Jet Propulsion Laboratory
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Thermal and Flow Analysis of Europa Clipper Thermal Control Valves

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Propulsion, thermal & materials systems

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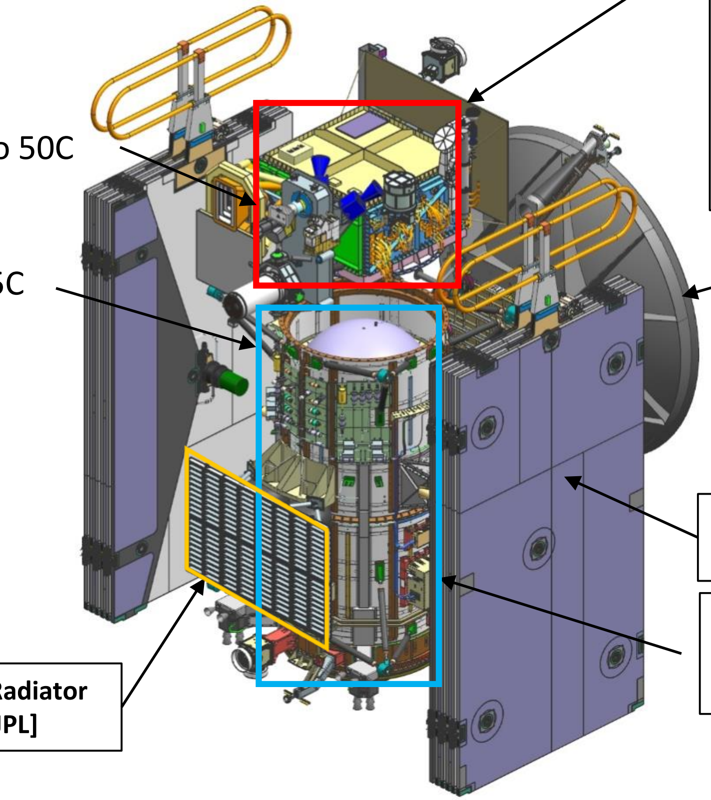
Europa Clipper MPFL

- Europa Clipper is a solar powered spacecraft that will orbit Jupiter and flyby Europa
  - It is power constrained due to the weak solar irradiance at 5 AU and due to projected solar cell and battery degradation in the Jovian radiation environment
  - VEEGA launch trajectory means Europa Clipper has to survive 0.65 AU environment
  - Spacecraft has to be designed to operate exposed to 50-3200 W/m^2 solar irradiance

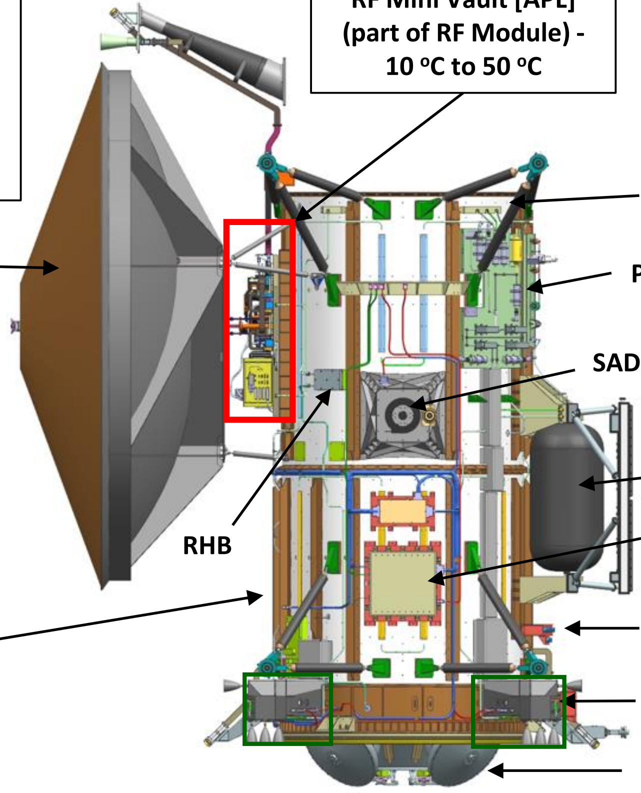
- Clipper thermal subsystem has designed a dual purpose single phase mechanically pumped fluid loop for the mission often called Heat rejection system (HRS) to
  - Reject excess heat during inner cruise (Venus and earth flybys)
  - Harvest heat from the electronic boxes and utilize it to maintain propulsion component temperatures above their allowable limits during Jupiter orbit

- HRS needs to modulate heat loss from the spacecraft from 350 W at 0.65 AU to 10 W at 5.6 AU achieved through the use of
  - Thermal control valves for fluid to bypass the radiator
  - Radiator Louvers to minimize heat loss from the radiator

Europa Clipper Thermal Design



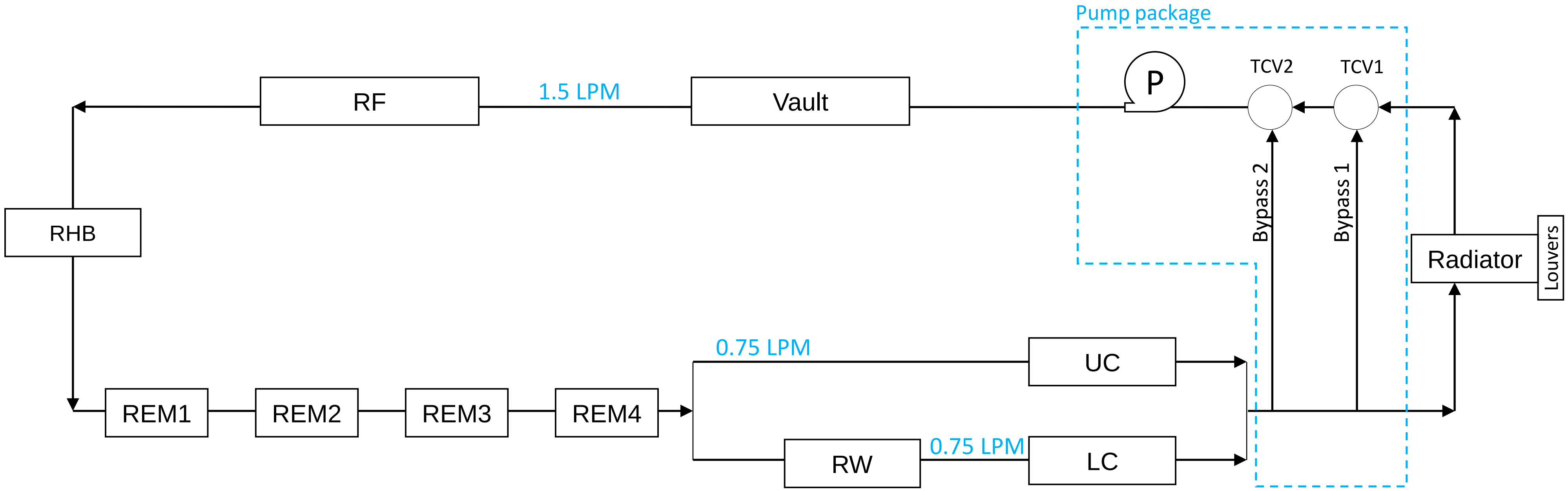
REM – Rocket Engine Module
RF – Radio Frequency
RW – Reaction Wheels
UC – Upper Cylinder
LC – Lower Cylinder
PIA – Propellant Isolation Assy
PCA – Pressurant Control Assy
PME – Prop Module Electronics
SADA – Solar Array Drive Assy



Europa Clipper has a mechanically pumped fluid loop (MPFL) that harvests heat from the e-boxes in the Vault and dissipates the heat to the propulsion components or out the radiator when vault dissipation is too large

HRS flow diagram

- Europa Clipper heat rejection system (HRS) uses an integrated pump package with two mixing valves for thermal control



- The design is able to turn down heat loss 35:1 by
  - Bypassing radiator through the use of thermal control valves
  - Changing emissivity of the radiator by using louvers

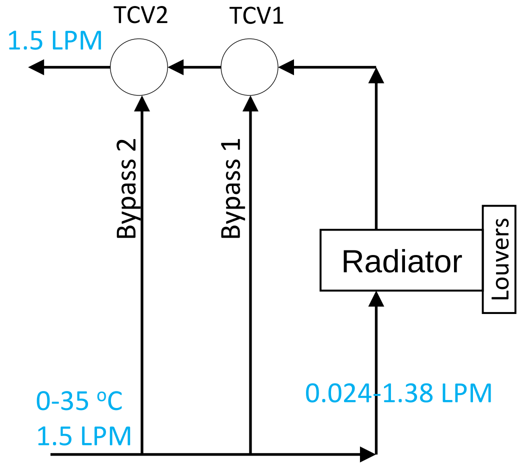
Thermal control valves (mixing valves)

- Energy balance on the radiator $Q = \dot{m}C_p\left(T_{rad,out} - T_{rad,in}\right) = \varepsilon A \sigma T_{rad}^4$

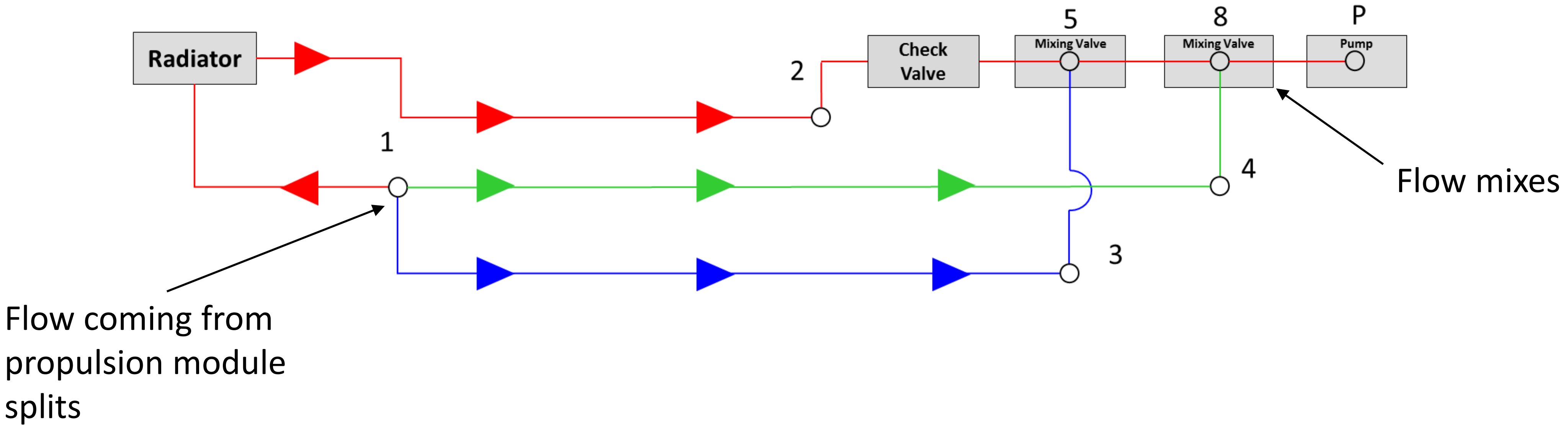
- To minimize heat loss from the radiator to < 10 W
  - Radiator temperature will be maintained at -95 ^oC to prevent Freon-11 from freezing at -111 ^oC
  - Louvers modulate radiator emissivity ε from 0.74 when T_{rad}>0 ^oC to 0.14 when T_{rad}<-80 ^oC
  - The radiator is sized to reject 350W in worst case hot and is equal to 1.29 m^2

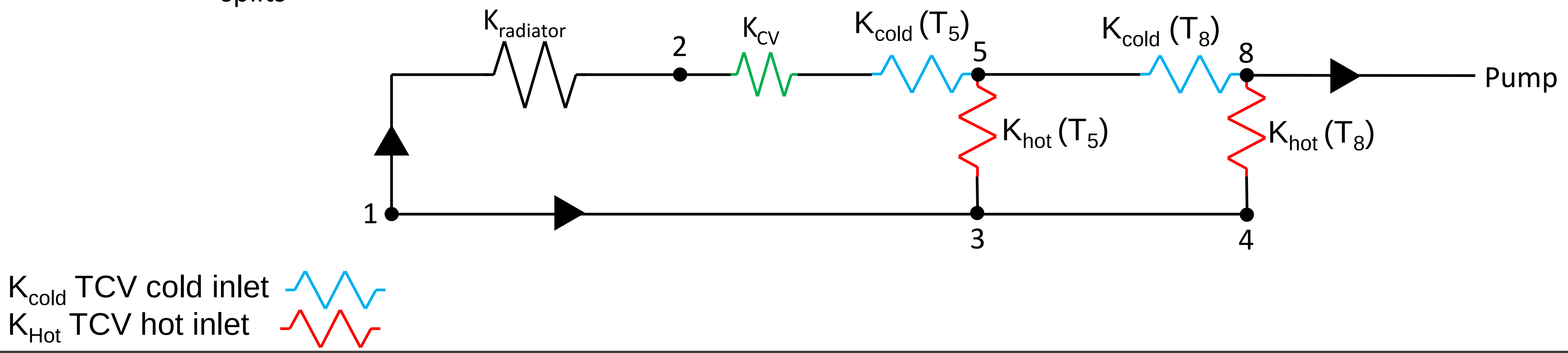
- $\dot{m}C_p$ must be minimized such that $Q < 10\ W$
  - The radiator flow rate must be reduced from 1.5 LPM to < 0.3 % to achieve target heat loss
    - Individual mixing valves have the capability of bypassing flow to 4 % we have placed two in series to achieve 4% x 4% = 0.16%

- The objective of this study was to determine two valves in series behavior as a function of fluid temperature
  - Flow rate to the radiator in the cold and hot cases as well as intermediate cases



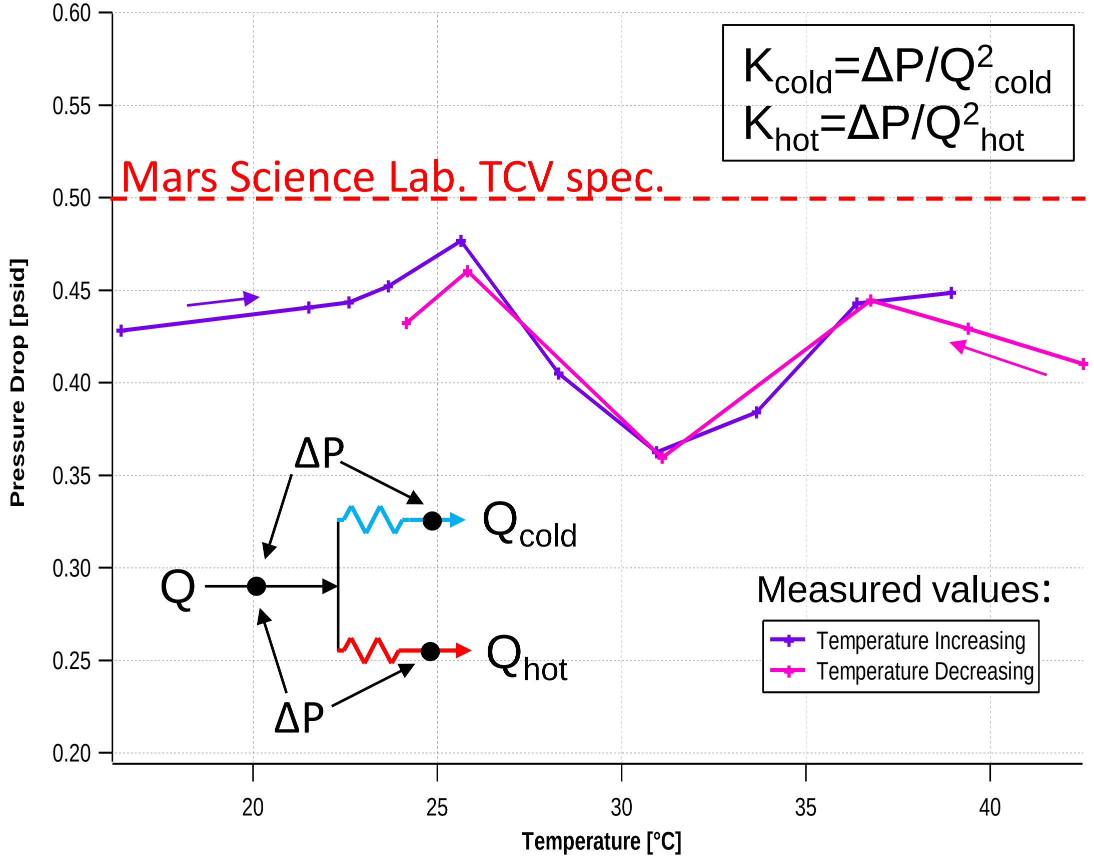
Fluid impedance diagram



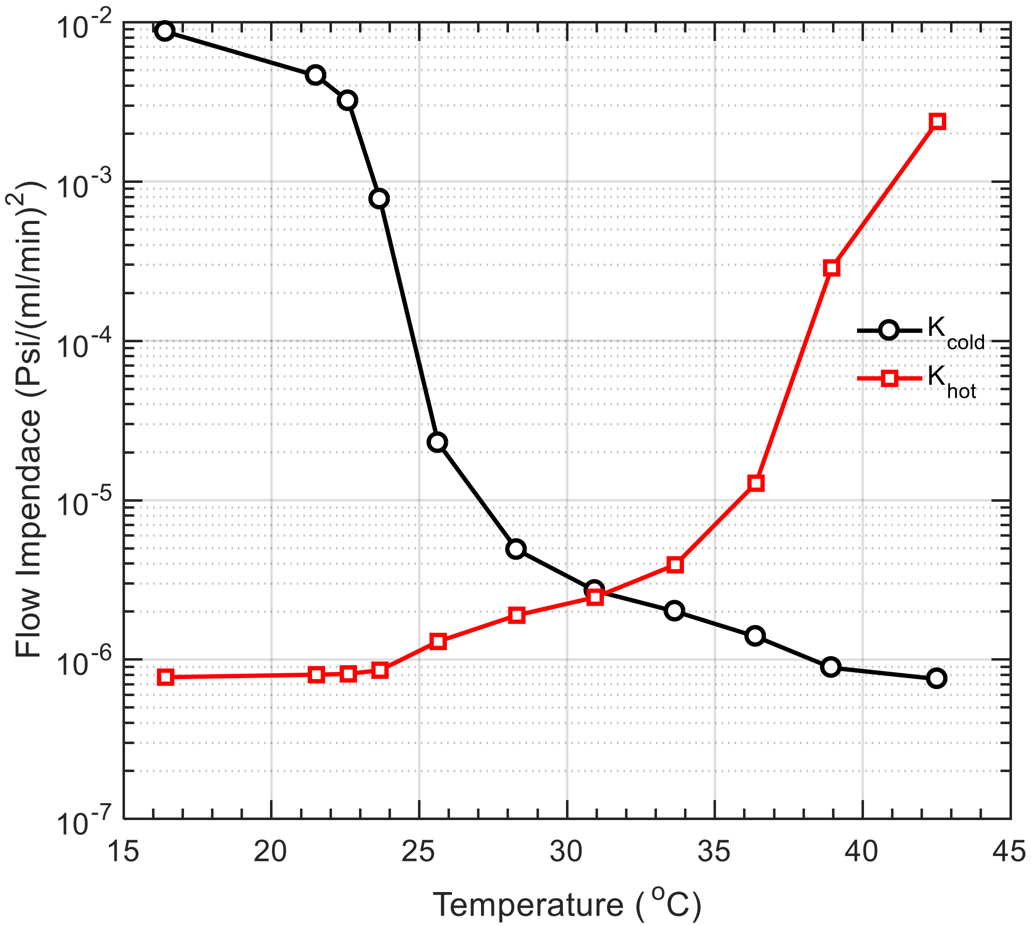


MSL TCV impedance values

- Pressure drop (spec dP=0.5 psid at 0.75 LPM)

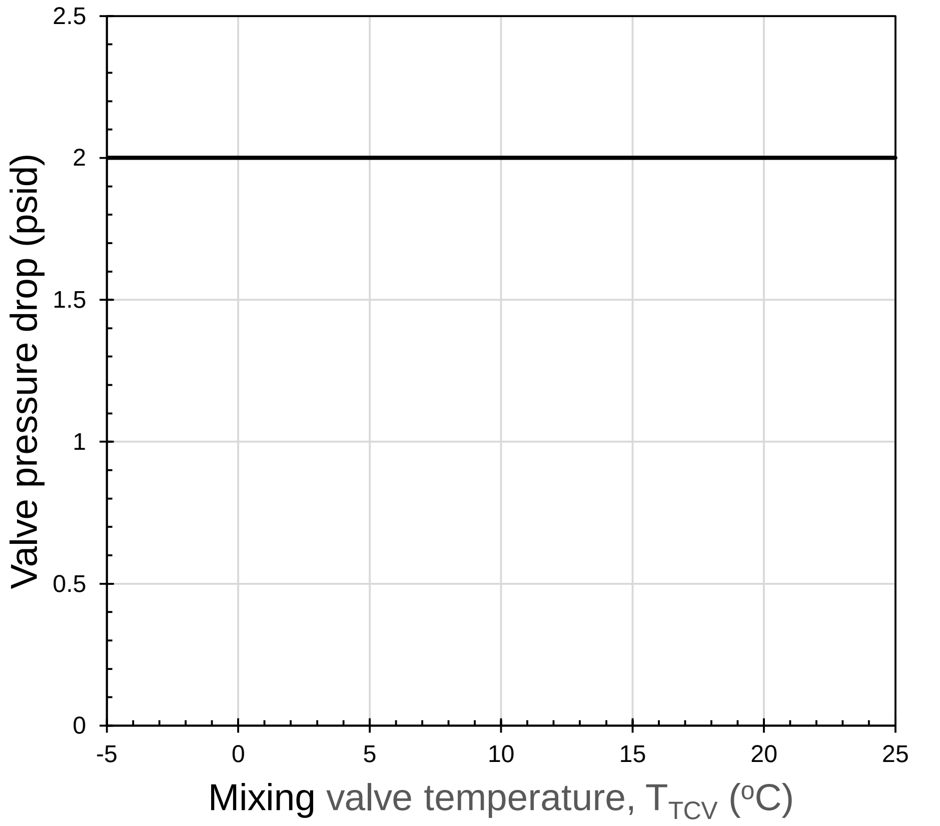


- TCV impedances as a function of temperature

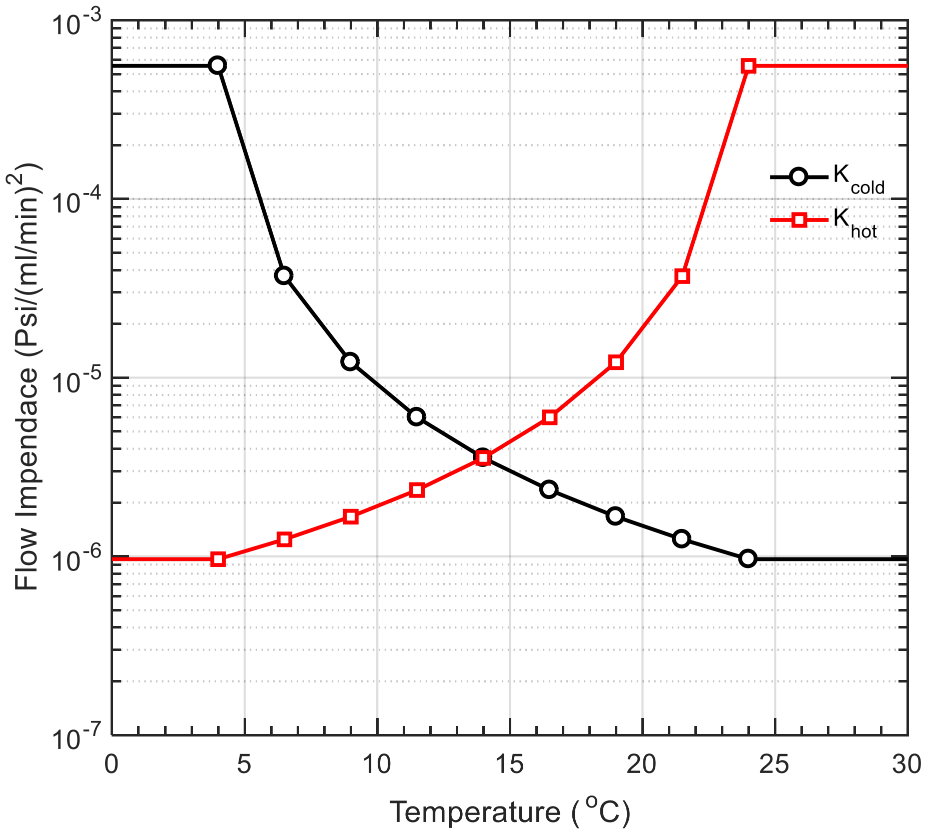


Same process for Europa Clipper TCV

- Assumed constant pressure drop at 2 psid (4x MSL due to 2x flow rate)

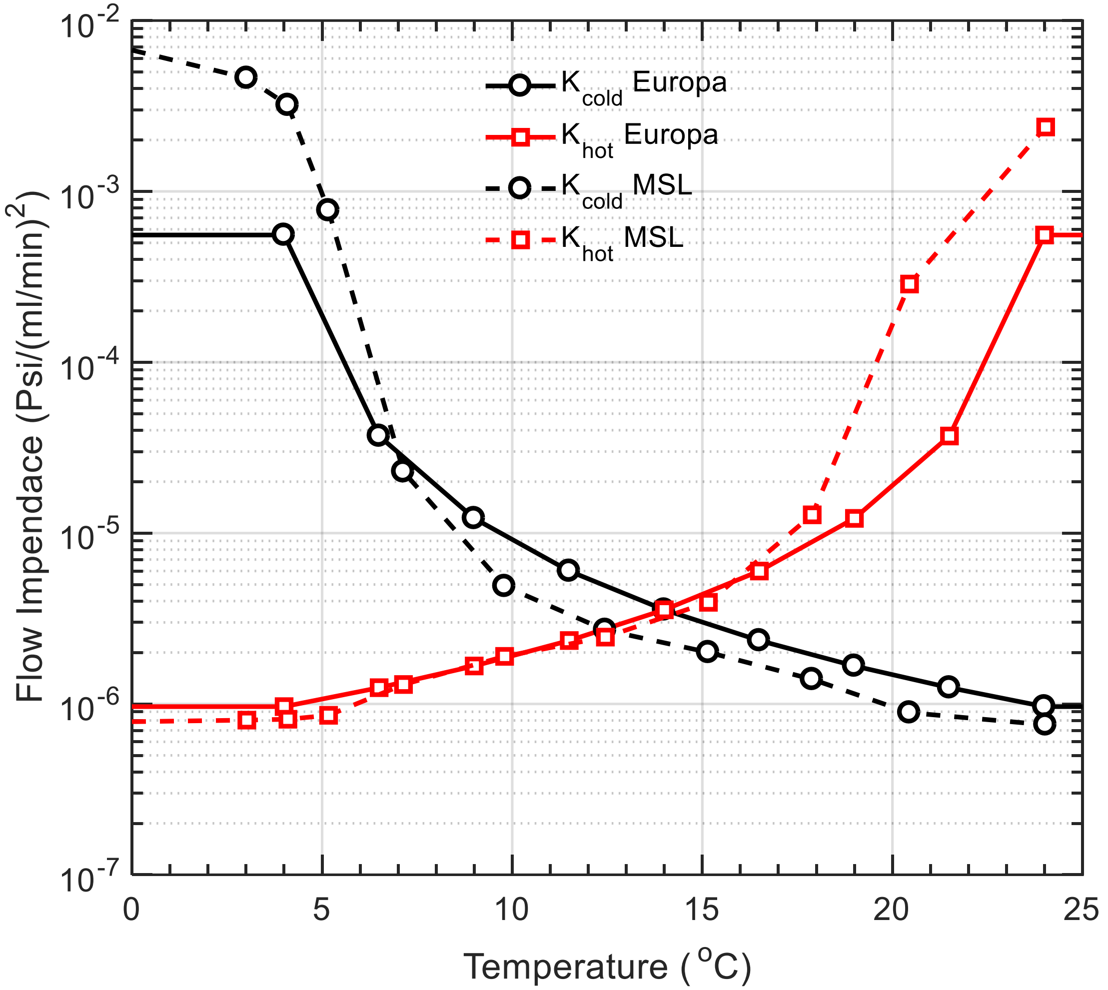


- Resulting impedance curve based on spec. of minimum 4% flow increasing linearly to 96% between 0 °C and 20 °C



Comparison of the two valve impedances

- Impedance controls flow split
  - Large impedance in the cold inlet at low temperatures allows more flow from the hot inlet
- Used the same process as used in MSL to estimate worst case impedances for Europa Clipper TCVs
  - These temperature dependent impedance values will be used in the flow analysis
- Large variability in MSL TCV leak rates and impedances
  - The valve tested and shown had 1% leak rate in fully closed state compared to 4% worst case we are assuming in the analysis



Method of solution

- ThermXL was used to solve the network diagram
  - Repurposed a thermal solver to perform fluid and thermal analysis

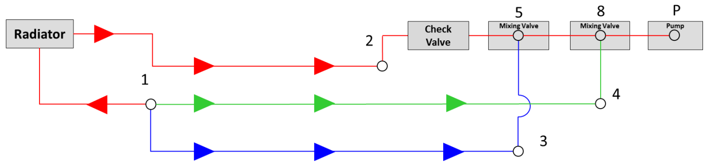
- ThermXL solves the equation $Q = \frac{\Delta T}{R}$

- Pressure drop equation $\dot{V}^2 = \frac{\Delta P}{K}$

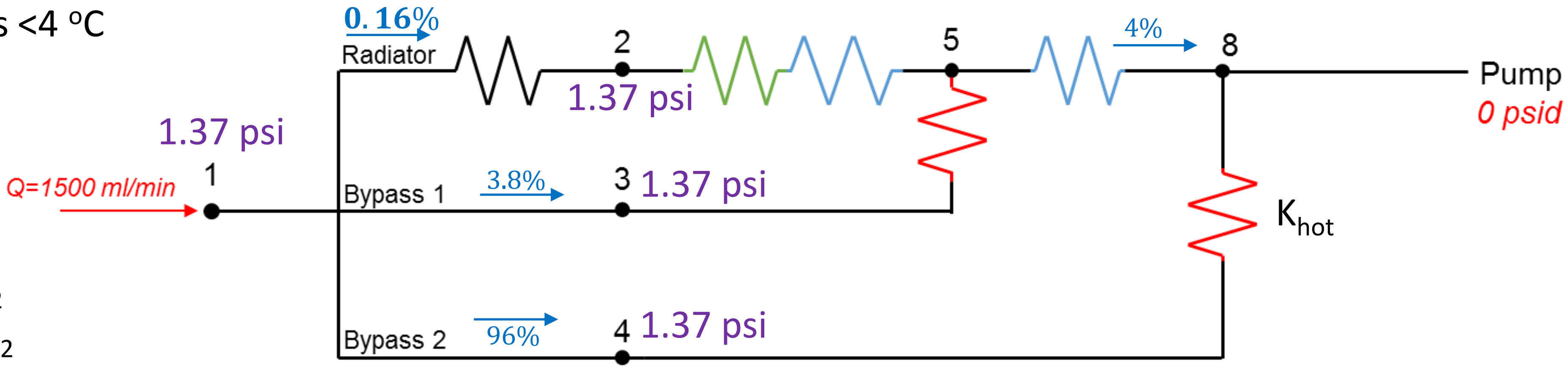
- Pressure drop equation in the form of the heat equation $\dot{V} = \frac{\Delta P}{K'}$ where $K' = (\Delta P \cdot K)^{0.5}$
  - The analogy to heat equation $\text{Q} = \dot{V}$, $\Delta T = \Delta P$, $R = K'$

- Boundary conditions
  - $\dot{V}_1 = 1500 \frac{ml}{min}$
  - $P_{pump} = 0\ psi$

Fully open/shut flow analysis

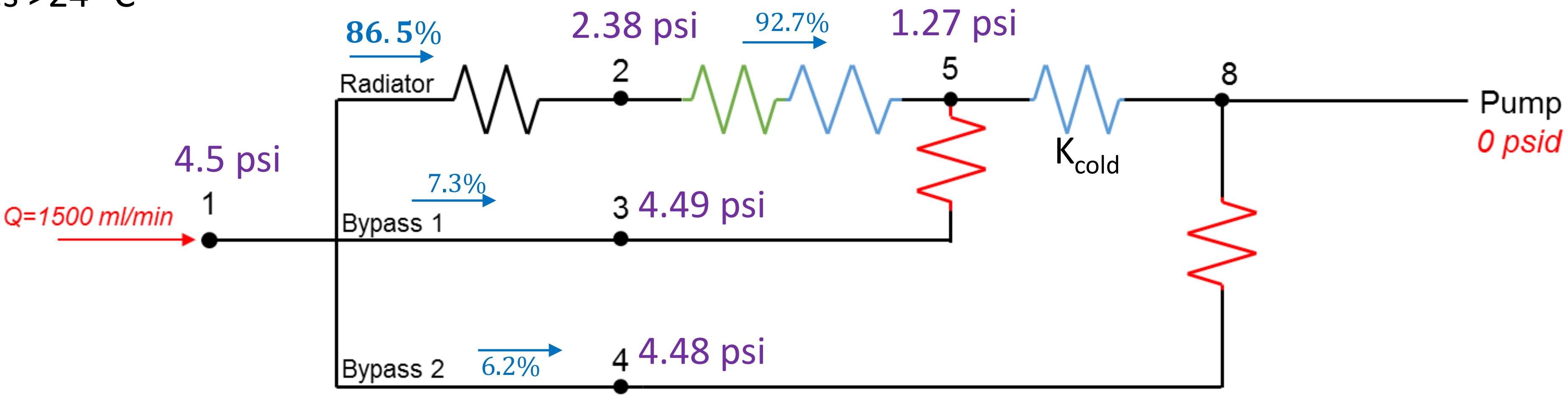


Radiator fully shut: both valves <4 °C



$K_{hot} = 9.65 \times 10^{-7}$ psi/(ml/min)^2
$K_{cold} = 5.56 \times 10^{-4}$ psi/(ml/min)^2

Radiator fully open: both valves >24 °C



$K_{hot} = 5.56 \times 10^{-4}$ psi/(ml/min)^2
$K_{cold} = 9.65 \times 10^{-7}$ psi/(ml/min)^2

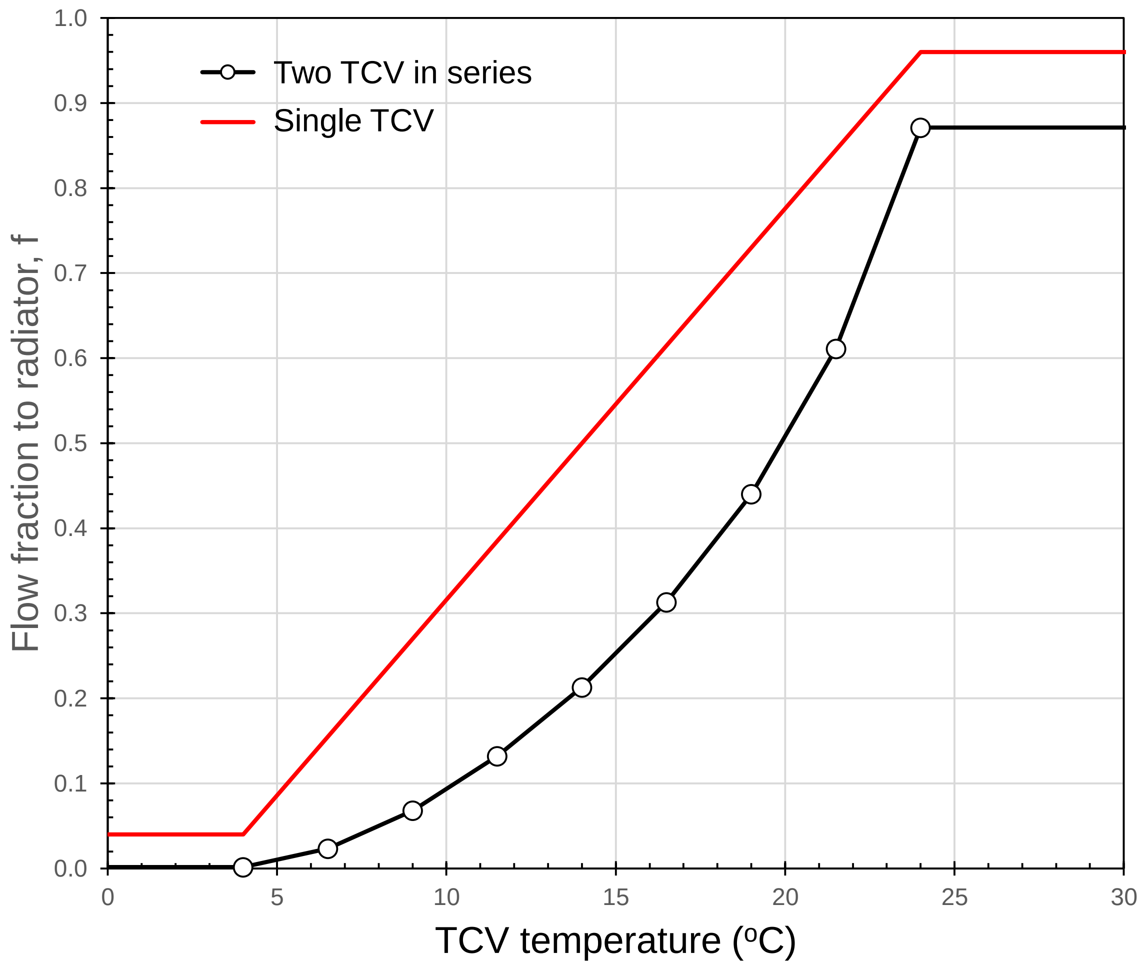
Flow rate to radiator at different TCV temperature

- Flow analysis assuming both thermal control valves are at temperature T_{TCV}
  - Impedance of the valves K_{hot} and K_{cold} were used for a given temperature in the analysis

- Individual TCV have linear flow fraction *f* vs. temperature
  - Two TCVs in series should have f^2 shaped profile (*f* % x *f* %)

- Maximum flow to radiator in the hot case is 86.5%
  - Cannot achieve maximum 92% (96% x 96%) flow in the hot case due to additional impedance by the radiator

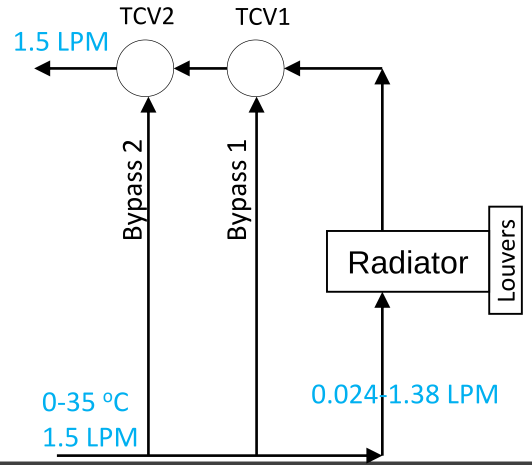
- Minimum flow to radiator in the cold case is 0.16%
  - Achieves the desired <0.3% flow in the cold cases



Simultaneous thermal and fluid analysis

- Previous flow analysis assumed TCV-1 and TCV-2 were at the same temperature, in reality they may be well isolated from each other
  - Each TCV will be at a different temperature as cold fluid from radiator is serially mixed with the warm bypass
  - Each TCV will have different hot/cold side flow impedance based on its mixed fluid temperature
  - In Europa Clipper design TCV-1 will always be cooler than TCV-2 since the warm bypass is only mixed once with the cold radiator fluid

- The same flow model was coupled to a thermal model of the radiator and louver in order to assess the actual flow rate to the radiator during inner cruise and Jupiter orbit



Simultaneous thermal and fluid analysis

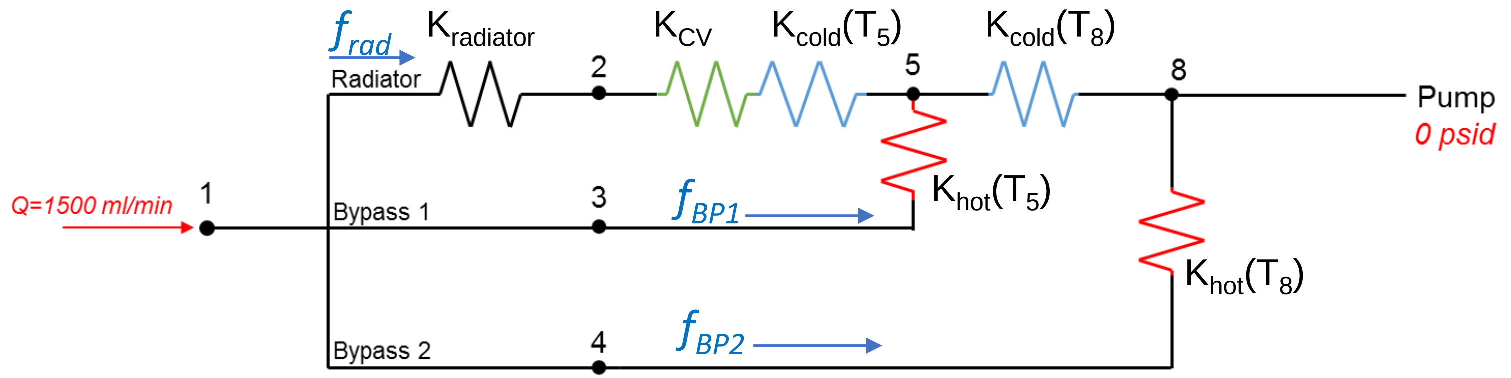
- Louver was modeled with -80 to 0 ^{o}C setpoints with linearly increasing emissivity from 0.14 to 0.74

- The system was modeled with 6 fluid nodes and 30 temperature nodes
  - Thermal model consisted of one way conductors to represent the flow and the flow rate was determined from the flow analysis

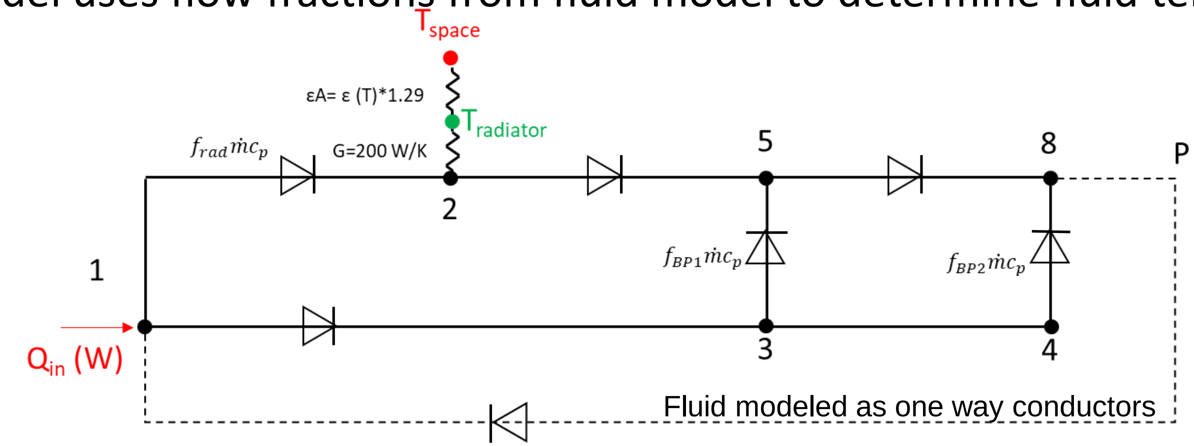
- Fluid and thermal analysis were performed simultaneously using ThermXL to estimate the flow fraction in the radiator at different HRS heat input

Thermal and fluid model

Fluid model uses fluid temperatures from the thermal model to determine impedances



Thermal model uses flow fractions from fluid model to determine fluid temperatures

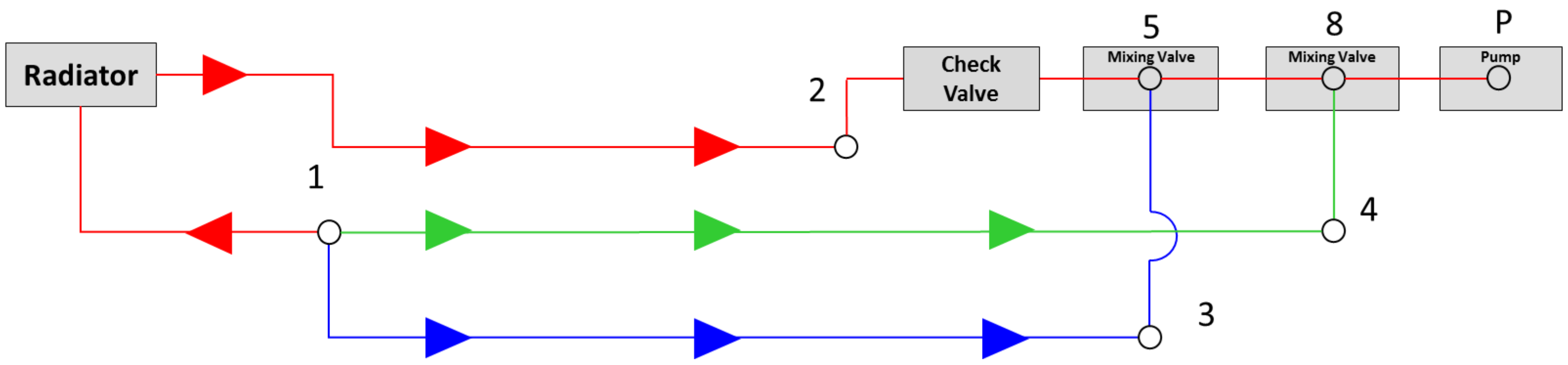


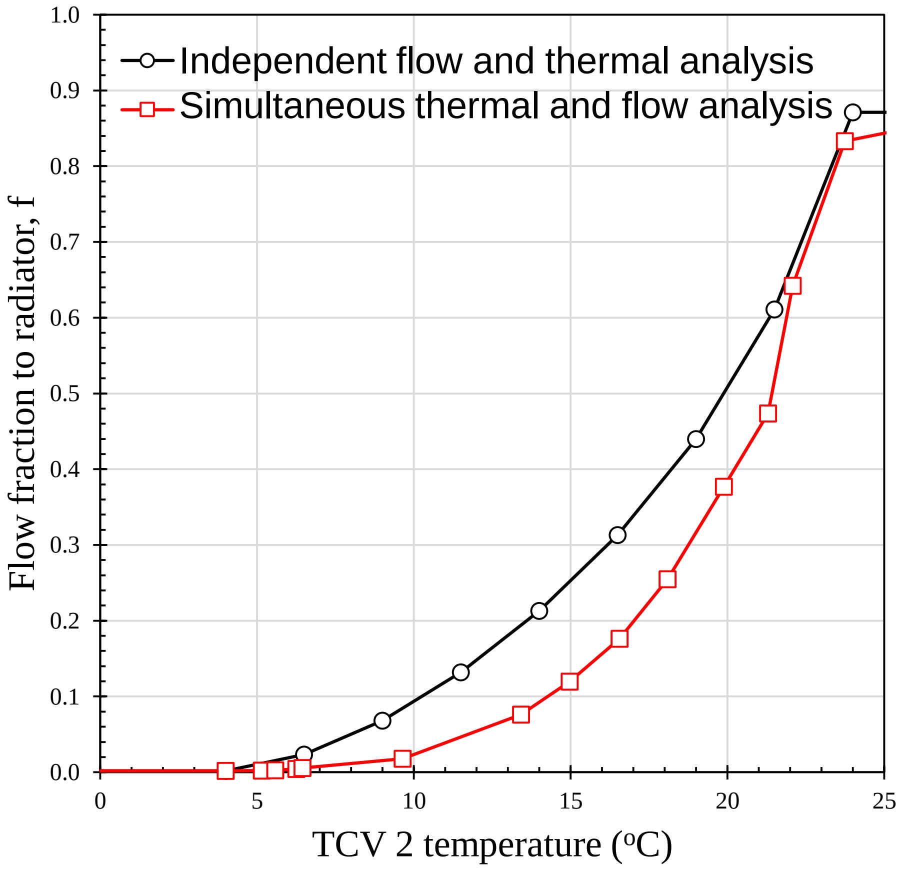
Solver iterates until solution converges

Results

- TCV 2 is warmer than TCV 1 resulting in reduced flow to the radiator in the hot case

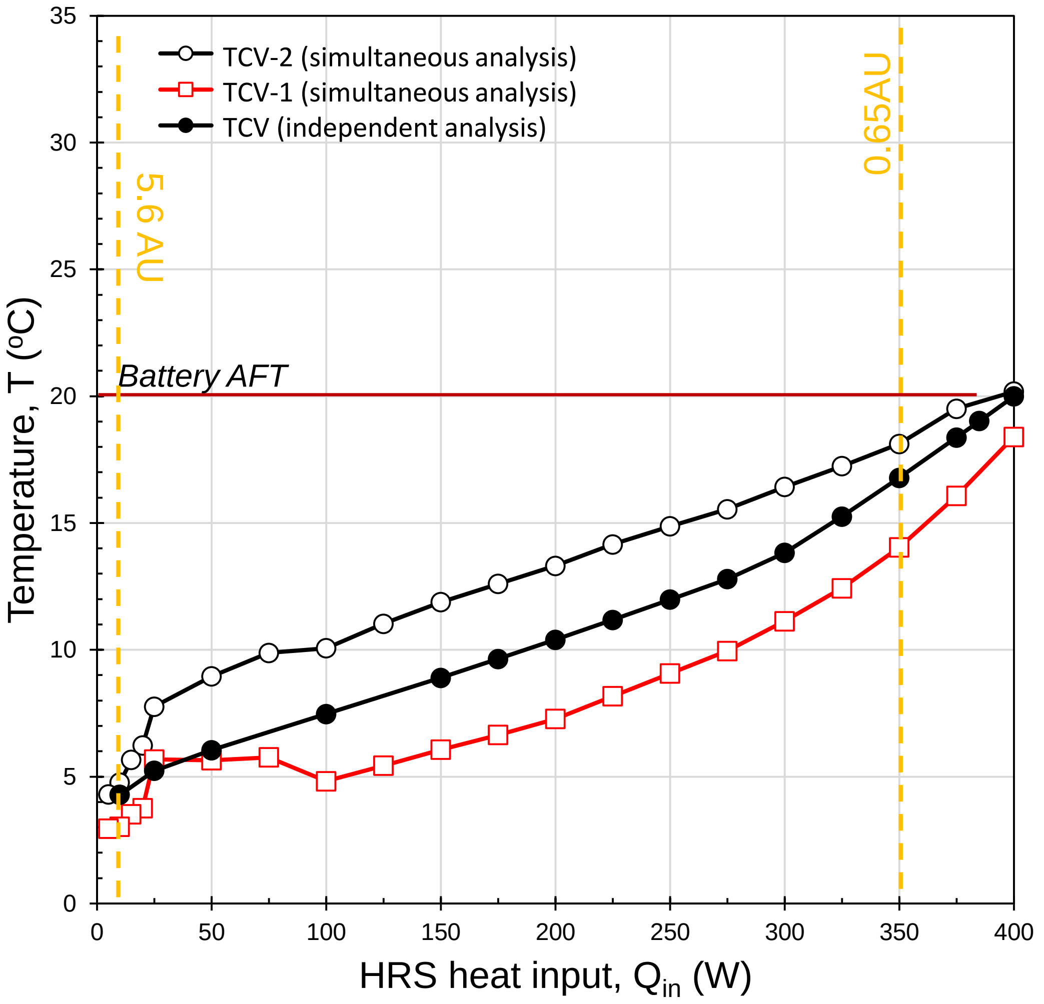
- The two curves converge at hot and cold ends of the curve when both valves are open or closed





Temperatures

- Coupled thermal and fluid analysis predicts 1-3 °C warmer fluid temperatures compared to when thermal and fluid analysis are performed independently
  - Assuming both TCVs are at the same temperature leads to averaging of the two TCV temperatures T_{TCV}
- TCV-2 is up to 5 °C warmer than TCV-1 at intermediate Q_{in}
- In the case of Europa Clipper TCV-2 fluid temperature controls the battery temperature



Summary and conclusions

- This study presents methodology to analyze mechanically pumped fluid loops with one or more passive thermal control valves based on:
  - Independent flow and thermal analysis based on balancing pressure in all split flow paths
  - Simultaneous flow and thermal analysis based on pressure and temperature balance in all split flow paths

- Performing independent flow and thermal analysis under predicts temperature of fluid controlled interface by up to 3 ^{o}C in the case of Europa Clipper spacecraft

- Presented a method to perform fluid and/or thermal analysis in thermal solvers such as thermXL

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