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Europa Clipper Thermal Control Valve Thermal and Hydraulic Analysis and Development Testing

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This paper describes the thermal and hydraulic analysis performed for Europa Clipper heat recovery system (HRS) thermal control valves as well as a total ionizing dose (TID) radiation test to reduce risk of hardware failure during the mission. Europa Clipper is a solar powered mission to Jupiter that flies by Venus for gravity assist leading to a variation in solar irradiance between 48 W/m^2 and 3300 W/m^2 during the mission. Therefore, the spacecraft thermal design necessitates the conservation of heat to the maximum extent possible near Jupiter where solar flux is small and rejection of large amounts of heat during the closest approach to the sun. To achieve this, the HRS employs two thermal control valves operating in series to modulate flow to the radiator between 0.0024 and 1.3 LPM. The thermal and hydraulic analysis were key in determining flow rate to the radiator as a function of fluid temperature and to predict spacecraft temperatures. Hydraulic analysis was also performed to determine leak paths between the block redundant pairs of the thermal control valves. Finally, a development test was undertaken to determine the effects of ionizing radiation on the performance of the thermal control valve. The valve was exposed to a TID of 300 krad (Si), the maximum expected dose in the Vault where the valves are located. The flow characteristics of the valve were measured as a function of temperature before and after radiation exposure to determine the impact of ionizing radiation on valve performance

Nomenclature

A = *Area (m^2)*
CFC-11 = *Trichlorofluoromethane (R-11)*
D = *Diameter (m)*
ECIPA = *Europa Clipper Integrated Pump Assembly*
F = *Friction Factor*
HRS = *Heat Recovery System*
K = *Loss Coefficient*
L = *Length (m)*
MSL = *Mars Science Laboratory*
ρ = *Density (kg/m^3)*
RDF = *Radiation Design Factor*
RTD = *Resistance Temperature Detector*
TC = *Thermocouple*
TCV = *Thermal Control Valve*
TID = *Total Ionizing Dose*
$\dot{V}$ = *Volumetric Flow Rate (m^3/s)*
v = *Flow Velocity (m/s)*
WCC/H = *Worst Case Cold/Hot*

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I. Introduction

Europa Clipper is a deep space planetary exploration mission with the objective of evaluating the potential habitability of Jupiter's icy moon Europa. It aims to (i) characterize the icy shell of Europa and the properties of the subsurface water including ocean salinity and ice sheet thickness, (ii) determine the chemical composition of the surface matter and the atmosphere including potential plumes, and (iii) characterize the geology of the moon to aid with the selection of future landing sites as well as to understand the formation of magmatic, tectonic, and impact landforms [1]. The Europa Clipper spacecraft thermal design utilizes a mechanically pumped fluid loop to control the temperature of the spacecraft components within their allowable limits [2]. The primary components of the loop are the pump, thermal control valves, various aluminum heat exchanging tubes, and stainless-steel transfer tubes to move the CFC-11 fluid around the spacecraft. The purpose of the heat recovery system (HRS) is to absorb heat dissipated by the electronic boxes and transfers it to the rest of the spacecraft. Specifically, the heat is used to maintain propulsion module component temperatures within their specified limits including the propellant tanks, the reaction control system thrusters, reaction wheel units and tubing used for transporting propellant across the spacecraft. The spacecraft is designed to operate between 0.65 AU and 5.6 AU where the solar flux varies from 3300 W/m^2 to 49 W/m^2. When the heat recovered by the HRS exceeds the spacecraft needs the excess heat is rejected out of the radiator. The spacecraft is designed to modulate heat rejection from 15 W when orbiting Jupiter to 300 W during the closest approach to the Sun. To achieve this the HRS uses two passive thermal control valves (TCV) placed in series and low temperature Louvers. The TCVs used for Europa Clipper HRS were initially developed during the Mars Pathfinder program [3] and updated for the Mars Exploration Rover [4] and Mars Science Laboratory [5] missions. It is a three way valve that uses an oil filled actuator to modulate flow coming from each of the inlets between 4% and 96% of the total flow over a temperature range of 20 ^{o}C [6].

The Europa Clipper Integrated Pump Assembly (ECIPA) containing the pump and the TCVs is located within Europa Clipper's Avionics Vault. The latter is an aluminum box with 9.2 mm thick walls that houses all the electronics boxes [7]. It is designed such that the total ionizing dose of the components housed inside will not exceed 300 krad (Si) (RDF=2). The spacecraft will be exposed to ionizing particles composed primarily of electrons and protons trapped in the Jovian radiation belt and solar protons. An ionizing particle is a particle that individually carries enough energy to liberate an electron from an atom. TID damage to dielectric materials presents a major concern to the spacecraft as radiation can degrade the performance and reduce the life of these materials by causing polymer cross-linking and/or breaking down bonds in molecules. The type and degree of damage resulting from exposure to ionizing radiation will depend on the dielectric material as well as radiation type and dose. The DC-200 silicone oil in the TCV actuator is the only dielectric that is present in the valves that may be susceptible to radiation damage.

II. Background

Figure 1 shows a simplified internal ECIPA flow diagram. The fluid leaves ECIPA to service the Vault, the replacement heater block (RHB), the propulsion module and returns to the ECIPA, where the flow is directed to the radiator in WCH conditions or the flow bypasses the radiator in WCC conditions. This is achieved by utilizing two TCVs in series. Figure 1 also shows block redundancy of check valves, TCVs, and the pump where the primary and backup sides are labeled A and B, respectively. The role of check valve 2 is to prevent back flow from the active pump through the inactive side creating a recirculating loop and reducing flow rate of the main system. On the other hand, check valve 1 is used to prevent parasitic recirculating flow from ECIPA inlet (node 1) through the inactive block redundant TCVs. Such unintended parasitic flow paths may have the potential to increase flow rate through the radiator in WCC conditions causing excess heat loss from the spacecraft or it may reduce the flow rate to the radiator in WCH conditions leading to a warmer spacecraft temperature. However, placing a check valve in the flow path contributes approximately 6.9 kPa (1 psi) to the system pressure drop. The Europa Clipper pump is designed to deliver 1.5 LPM of CFC-11 at 152 kPa (22 psid) in pressure drop. Therefore, eliminating a check valve could reduce the system pressure drop by up to 5% potentially adding margin to the system design flow rate that could be helpful in addressing other problems as the spacecraft design evolves.

Figure 1 also illustrates the function of the thermal control valves in ECIPA. When the TCV mixed fluid temperature exceeds 24 ^{o}C, the hot inlets of the TCVs have much larger impedance than to the cold inlets and therefore majority of the fluid coming into ECIPA is directed to the radiator (from node 1 to node 2). On the other hand, in WCC conditions when the TCV mixed fluid temperature is less than 4 ^{o}C the cold inlets of the two TCVs have significantly larger impedance compared to the hot inlets and the fluid bypasses the radiator and recirculates back into the system, i.e., the flow coming in ECIPA flows through nodes 1-3-5 and 1-4-7 to the pump and then to the rest of the system.

Finally, ray trace analysis was performed on the spacecraft to predict the TID the TCV actuator will be exposed to during the mission. This analysis took into account shielding due to the Vault structure and the electronics boxes surrounding the ECIPA, the ECIPA chassis and the stainless steel TCV housing. The estimated end of mission TID (RDF=2) of the actuator was equal to 50 krad (Si). Note that all components in the Vault have a maximum TID of 300 krad (RDF=2) but shielding from neighboring components provided a six-fold reduction in end of mission TID of the valve actuator.

The three objectives of this study were (i) to determine the need for check valves upstream of the thermal control valves and assess the impact of eliminating them, (ii) determine the flow rate to the radiator as a function of TCV mixed fluid temperature, and (iii) determine if the TCV will function as designed in the Jovian radiation environment.

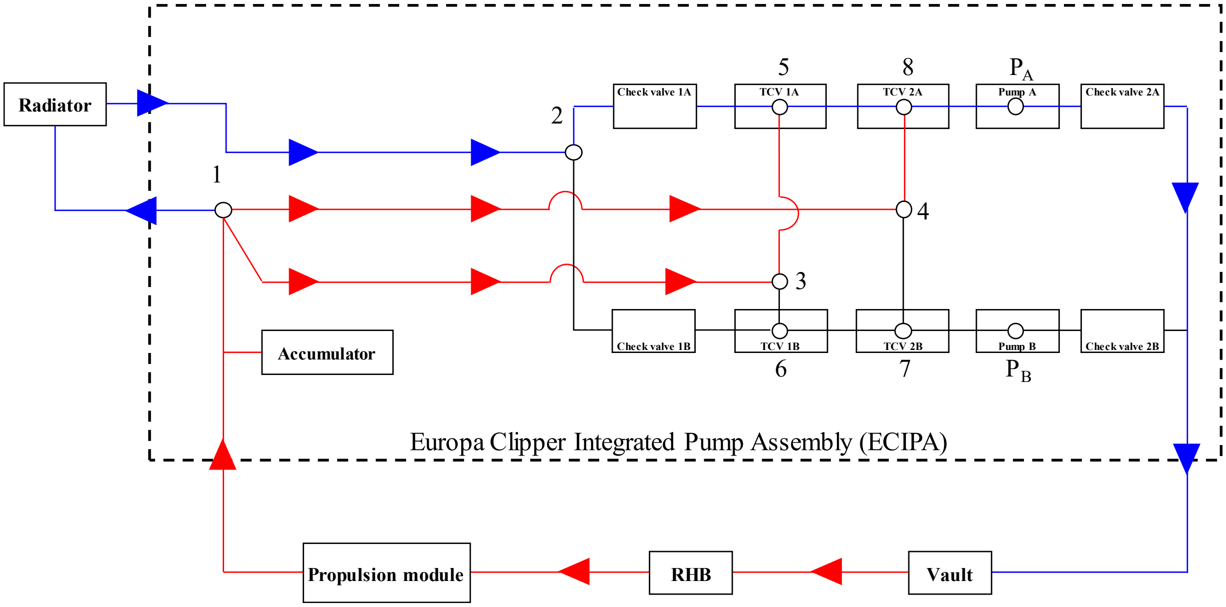

Figure 1: Europa Clipper Integrated Pump Assembly (ECIPA) simplified flow schematics.

III. Analysis

The TCVs are designed to maintain the mixed fluid temperature exiting ECIPA between 4 and 24 °C. The vendor specifies a maximum flow rate of 4% from the cold inlet below a mixed temperature of 4 °C and 96% when the mixed temperature is greater than 24 °C with a linear flow rate versus temperature profile in between 4 and 24 °C. Similarly, the vendor specifies a maximum pressure drop of 13.8 kPa (2 psid) through the TCV when flowing CFC-11 at 1.5 LPM. The TCV design has various orifices, passages, and bends in the flow path causing a drop in the fluid pressure. Pressure drop ΔP is expressed as [8]

$$\Delta P = \frac{1}{2}\rho\left(\frac{fL}{D}\right)v^2 = \frac{1}{2}\rho K v^2 \tag{1}$$

The friction factor f for laminar flow (Re<4000) can be expressed as [8]

$$f = \frac{64}{Re} \tag{2}$$

where Re is Reynolds number. The friction factor f for Turbulent flow ($2\text{x}10^4 < Re < 3\text{x}10^5$) is given by [9]

$$f = 0.18Re^{-0.2} \tag{3}$$

The volumetric flow rate $\dot{V}$ and the flow velocity v are related according to $v = \dot{V}/A$. Then Equation (1) can be written as

$$\Delta P = \frac{1}{2}\rho K \frac{\dot{V}^2}{A^2} = K_{eff}\dot{V}^2 \tag{4}$$

Then the effective impedance K_{eff} of the TCVs were estimated using Equation (4) based on the vendor specification of ΔP=13.8 kPa at $\dot{V}_{\text{hot}}$=2.4 x10^{-5} m^3/s (1.44 LPM) and $\dot{V}_{\text{cold}}$= 0.1 x10^{-5} m^3/s (0.06 LPM) at 24 °C mixed fluid temperature. Here, $\dot{V}_{\text{hot}}$ and $\dot{V}_{\text{cold}}$ correspond to flow rate at the cold and hot inlets, respectively. Figure 2 shows the hot and cold inlet flow impedance estimated for Europa Clipper TCVs as a function of mixed fluid temperature. It also plots experimentally measured values for MSL engineering model (EM) TCVs reported by Birur et al. [6]. There was very good agreement between the Europa Clipper and MSL impedance values between temperatures of 8 and 20 °C. The two curves diverge owing to the fact that MSL EM valves featured significantly lower cold inlet flow rate below the cold set point temperature than what was in the specification. Indeed, Birur et al. [6] reported a 1% flow fraction at the cold inlet instead of 4% in the specifications when the TCV was fully shut, i.e., below the TCV cold set point. Here, we assumed the TCV will perform as specified by the vendor, i.e., it will feature a cold inlet flow rate of 4% at 4 °C linearly increasing to 96% at 24 °C.

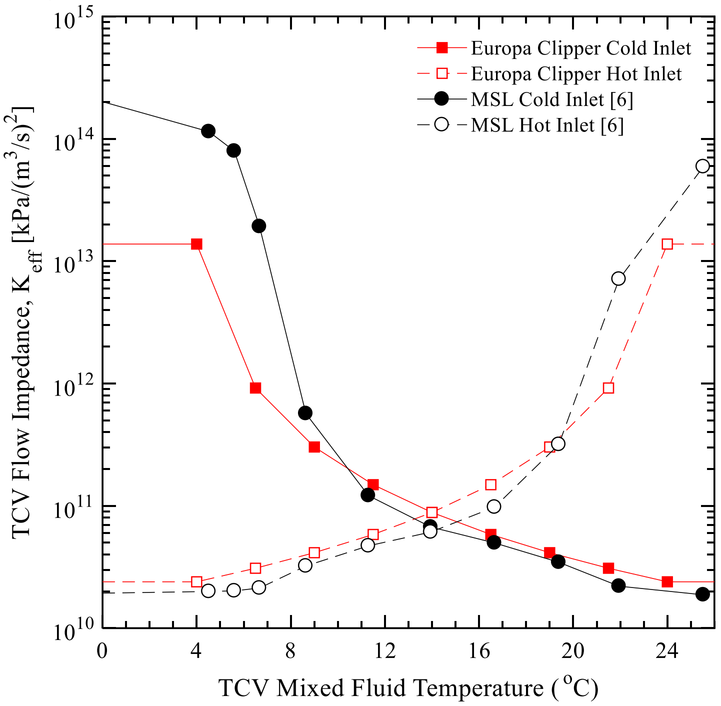

Figure 2: Europa Clipper estimated and measured MSL [6] TCV Hot and cold inlet effective flow impedance K_{eff} as a function of temperature for TCVs with lower and upper setpoint of 4 and 24 °C.

The Europa Clipper thermal radiator consists of 10.2 m of aluminum tubing bonded to the radiator plate and 12.7 m of stainless steel tubing to transfer the fluid from ECIPA, where the TCVs are located, to the radiator and back. Total L/D of the radiator circuit was equal to 5816 when all major and minor losses were taken into account. The check valves featured a cracking pressure of 1.38 kPa (0.2 psid) and a effective flow impedance K_{eff} of 1.39 x 10^9 kPa/(m^3/s)^2. The finite difference solver ThermXL was used to solve for the pressure at each node and the flow rate between individual nodes.

IV. Test setup

Figure 3 shows the schematics of the setup used to test the TCV. It consisted of two piston flow meters (P213 Max Machinery Healdsburg, CA) located at the cold inlet and the outlet of the TCV, two calibrated ΔP transducers (Setra 230 Boxborough, MA) to measure pressure difference between the outlet and each of the TCV inlets and two RTDs (PR-10 Omega Engineering, Norwalk, CT) to measure fluid temperature at the inlet and the outlet of the TCV. Finally, a needle valve was used to control the flow rate of the system. The fluid loop was connected to the ECOSTRESS flow control unit (FCU) which consisted of a rotary vane pump, a vacuum pump, an accumulator, a heater, a cooler, and a PID temperature controller. The working fluid of the FCU is Fluorinert FC-72 and the output fluid temperature can be controlled between 10 ^{o}C and 42 ^{o}C. Note that Europa Clipper uses CFC-11 as the working fluid, however, FC-72 was chosen for this test since the two fluids have similar fluid properties in the temperatures of interest and due to the fact that FC-72 is non-hazardous for health and environment and enjoys wider availability. The TCV used in the test was a development unit PDT 5262 (Pacific Design Technology, Goleta, CA) with set points of 22 ^{o}C and 42 ^{o}C. Data was collected using Keysight 34970A data acquisition system with a 34901A multiplexer. Temperature and flow rate measurements reported were the mean of the values recorded for 30 minutes once the inlet and outlet temperatures reached steady-state ($\Delta T/\Delta t < 0.2$ ^{o}C/hr). All tests were performed with temperature increasing from 20 ^{o}C to 42 ^{o}C and decreasing from 42 ^{o}C to 20 ^{o}C. All measurements were performed with fluid flow rate of 1.5 LPM. The TCV was exposed to gamma radiation using the Co-60 source at JPL high dose rate chamber. The exposure was performed in three steps: 50, 150, and 300 krad (Si). Flow fraction from the cold inlet was measured before radiation exposure and after each of the exposures.

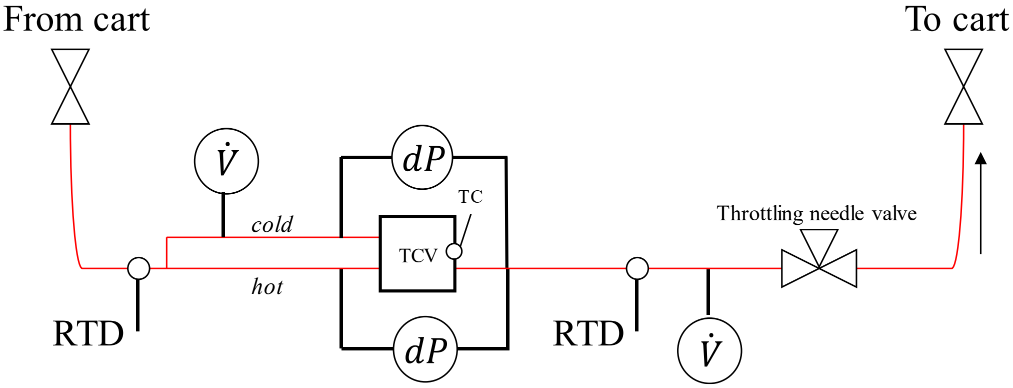

Figure 3: Europa Clipper TCV radiation test loop diagram.

V. Results and Discussion

A. Effects of placing a check valve upstream of the mixing valves

Figure 4 shows the flow schematic of ECIPA in WCH conditions with and without check valves placed upstream of the mixing valves. First, removing check valve 1 reduces flow rate to the radiator in WCH conditions by approximately 10% from 1.3 LPM to 1.18 LPM due to parasitic flow from ECIPA inlet (the node 1) through the block redundant TCV to downstream of the radiator (node 2). This was due to larger pressure at nodes 3 and 4 compared to node 2 where pressure is lower due to the large pressure drop caused by the radiator. However, placing a check valve upstream of TCV1 eliminates this parasitic flow through the block redundant TCVs. Reducing flow rate in the radiator circuit in WCH conditions will result in warmer average spacecraft temperature and potential violations of temperature limits of components on-loop components. Additionally, pressure at the ECIPA inlet (node 1) is 31 kPa relative to the pump when check valve 1 is included in the system compared to 28.6 kPa without a check valve upstream of the TCVs. This corresponds to a 1.5% increase in total system pressure drop. Such small increase in system pressure drop has negligible impact on fluid flow rate [10]. Note that the differential pressures shown in Figure 4 are relative to the pressure at the inlet of the pump. The absolute pressure of the system ranges from 0.48 MPa (69.6 psia) to 1.38 MPa (200 psia). Additionally, Figure 4 illustrates that the radiator and check valve flow impedances limited the maximum flow to the radiator to 1.3 LPM (87% of full flow rate of 1.5 LPM) compared to 1.38 LPM (92.1% of full flow rate) if the radiator and check valve were not present. Indeed, the impedance of the TCV cold inlet for mixed temperature >24 ^{o}C was comparable to the radiator and check valve flow impedances resulting in flow reduction in the radiator branch.

Figure 5 shows the flow schematic of ECIPA in WCC conditions with and without check valves placed upstream of the mixing valves. First, the pressure drop between the inlet of ECIPA (node 1) and the pump is significantly lower in WCC conditions due to fluid bypassing the 23 m long radiator circuit. This corresponded to 15% reduction in the system pressure drop resulting in slightly faster system flow rate in the WCC conditions compared to WCH conditions. Additionally, placing check valves upstream of TCV 1 had no impact in the WCC conditions as nodes 1, 2, 3, and 4 were all at equal pressure and therefore no parasitic flow was present between node 3 or node 4 and node 2.

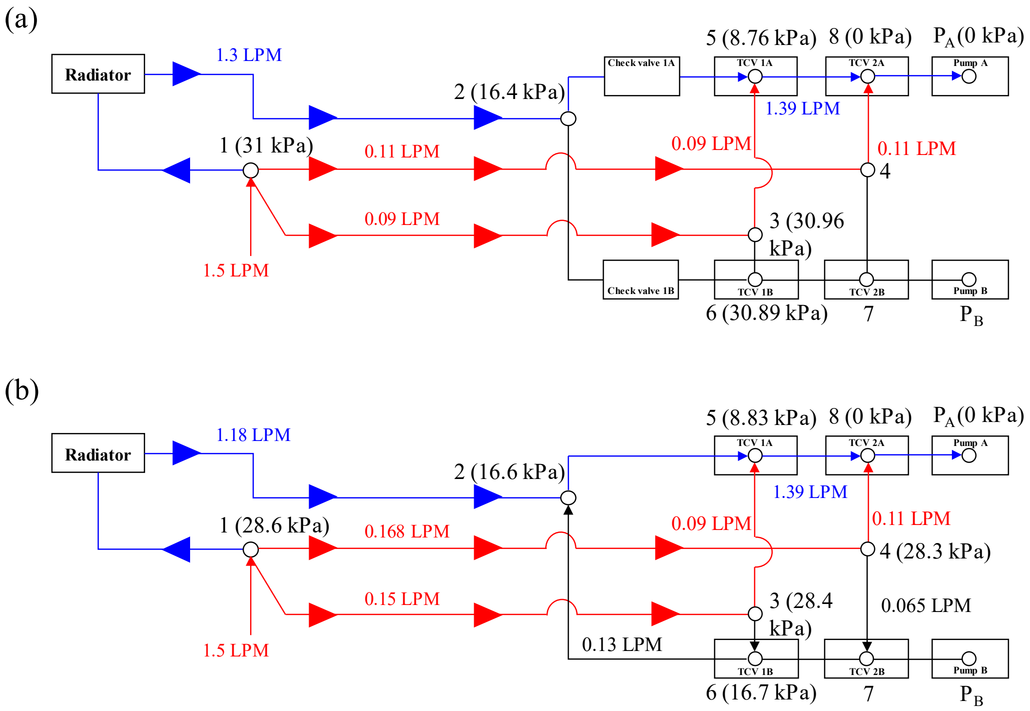

Figure 4: ECIPA flow schematics showing differential pressure and flow rates in the radiator circuit and the two bypass legs at 0.65 AU WCH conditions (a) including check valves upstream of the TCV and (b) with no check valves upstream of the radiator.

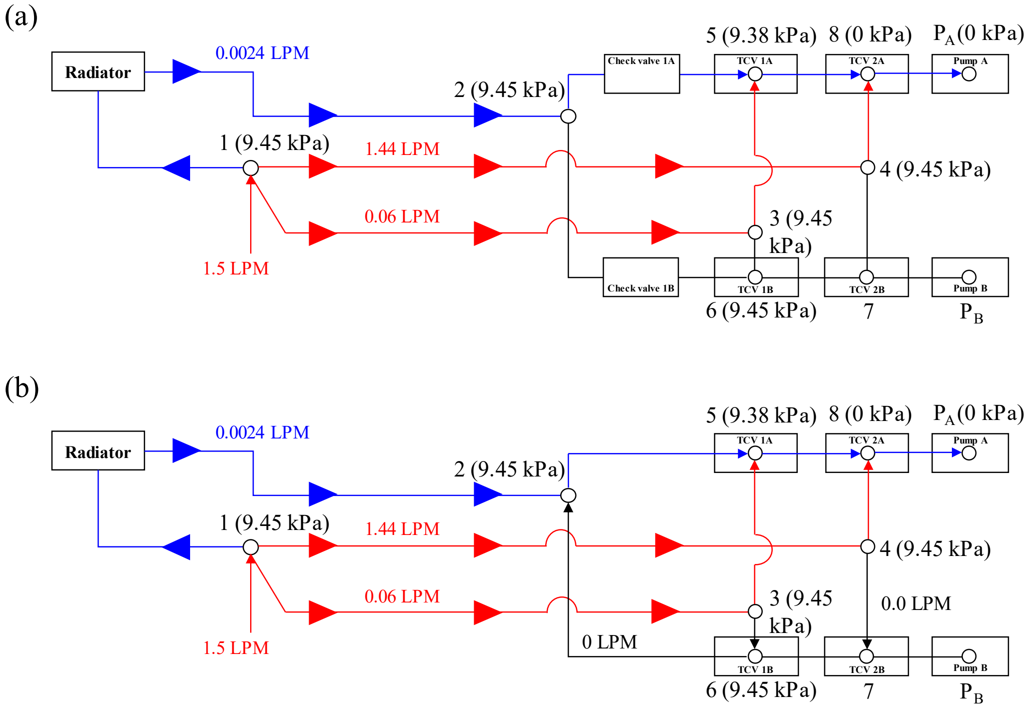

Figure 5: ECIPA flow schematics showing differential pressure and flow rates in the radiator circuit and the two bypass legs at 5.6 AU WCC conditions (a) including check valves upstream of the TCV and (b) with no check valves upstream of the radiator.

B. Flow rate to the radiator for different mixed temperature

Figure 6 displays the TCV 1 cold inlet flow fraction as a function of mixed fluid temperature. The minimum flow rate that can be achieved by a single TCV is 4% at the cold set point of 4 ºC while it is 0.16% for two TCVs in series. By contrast, the maximum flow rate from the cold inlet of an individual TCV is 96% at the hot set point of 24 ºC while it is 87% for two TCVs in series. Without the radiator and check valve flow impedances two TCVs in series can achieve a maximum cold inlet flow rate of 92% at 24 ºC. However, due to ECIPA's location within the Vault and the large radiator area of 1.81 m^2 the radiator circuit consists of 23 m of tubing adding a large impedance in the flow path resulting in reduction in the maximum flowrate to the radiator. Additionally, an individual TCV cold inlet flow rate increases linearly between its cold 4 ºC and hot 24 ºC set points while two TCVs in series featured a parabolic increase in flow rate to the radiator as a function of TCV mixed fluid temperature. For example, at 14 ºC an individual TCV allows for a flow rate of 50% through the cold inlet while two TCVs in series allows for 21.7%. This will cause the components located on the HRS loop to operate warmer during the cruise to Jupiter.

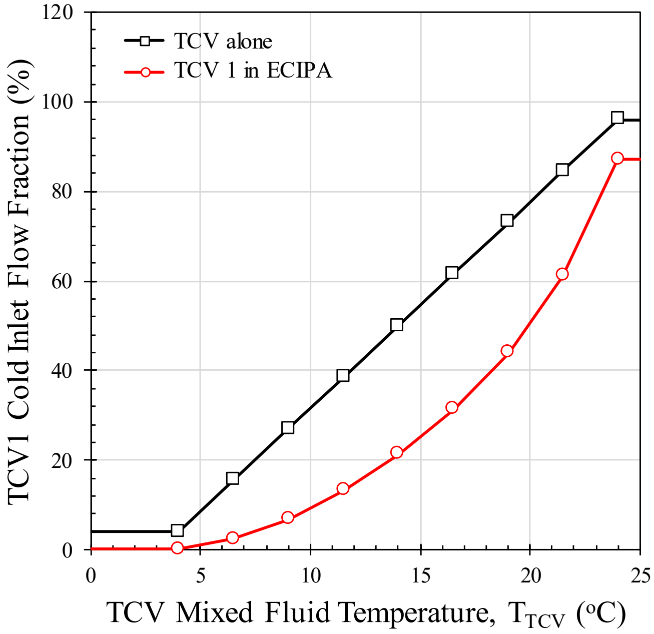

Figure 6: TCV 1 cold inlet flow fraction as a function of mixed fluid temperature for an individual TCV and the ECIPA including two TCVs in series with the radiator and the check valve.

C. Radiation testing of the thermal control valve

Figure 7 illustrates cold inlet flow fraction as a function of TCV fluid outlet temperature pre and post 50, 150, and 300 krad (Si) exposure to gamma radiation. The pre-radiation test was repeated three times and the measurements from all three tests fell within 15% of their mean value. The minimum and maximum cold inlet flow fractions were equal to 0.07% and 99.2% at 21 and 42 ºC, respectively. Note that cold inlet flow fraction for this TCV was much smaller than the maximum value of 4% specified by the vendor. Moreover, the cold inlet flow fraction was approximately linear with respect to temperature from 25 ºC to 40 ºC. Finally, no hysteresis was observed, i.e., the cold inlet flow fraction was the same for a given temperature regardless if it was cooling or heating. Figure 7b plots cold inlet flow fraction as a function of TCV fluid outlet temperature between 21 ºC and 25 ºC. It illustrates that cold inlet flow rate increases exponentially with respect to temperature.

Radiating the TCV with a total ionizing dose (TID) of up to 300 krad (Si) resulted in no appreciable change in cold inlet flow fraction as a function of temperature. For example, pre-radiation cold inlet fraction was 0.07% at 21.4 ºC while it was measured to be 0.065%, 0.063%, 0.067% after 50, 150, and 300 krad (Si). This demonstrated the heritage TCV to be tolerant to the maximum total ionizing dose the Vault components are expected to be subjected to during the mission. Note that ray trace analysis predicted end of mission TID of only 50 krad (Si) for the TCV actuators.

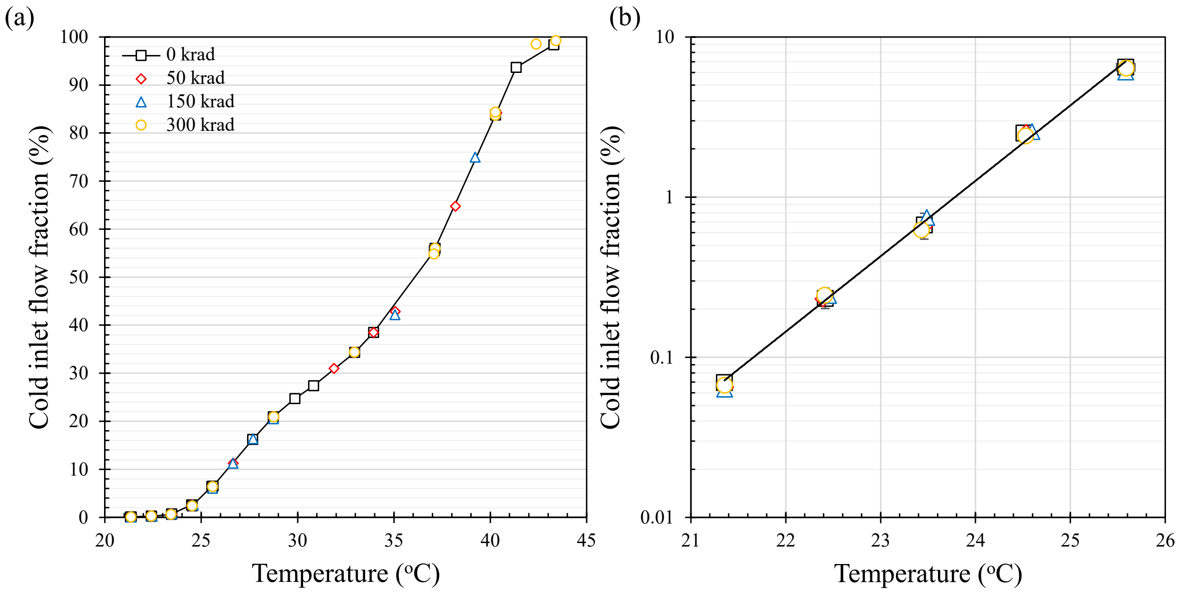

Figure 7: Measured cold inlet flow fraction as a function of temperature after exposure to TID of 0, 50, 150, and 300 krad (Si) for mixed fluid temperature of (a) 21-42 °C and (b) 21-25 °C.

VI. Conclusion

This paper described the thermal and hydraulic analysis performed for Europa Clipper heat HRS TCV as well as a TID radiation test to reduce risk of hardware failure during the mission. Hydraulic analysis determined there to be parasitic flow paths through the block redundant pairs of TCVs that reduced total flow to the radiator in WCH conditions. Additionally, two TCVs in series was shown to minimize flow rate to the radiator to 0.16% at mixed fluid temperatures of <4 °C. By contrast at mixed fluid temperature >24 °C the maximum flow to the radiator was 87%. Flow analysis also revealed that two TCVs in series feature a parabolic increase in flow rate to the radiator as a function of TCV mixed fluid temperature. Finally, a development TCV unit was exposed to a TID of 300 krad (Si) and the flow characteristics of the valve was measured as a function of temperature before and after radiation exposure. Radiating the TCV with a total ionizing dose (TID) of up to 300 krad (Si) resulted in no appreciable change in cold inlet flow fraction as a function of temperature.

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