56 | 172 | NN | 20 | 20 | 0 | 3500 | 86 hr | 1.466 |
| LLO AtS cold | 90 | 400 | AtS | 0 | 0 | 0 | 1725 | | 2.465 |
| Lt AtS cold | | | AtS | 20 | –20 | 0 | 2512 | | 2.0 |
| LLO AtS hot | 0 | 90 | AtS | 5 | –5 | 0 | 3799 | 83 hr | 1.949 |
| LLO NF hot | 0 | 90 | NF | 0 | 0 | 180 | 3650 | 2 hr | 1.949 |
| LLO NN hot | 0 | 75 | NN | –20 | 20 | 0 | 2571 | 161.67 hr | 1.925 |

[a]LEO, low Earth orbit; AtS, aft to Sun; NF, nose forward; TN, tail nadir; NN, nose nadir; LLO, lower lunar orbit; Lt, lunar transit.
[b]ATCS, active thermal control system.

TABLE 4.—ACTIVE THERMAL CONTROL SYSTEM (ATCS)
PERFORMANCE FOR LUNAR MISSIONS

| Cases[a] | Lockheed Martin baseline seven-panel radiator with AZ–93 coating | | Reduced-curvature seven-panel radiator with AZ–93 coating | |
|---|---|---|---|---|
| | ATCS water usage per orbit, lb | Water flow to regenerative heat exchanger, percent | ATCS water usage per orbit, lb | Water flow to regenerative heat exchanger, percent |
| LEO AtS hot | 0 | 0 | 0 | 0 |
| LEO NF hot | 0 | 0 | 0 | 0 |
| LEO TN hot | 0 | 0 | 0 | 0 |
| LEO NN hot | 0 | 0 | 0 | 23 |
| LLO AtS cold | 0 | 80 | 0 | 85 |
| Lt AtS cold | 0 | 58 | 0 | 64 |
| LLO AtS hot | 0 | 0 | 0 | 32 |
| LLO NF hot | 2.33 | 0 | 1.56 | 20 |
| LLO NN hot | 0 | 50 | 0 | 60 |

[a]LEO, low Earth orbit; AtS, aft to Sun; NF, nose forward; TN, tail nadir; NN, nose nadir; LLO, lower lunar orbit; Lt, lunar transit.

The PCM is planned to be used for lunar missions only for thermal topping. The wax in the PCM will melt during hot operations and will freeze during cold operations. For the LLO nose-forward hot case, the ATCS with the RC radiator sublimated slightly less water than did the LM baseline radiator. For other hot cases, the ATCS with the RC radiator melted less wax in the PCM than did the LM baseline, but no water was sublimated in either configuration. In all cases, the ATCS with the RC radiator had more flow going through the regenerative HX because this radiator has more surface area, but it never reached 100-percent flow to the regenerative HX. Overall, the ATCS with RC seven-panel radiator had similar performance to the LM baseline ATCS.

In conclusion, the ATCS with RC seven-panel radiator could be used for both ISS and lunar missions, but with two different coatings—STC for ISS missions and AZ–93 for lunar missions—to minimize water usage.

## Conclusions

The RC radiator concept was investigated for the *Orion* ATCS. The thermal performance of the ATCS with the RC radiator concept was computed and compared with the LM baseline design for both ISS and lunar missions. It was concluded that, for ISS missions, the ATCS with the RC seven-panel radiator with STC performs better than the LM baseline and would use less water for sublimation; however, the ATCS with the RC seven-panel radiator with AZ–93 coating would sublimate twice as much water as the LM baseline ATCS. For lunar missions, the ATCS with RC seven-panel radiator would have performance similar to that of the LM baseline. Further studies are planned to validate the results presented here and the ATCS performance on the entire timeline will be compared for each configuration.

# References


1. Thomas Goodnight, Thomas Cressman, private communications, NASA Glenn Research Center, Cleveland, OH
2. Wang, Xiao-Yen J.; and Yuko, James: "*Orion* Active Thermal Control System Dynamic Modeling Using Simulink/MATLAB," AIAA–2010–0810 (see also NASA/TM—2010-216252), 2010.

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**14. ABSTRACT**
The active thermal control system (ATCS) of the crew exploration vehicle (*Orion*) uses radiator panels with fluid loops as the primary system to reject heat from spacecraft. The Lockheed Martin (LM) baseline Orion ATCS uses eight-panel radiator coated with silver Teflon coating (STC) for International Space Station (ISS) missions, and uses seven-panel radiator coated with AZ-93 white paint for lunar missions. As an option to increase the radiator area with minimal impact on other component locations and interfaces, the reduced-curvature (RC) radiator concept was introduced and investigated here for the thermal perspective. Each RC radiator panel has 15 percent more area than each Lockheed Martin (LM) baseline radiator panel. The objective was to determine if the RC seven-panel radiator concept could be used in the ATCS for both ISS and lunar missions. Three radiator configurations-the LM baseline, an RC seven-panel radiator with STC, and an RC seven-panel radiator with AZ-93 coating-were considered in the ATCS for ISS missions. Two radiator configurations-the LM baseline and an RC seven-panel radiator with AZ-93 coating were considered in the ATCS for lunar missions. A Simulink/MATLAB model of the ATCS was used to compute the ATCS performance. Some major hot phases on the thermal timeline were selected because of concern about the large amount of water sublimated for thermal topping. It was concluded that an ATCS with an RC seven-panel radiator could be used for both ISS and lunar missions, but with two different coatings-STC for ISS missions and AZ-93 for lunar missions-to provide performance similar to or better than that of the LM baseline ATCS.

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