Novel Concept for Detection of a Fluid Flow Fault in a Pumped Fluid Heat Rejection System

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A pumped fluid heat rejection system (HRS) requires continuous flow of the working fluid to ensure that the components controlled by the HRS stay within their allowable temperature limits. An interruption of flow could result in violations of hardware qualification limits and mission failure. Some of these violations can happen within a few hours. Hence, quick detection of a flow fault to invoke mitigation measures is very critical. In typical pumped fluid HRS, dual or triple pumps are employed to switch the backup units in case the primary unit were to fail. The key metric for the selection of a fault detection system is that it should detect the fault much before the fault's impact on the thermal health of the HRS controlled components is realized. A trade study was conducted to select such a system for the Europa Clipper Mission to Europa, a moon of Jupiter that is planned for a launch in 2023. Out of the several concepts studied, the most attractive one was a novel and simple concept that uses a low power film heater attached to a section of the HRS tubing. While the fluid flows at its nominal rate, the high thermal coupling of the flowing fluid leads to the tube being close to the fluid's temperature. However, when the flow stops, the heater warms the small thermal mass of the tubing to a high temperature in a short span of time (~15 minutes). This large temperature rise would then imply that the flow must have stopped. This paper will describe the various concepts considered, the chosen concept, its implementation, and the results of developments tests to validate its performance.

Nomenclature

HRS	=	heat rejection system
UC	=	upper cylinder
LC	=	lower cylinder
PM	=	propulsion module
PRT	=	platinum resistance thermometer
RF	=	radio frequency
REM	=	rocket engine module
RW	=	reaction wheel
RHB	=	replacement heater block
RCS	=	reaction control system
WCC	=	worst case cold

I. Introduction

The heat rejection system (HRS) employed by several JPL missions, e.g. Mars Science Laboratory (Curiosity Rover), the twin Mars Exploration Rovers (Spirit/Opportunity) and the Europa Clipper Mission, utilizes a single phase working fluid (CFC-11) that is circulated in a loop by virtue of a mechanical pump. This loop's tubing is attached to thermally controlled components in the spacecraft and either provides heat to them or removes it from them via convective coupling. The system functions as long as the fluid circulates through the loop. If the pump were

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to stop working for any reason, the functionality of this loop's thermal control would be lost causing a potentially mission jeopardizing situation because the temperatures of the controlled components could violate their allowable limits. Due to the importance of the thermal health of the spacecraft, the pumped loop utilizes two pumps, one primary and the other redundant, with only one on at any time to conserve redundancy, lifetime and power. To enable this redundancy to function correctly, one needs to detect this fault before the ramifications of it are realized in terms of components violating their allowable temperature limits. If detected early, the backup pump would be automatically energized by the flight software and the information about the state change transmitted to mission operators on Earth.

Several schemes to detect this fault were investigated and an early detection scheme was baselined as the primary one but others serving as backups. The scheme is based on first principles by continuously heating a small section of the HRS tubing by a very small power film heater. As long as fluid flow persists, the large flow heat capacity of the working fluid exhibits an extremely small temperature increase along the flow length of the heated section of the tubing. However, as soon as the flow stops due to a failure of the pump, the heated section of the tube heats up very rapidly as a response to the inserted heat due to its small thermal mass. A temperature sensor mounted on the tube would detect it and the associated flight software would turn on the back up in response.

II. Unique Thermal Characteristics of Europa Spacecraft

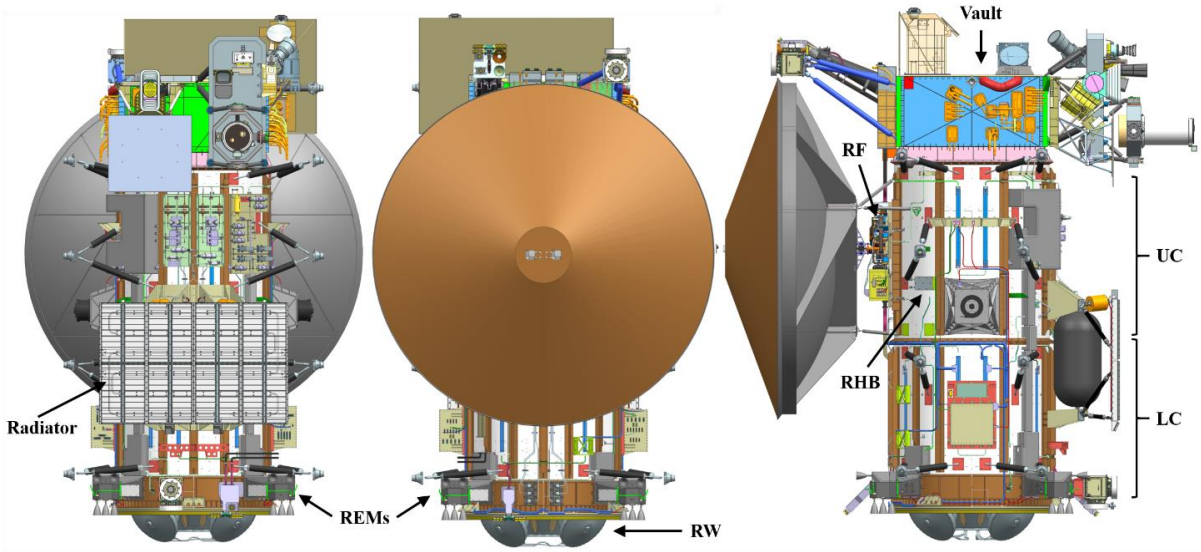


Figure 1. Europa Clipper spacecraft model showing the major modules and thermal control components.

The Europa Clipper mission is a deep space planetary exploration mission with an objective to evaluate the potential habitability of Jupiter's icy moon Europa. Specifically, it aims to 1) characterize the icy shell of Europa and the properties of the subsurface water including ocean salinity and ice sheet thickness, 2) determine the chemical composition of the surface matter and the atmosphere including potential plumes, and 3) 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. Figure 1 illustrates the Europa Clipper spacecraft showing the Vault, Radio Frequency (RF), and Propulsion Modules (PM) as well as thermal control components such as the replacement heater block (RHB) and the radiator.

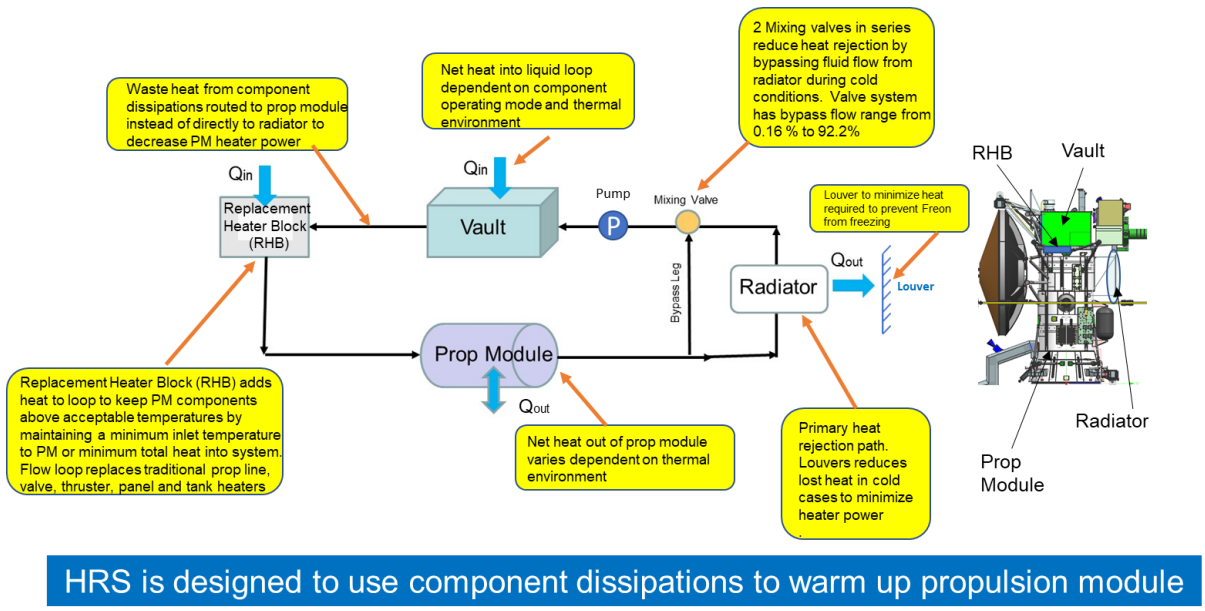


Figure 2. HRS flow diagram showing various components in the fluid loop.

Figure 2 shows a schematic of the Europa Clipper HRS loop servicing the following modules and components:

a) Avionics Vault module where the electronic components reside
b) Radio Frequency (RF) Module
c) Replacement heater block (RHB), used to supply supplemental heat to the loop
d) Rocket engine modules (REMs) each housing six reaction control system (RCS) thrusters
e) Upper cylinder (UC) and lower cylinder (UC) of propulsion module
f) Thermal control radiator used to reject excess heat

The components controlled by the HRS constitute a very large mass (mostly aluminum) of about 750 kg. A pump flow stoppage would lead to a very slow change in the temperature of the components thermally coupled to the HRS. Additionally, the PRTs (Platinum Resistance Thermometers) coupled with the flight system avionics would have an uncertainty of ~2ºC. These two characteristics would lead to a very slow detection of the root cause of the fault (pump flow stoppage) – up to several hours to reach their allowable limits.

Autonomous detection of the root cause (stoppage of fluid flow) is a key requirement before the impact of implication of that root cause is made evident (in the form of allowable temperature limit violations). The proposed concept (which has been baselined for implementation in the Europa Clipper design) meets this requirement whereas none of the other options do.

III. Basic Constraints and Criteria for Judging Viable Concepts for Fault Detection

Several concepts for detection of a flow fault were investigated. A set of constraints are listed below and used to down select the number of concepts:

- Minimal impact on FS resources
  - Power, mass, size, location, software, avionics, cost and schedule
- Autonomous, needing no oversight from ground control
- Allow for long blackouts of communication between spacecraft and ground control (could be as long as days in a 10 year long cruise)
- Simplicity in implementation
- Very robust and reliable
  - Should itself be fault tolerant
- Fast response (minutes)
  - Detect root cause before deleterious ramifications on controlled components are realized
    - Detect cause before negative impact happens

- Provide information to flight software to react to flow fault
- Turn on backup pump and call Earth
- Minimal interaction (or none) with nominal control of HRS in flight
- Differentiate between fault protection and nominal operation scenarios
- Should work in both hot and cold conditions

IV. Concepts Investigated and Traded Off

In total 6 concepts were investigated. A brief description of each is provided below.

1. *Pump Current Telemetry*

This deals with monitoring the primary (active) pump's power draw. If the measured power draw were zero, that would imply that the pump has stopped and the redundant pump would then be energized and the primary pump left unpowered. In concept this is very simple, utilizes pre-existing hardware, with minimal software impacts and would be applicable to both hot and cold conditions. The limitations are that the current measurement threshold is only 0.5 A, whereas the pump's nominal power draw is >1 A. Additionally, this could be due to a power switch failure and not the pump itself. Finally, even if the appropriate power or current were supplied to the pump, and no power fault is detected, the pump may not be producing any flow rate due to internal faults. For these reasons this option was not comprehensive, hence it was rejected from further study.

2. *Employ a Flow Meter*

This concept would use a traditional electronic flow meter to monitor the fluid flow in the loop. A measurement of zero flow would trigger a fault flag which in turn would turn on the backup pump and turn off the primary. This is an attractive concept because it directly identifies and measures the root cause – flow stoppage. It would be reasonable to implement, have minimal flight software ramifications and would be applicable for all thermal conditions. One major handicap with this approach is the lack of flowmeters that are qualified for flight while being subjected to ionizing radiation that would be present near Jupiter and Europa. There are versions of flow meters that can be made tolerant to radiation exposure with significant amount of shielding (quite heavy). Unfortunately due to schedule, cost and volume/mass constraints this concept was shelved.

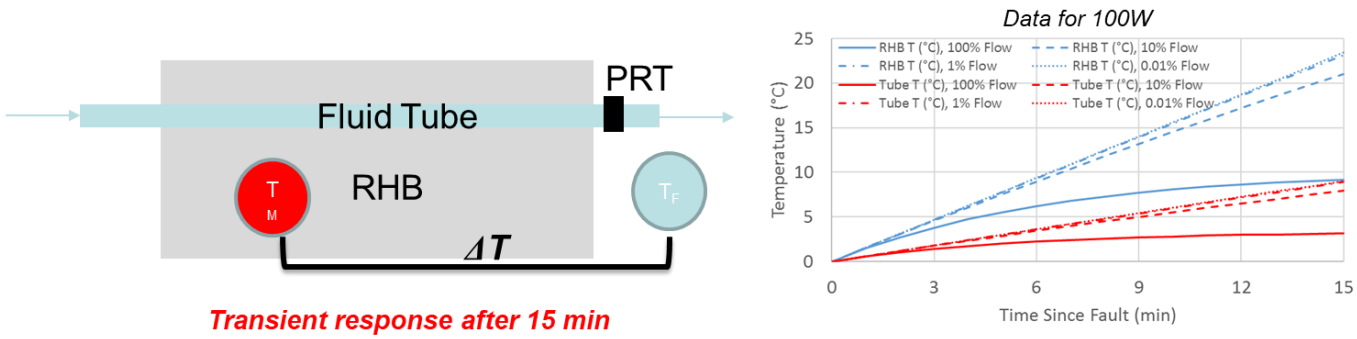
3. *Attach a Tachometer to the Pump Body*

This is similar to concept 1 but suffers from the main disadvantages that it is low in resolution and does not guarantee that flow is present even if the motor is spinning due to a malfunction in the pump's impeller. Also this would require significant development effort that could not be entertained from the project's schedule and cost constraint. Hence this option was shelved.

4. *Detect Temperature change in the RHB metal casing*

This concept would rely on measuring the change in the temperature of the RHB if the flow were to stop for any reason. Since the RHB is heated and has a relatively small thermal mass (~5 kg of Aluminum) compared to the rest of the system, the RHB would respond to flow stoppage much quicker than the rest of the system controlled by the fluid loop. One significant handicap is that this scheme only works in cold conditions when the RHB provides heat to make up for the heat losses from the spacecraft.

A simple thermal model was created of the RHB along with the tubing connected to it. This was done to make a numerical assessment of the thermal response of the RHB during cold conditions by examining the local RHB temperatures, both on the RHB and a distance away from it, before and after flow stoppage. For the known thermal conductance between the flowing fluid and the RHB metal surface, a correspondence is created between the two temperatures as a function of the inserted power. The RHB power was varied between 10 W and 200 W, which represents a range of powers expected in the RHB during cold conditions. The difference between full flow and no flow temperature differences represents the metric for uncovering the flow stoppage fault. A key observation was that, unless the inserted power was large enough (~>100 W), the difference in the sets of temperature is very small and would be overshadowed by the measurement accuracy of the temperature sensor used to measure these temperatures. Since this scheme is required to work in all operating conditions, this option was deemed unacceptable. Figure 3 depicts the basic concept and the underlying numerical results of this assessment.



Transient response after 15 min

		Flow = 100%			Flow = 0.01%			
	RHB Q (W)	T_M (°C)	T_F (°C)	ΔT_{M-F} (°C)	T_M (°C)	T_F (°C)	ΔT_{M-F} (°C)	$\Delta\Delta T_{M-F,\ 0.01\%-100\%}$ (°C)
Intermediate cruise →	10	0.9	0.3	0.6	2.3	0.9	1.4	0.8
	50	4.6	1.6	3.0	11.7	4.5	7.2	4.2
	100	9.2	3.1	6.1	23.4	9.0	14.4	8.3
	150	13.8	4.7	9.1	35.1	13.6	21.5	12.4
WCC →	200	18.4	6.3	12.1	46.8	18.1	28.5	16.4

Figure 3. Concept to employ the RHB thermal response to detect flow stoppage in the fluid loop.

5. Detect Temperature change in the HRS Radiator due to Flow Stoppage

The shortcoming of option 4 is that it would only be useful in cold conditions when the RHB power is significant (~>100 W). This could be partially overcome by the simultaneous measurement of the HRS radiator response due to a flow stoppage. In cold conditions the radiator flow is bypassed by the thermal control valves (by design) to minimize heat transferred to it from the spacecraft, which would result in heat wastage. Hence in cold conditions the radiator temperature is unaffected by flow stoppage in the primary HRS loop circuit. However, in hot conditions (near Earth and Venus gravity assist flyby), there is significant flow in the radiator and its temperature would change due to stoppage of flow. A radiator thermal model was constructed to evaluate this concept numerically. In this transient thermal simulation the radiator temperature was plotted as a function of time starting from full flow to a sudden flow stoppage. The radiator thermal mass and its radiative coupling to space then determines its thermal profile as depicted in Figure 4. The large thermal mass of the radiator coupled with its relatively poor thermal conductance to space (due to its limited heat loss to thermal mass ratio) leads to relatively small change in temperature (about 6ºC in 15 minutes, and 11ºC in 30 minutes). Additionally, the radiator's temperature response would be a function of its orientation to hot sources like the Sun, Earth or Venus. In order to decipher the root cause of the fault one would need sophisticated software algorithms to de-convolve the nature of the fault. For these reasons this concept 5 coupled with concept 4 was rejected for further investigation.

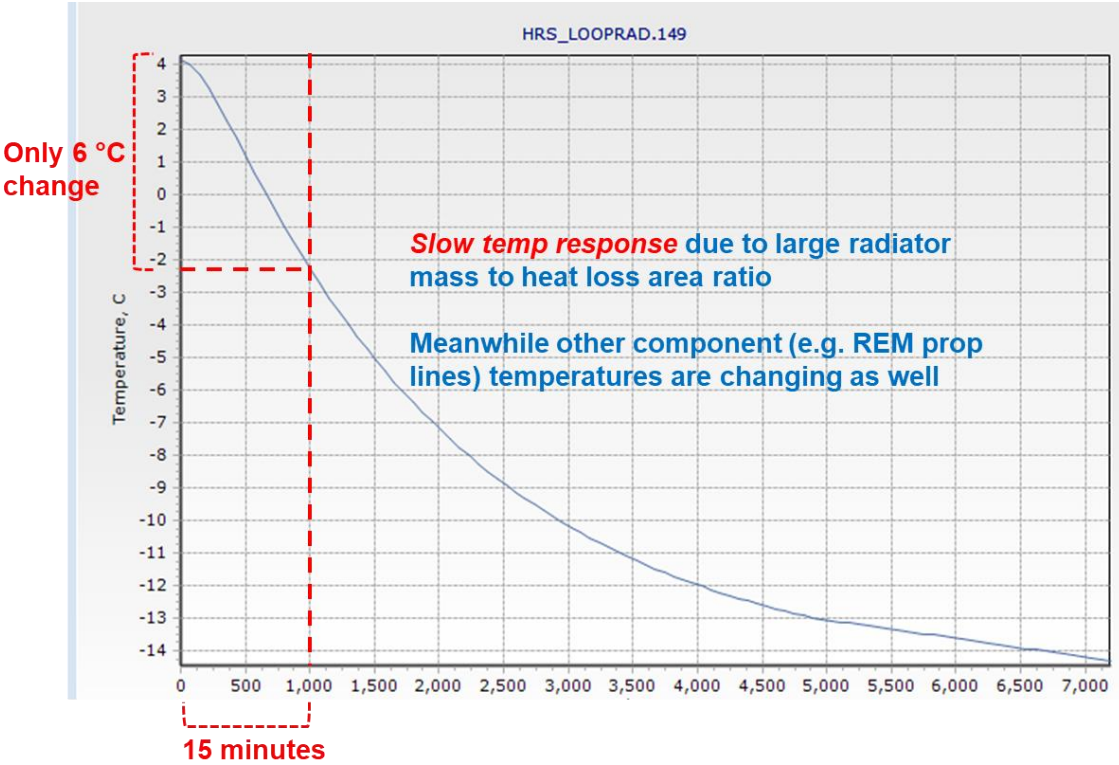


Figure 4. Employment of HRS Radiator thermal response to detect flow stoppage in the fluid loop.

V. Baselined Concept Utilizing a Heated Section of HRS Tubing as a Watchdog for Flow Stoppage Detection

The concept baselined for implementation utilizes a small section of pre-existing HRS tubing that has a patch film heater attached to its outer surface. This heater is constantly energized throughout the mission. To minimize the resource impact, the heater is sized to dissipate a very small amount of power (<1 W). The stainless steel HRS tubing has poor lateral conduction due to the low thermal conductivity. The tubing is wrapped with a MLI blanket to minimize its heat loss to the environment. Additionally the tube is on supports that are thermally isolated from the structure they are mounted on. The combination of these isolations renders the heated section almost adiabatic, almost simulating a lumped capacity heated mass. These design features confine the heat to the section of the tube where the heater is attached. Only a short section of the tubing is heated (about 3" or 8 cm in length). The unheated portion of the tubing around the heated section between the supports is 3" or 6 cm on either side. Figure 5 shows a schematic of this concept. A thermal simulation of this concept was conducted to assess its validity numerically. Heater powers of 0.5 W and 1 W were modeled on the heated section and the transient response of the tubing and the flowing fluid were created as a function of full flow vs. partial flow vs. no flow. The key conditions that were analyzed were a fluid and tube initial temperature of 45°C (worst case hot temperature for vault structure), MLI e* of 0.1 (conservative for heat loss), and a conductive thermal isolation of 0.01 W/K per support. These represent the worst case conservative set of conditions for this assessment.

These are shown in Figure 5. It is evident that in spite of the very small heat insertion, the small thermal mass of the tubing responds very rapidly to the heat when the fluid flow stops. For example, even with only a 0.5 W heater power, the tube rises by 15°C in 7 minutes when the flow stops. On the other hand the tube temperature remains almost identical to the fluid temperature when full fluid flow is maintained.

One point to note is that the inserted power imposes essentially no additional power required for the spacecraft as long as the RHB power required for the makeup heat is greater than the power inserted in the heated tube section. It is power neutral because all the heat from this heated tube goes into the HRS flow and the RHB power would then go down by the same amount to supply the requisite total power for the HRS to control the spacecraft's temperatures. In

hot conditions, when the RHB power is zero (RHB off), it would pose an additional power tax, but usually those situations arise when the spacecraft has more power margin to overcome this "tax."

The implementation of this concept for flight consists of employing two temperature sensors, one on the heated section of the tube and the other several cm downstream of it, as depicted in Figure 5. Then a significant difference between these sensors' readings would signal a flow fault.

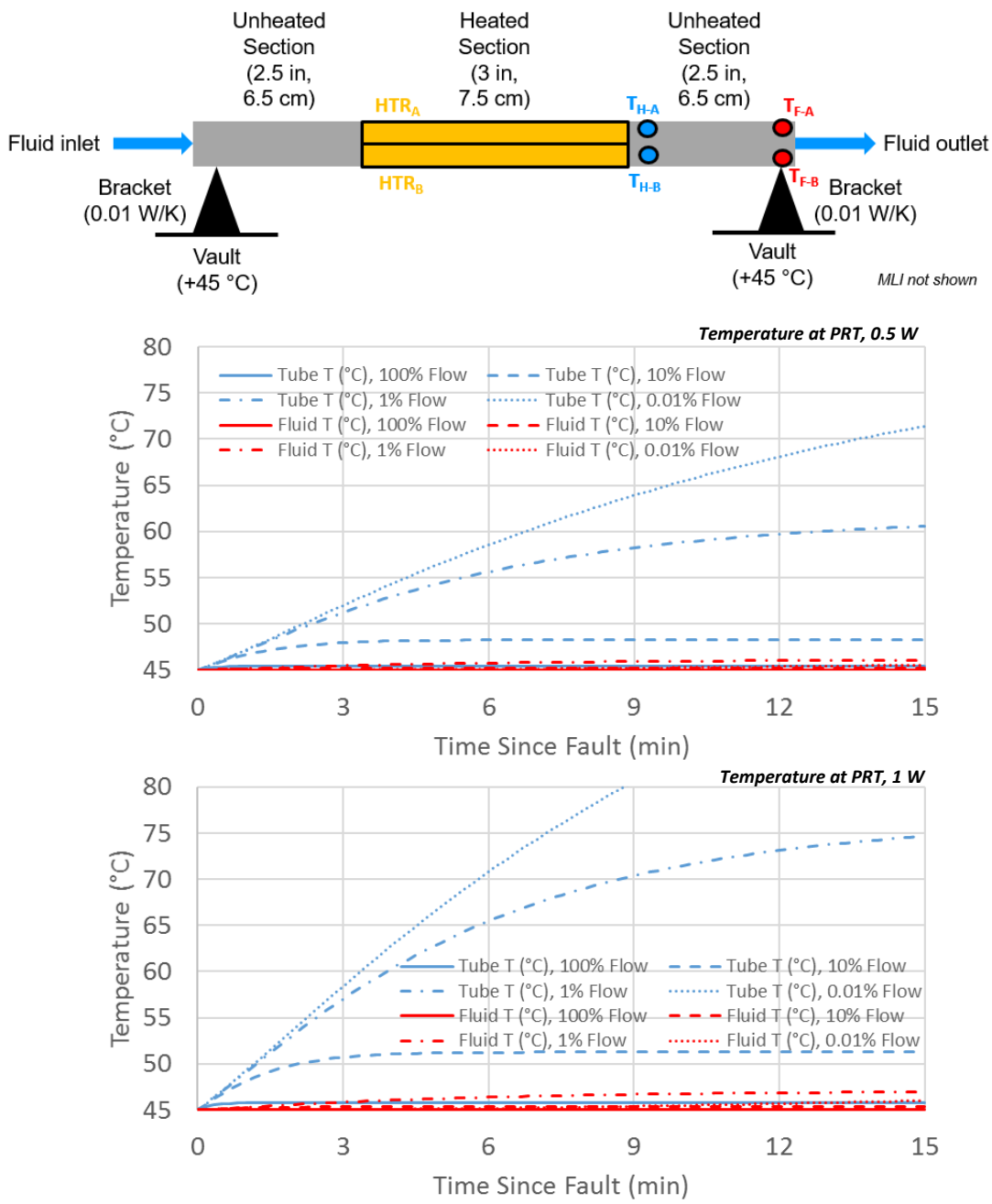


Figure 5. Heated HRS tube section's thermal response to detect flow stoppage in the fluid loop.

VI. Applicability for Other Missions

Even though this heated tube section thermal watchdog concept was conceived for the Europa Clipper HRS, it is applicable to other missions utilizing a pumped fluid loop (single or two phase) to detect a fluid flow fault. It has several positive attributes:

- Provides very rapid detection of the root cause of the fault (flow stoppage), much earlier than the ramifications of the root cause fault are realized (temperature limit violations of HRS controlled hardware)
- Simplicity
- Requires minimal power, mass and volume
- Very easy to implement (film heater bonded to tube section and a PRT temperature sensor)
- Easy to monitor by flight software
- Works in all thermal and operational conditions with no exception

VII. Conclusions

A flow stoppage fault in a pumped fluid loop heat rejection system (HRS) would pose a serious risk for the thermal health of the hardware served by the HRS. Very early detection of the fault is necessary to ensure that a rapid remedy in the form of turning on the back up pump is invoked. Several schemes were investigated and traded off for the Europa Clipper HRS. The most attractive option was baselined for fault detection and it consists of utilizing a small film heater on a section of the HRS tubing. This watchdog utilizes a low power heater attached to that section of the line. Once energized, it provides rapid, accurate and highly discriminatory detection of a fluid flow stoppage indicated by a rapid rise in temperature of the heated section when the flow stops. Its simplicity, accuracy, speed, robustness, and ease of implementation make it very attractive for use in other missions that utilize pump fluid loops for thermal control.

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