

A Comparison between One- and Two-Loop ATCS Architectures Proposed for CEV

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ABSTRACT

In an effort to help future crewed spacecraft thermal control analysts understand the characteristics of one- and two-loop Active Thermal Control Systems (ATCS), a comparison was made between the one- and two-loop ATCS architectures officially proposed for the Crew Exploration Vehicle (CEV) in Design Analysis Cycle 1 (DAC1) and DAC2, respectively. This report provides a description of each design, along with mass and power estimates derived from their respective Master Equipment List (MEL) and Power Equipment List (PEL). Since some of the components were sized independent of loop architecture (ex. coldplates and heat exchangers), the mass and power for these components were based on the MEL and PEL of the most mature design (i.e. two-loop architecture). The mass and power of the two architectures are then compared and the ability of each design to meet CEV requirements is discussed.

INTRODUCTION

As the Crew Exploration Vehicle (CEV) evolved in recent years, several subsystems experienced major design changes, including the Active Thermal Control System (ATCS). Towards the end of Design Analysis Cycle 1 (DAC1), a series of analyses confirmed that the one-loop ATCS approach was unable to accommodate the operating range of the vehicle. In short, the one-loop design provided a limited 'turndown ratio' because its large radiator, designed to reject high heat loads in hot

thermal environments, became oversized when rejecting low loads in cold thermal environments. Turndown ratio is defined as the ratio between the highest and lowest system heat loads that the ATCS can handle in the hottest and coldest thermal environments, respectively. The issue was even more challenging because engineers were limited to non-toxic fluids, which generally have higher freezing temperatures and viscosities, and stall resistant radiator designs. Radiator stall is defined as the process in which fluid freezes and prevents flow in some radiator tubes in order to reduce the total heat rejection. As the time and resources needed to bring the one-loop technology up to speed became increasingly scarce, the Environmental Control and Life Support System (ECLSS) design team decided to resort to a two-loop architecture in DAC2.

ONE-LOOP ATCS DESIGN

The original design of the CEV ATCS in DAC1 was based on one single-phase, mechanically-pumped fluid loop that transferred the system heat load directly to a radiator using a 50/50 mixture (by mass) of propylene glycol and water (PGW). A one-loop ATCS approach was initially selected over a traditional two-loop ATCS because it consists of fewer components, which allows for mass and power savings and increased reliability. After several iterations on a one-loop architecture, which were primarily driven by weight reduction exercises, the ECLSS team arrived at the 606C configuration, released November 16, 2007. The lunar mission schematic for this configuration is shown in Figure 1 (see end of

paper). For redundancy, the one-loop design is shown to have two fully independent loops, A and B, each handling half of the system heat load during nominal operation.

The following is a brief description of the primary ATCS components that the coolant interacts with in each loop, starting where the coolant lines (shown in orange) leave the Crew Module (CM) and enter the Service Module (SM) in Figure 1. The coolant then passes through a set of SM coldplates, followed by a radiator with a total radiating surface area of 15.8 m² (170 ft²). After leaving the radiator, the coolant passes through a sublimator, which provides cooling during ascent, descent, and total radiator failure scenarios. The coolant then passes through a Phase Change Material (PCM) Heat Exchanger (HX), which provides additional heat rejection (via heat storage) when the radiator is unable to reject the total system heat load. After the PCM HX, the coolant reaches a bypass mixing valve. Here, a valve controller allows hot bypass fluid to mix with the cold fluid leaving the heat rejection devices in order to achieve a constant cabin inlet temperature. Downstream of the mixing valve, the coolant enters the pressurized cabin volume and encounters a Liquid Cooling Garment (LCG) HX, which is only active under suited crewmember conditions. Following the LCG HX, the coolant passes through an Air Revitalization System (ARS) HX and a Cabin Air HX plumbed in parallel. After the ARS and Cabin Air HXs, the coolant reaches another mixing valve, which is actively controlled to adjust the proportion of flow between the two HXs in order to maintain a cabin air temperature setpoint. The coolant then continues through a set of pressurized CM coldplates before reaching an accumulator and pump. After the pump, the coolant enters the un-pressurized portion of the CM and passes through another bank of coldplates. Finally, the coolant reaches the bypass split point where it either continues to the CM/SM interface or returns to the bypass mixing valve.

In order to optimize performance while keeping component and coolant temperatures within their limits, the 606C ATCS control algorithm has three main objectives: maintain a 281.5 K (47 °F) cabin inlet temperature, achieve but not exceed an SM coldplate bank outlet temperature (radiator inlet temperature) of 309 K (96.5 °F), and prevent coolant temperatures below 260.9 K (10 °F). The primary drivers that determined these temperature requirements were cabin dew point temperature, avionics box upper certification limits, and pump concerns (from increased fluid viscosity), respectively. The cabin inlet temperature setpoint is actively controlled by mixing warm radiator bypass flow with cold radiator outlet flow using the bypass mixing valves. The radiator inlet temperature and radiator outlet temperature (minimum coolant temperature) are controlled by decreasing or increasing pump flow rate. Nominally, slight variations in pump flow rate keep the radiator inlet temperature around 309 K (96.5 °F). In an off-nominal situation when the radiator

outlet temperature attempts to fall below 260.9 K (10 °F), the pump controller switches from maintaining the radiator inlet temperature setpoint to maintaining the radiator outlet temperature setpoint. Increasing the radiator outlet temperature is achieved by increasing pump flow rate, which is opposite the action for increasing the radiator inlet temperature.

The mass and power of the major components and subassemblies in the one-loop ATCS design, excluding any growth margin and any associated consumables, are shown in Table 1. These values were pulled directly from the last release of the MEL and PEL for the one-loop design. Since sizing of the coldplates, sublimator subassembly, Ground Support Equipment (GSE) HX (not shown in Figure 1), PCM HX, LCG HX, ARS HX, and Cabin Air HX was based primarily on system heat load rather than loop architecture, values from the latest release of the MEL and PEL for the two-loop design were used instead, due to their greater maturity. It should also be noted that the design assumes a mixture of pure and structural coldplates and the peak sublimator power is associated with heaters on the vent lines. The system mass and peak power for the one-loop design are also shown in Table 1, which resulted in 480 kg and 577 W, respectively.

Table 1. Mass and Power for the One-Loop ATCS Design (606C)

Component	Qty	Total Mass (kg)	Power (W)
Coldplate	20	132	0
Radiator	1	61	0
GSE HX	2	2	0
PCM HX	2	101	0
Sublimator Subassembly	1	46	400 (peak)
Pressurized CM Flow Control Valve Subassembly	1	9	30 (peak)
Un-Pressurized CM Flow Control Valve Subassembly	1	11	30 (peak)
CM/SM Interface Valve Subassembly	1	8	0
LCG HX	1	3	0
ARS HX	1	5	0
Cabin Air HX	1	12	0
Pump Subassembly	1	27	117
Plumbing and Fluid		62	0
System		480	577 (peak)

TWO-LOOP ATCS DESIGN

After realizing the one-loop ATCS design could not accommodate a significant turndown ratio given the wide range of CEV thermal environments, the ECLSS team switched to a traditional two-loop architecture in DAC2, consisting of an Internal Thermal Control System (ITCS) loop and an External Thermal Control System (ETCS) loop.

loop. Despite its physical drawbacks over a one-loop ATCS, the two-loop ATCS is considered a proven technology for human-rated spacecraft with a long history onboard the Space Shuttle and a more recent history on the ISS. The chosen fluids for the ITCS and ETCS loops were 50/50 PGW and 3M Novec HFE-7000, respectively. With several design iterations of this architecture already released, the 606D.03 configuration was selected for comparison since this configuration was already evaluated by the Engineering and Science Contract Group (ESCG). For consistency, the lunar mission schematic for this configuration is also referenced and can be seen in Figure 2 (see end of paper). The 606D.03 configuration also contains two fully independent two-loop systems, A and B, each handling half of the system heat load during nominal operation.

In the ITCS, the components are nearly identical to the 606C configuration, except that the ITCS coolant delivers the system heat load to an Interface (IF) HX, instead of the radiator, and the PCM HX is located in the SM. In the ETCS, the coolant receives the heat load from the IF HX and then passes through an accumulator and pump. After the pump, the coolant flows through a Regenerative HX and then through a radiator with a total area of 20.3 m² (218 ft²). The Regenerative HX was a key component added to the design to help the system achieve the required turndown ratio. Upon leaving the radiator, the ETCS coolant encounters an actively controlled bypass mixing valve. This mixing valve is responsible for maintaining a minimum IF HX outlet temperature on the ITCS side when the radiator heat rejection suddenly exceeds the system heat load. It achieves this by sending more flow to the Regenerative HX and less flow to the Regenerative HX bypass. In this manner, the chilled coolant returning from the radiator picks up heat before entering the IF HX in order to prevent freezing of the ITCS coolant due to its higher freezing point. For all other conditions however, the mixing valve sends all flow through the Regenerative HX bypass to insure the ITCS coolant temperature is low enough to achieve the cabin inlet temperature setpoint.

The objectives of the 606D.03 ATCS control algorithm are essentially the same as those for the 606C control algorithm. The only difference between the two designs is how the setpoints are achieved. In the two-loop design, all of the flow control can be achieved more efficiently using mixing valves. Therefore, the ITCS and ETCS pump flow rates are held constant, while the IF HX and Regenerative HX bypass mixing valves are controlled to maintain temperature setpoints around the loop. Under conditions when the radiator begins to exceed the system heat load, the Regenerative HX bypass mixing valve controller attempts to achieve the minimum coolant temperature at the outlet of the IF HX on the ITCS side, while the IF HX bypass mixing valve controller works to achieve the cabin inlet temperature setpoint. Under nominal conditions or when the radiator cannot handle the system heat load, the regenerative

HX bypass mixing valve controller shuts off flow to the regenerative HX and the IF HX bypass mixing valve controller attempts to maintain the cabin inlet temperature setpoint. If the SM coldplate bank outlet temperature begins to exceed the 309 K (96.5 °F) temperature limit, the IF HX bypass mixing valve controller switches from maintaining the cabin inlet temperature setpoint to maintaining the SM coldplate bank outlet temperature setpoint. To achieve this, the valve controller reduces the IF HX bypass flow, thus decreasing the cabin inlet temperature and subsequently the SM coldplate bank outlet temperature.

A similarly prepared list of the mass and power for the major components and subassemblies in the two-loop ATCS design is shown below in Table 2. The resulting system mass and peak power for the two-loop ATCS design were 605 kg and 711 W, respectively.

MASS AND POWER COMPARISON

A mass and power comparison between the one- and two-loop CEV ATCS design configurations is presented in Tables 3 and 4. For clarity, only the components affected by the change in loop architecture are shown. It is important to note, for the sake of radiator size, that the maximum and minimum system heat load for the CEV ATCS is constantly in flux, and although these values were similar between the two designs, one cannot assume they were identical.

Table 2. Mass and Power for the Two-Loop ATCS Design (606D.03)

Component	Qty	Total Mass (kg)	Power (W)
Coldplate	20	132	0
IF HX	2	22	0
Regenerative HX	2	16	0
Radiator	1	78	0
GSE HX	2	2	0
PCM HX	2	101	0
Sublimator Subassembly	1	46	400 (peak)
Pressurized CM Flow Control Valve Subassembly	1	9	30 (peak)
Un-Pressurized CM Flow Control Valve Subassembly	1	11	30 (peak)
SM Flow Control Valve Subassembly	1	18	30 (peak)
CM/SM Interface Valve Subassembly	1	8	0
LCG HX	1	3	0
ARS HX	1	5	0
Cabin Air HX	1	12	0
ITCS Pump Subassembly	1	27	90
ETCS Pump Subassembly	1	48	132
Plumbing and Fluid		66	0
System		605	711 (peak)