# Impact of Fluid Flow Pressure drop on Temperature of Components Controlled by Mechanically Pumped Fluid Loop Thermal Control System

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# Question:

# Is Pressure Drop in a Fluid Loop Heat Rejection System a "Wall" not to be crossed?

# Answer:

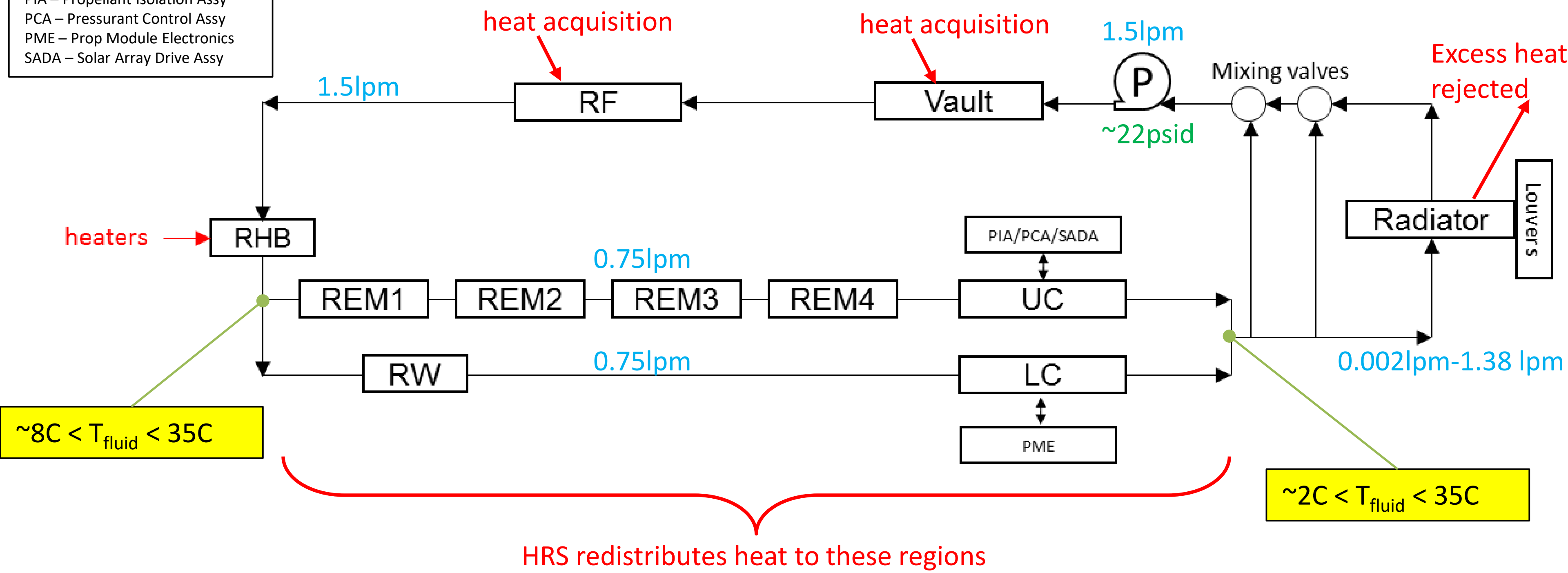
# Not really (within limits, of course) ☺

# Outline of Presentation

- Concerns
- Cause → Effect Linkage
- Process
- Pressure drop and operating point estimation
- Key pump characteristics
- Thermal Conductance Estimation
- Reduction of key interface temp. margins & survival power increases due to ΔP increases
- Summary
- Key Conclusions

# Simplified Clipper HRS Fluid Loop Schematic

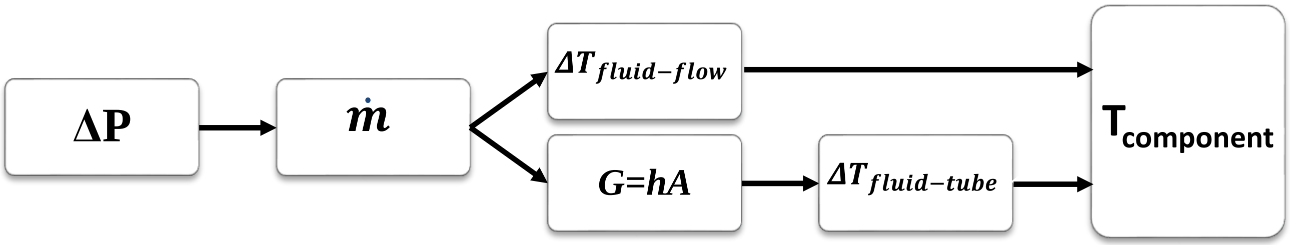
- REM – Rocket Engine Module
- RF – Radio Frequency
- RW – Reaction Wheels
- UC – Upper Cylinder
- LC – Lower Cylinder
- PIA – Propellant Isolation Assy
- PCA – Pressurant Control Assy
- PME – Prop Module Electronics
- SADA – Solar Array Drive Assy

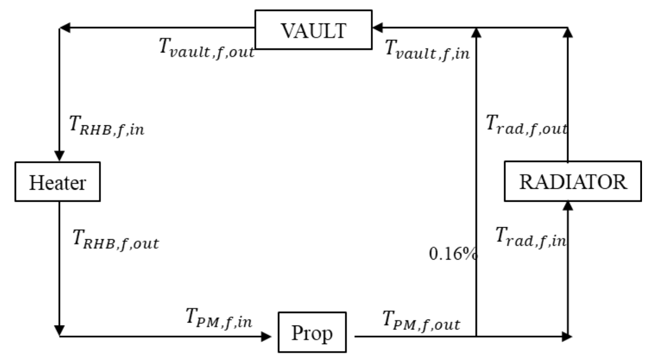


# The Concern

- **Pressure drop in Mechanically Pumped Fluid Loop Heat Rejection System (HRS) is due to tubing, fittings, etc.**
- **The typical "minor" pressure drops, beyond the straight lengths of tubing, can potentially be the "primary" ΔP**
  - Accounting for straight length ΔPs is relatively simple and accurate (textbook correlations)
- **But accounting for "minor" losses by analytical means is not easy**
  - Large variance in estimating methods
  - Only accurate way is to measure them in test setup to simulate flight configuration
  - Tests are performed much later but need to be solidified much earlier to finalize design
- **Hence ΔP estimates could have large error bars in estimation & due to incompleteness of design**
- ***The concern was that if there were large ΔP estimates, they could lead to temperature violations at the key interfaces***
  - *Which would be problematic & difficult to overcome*

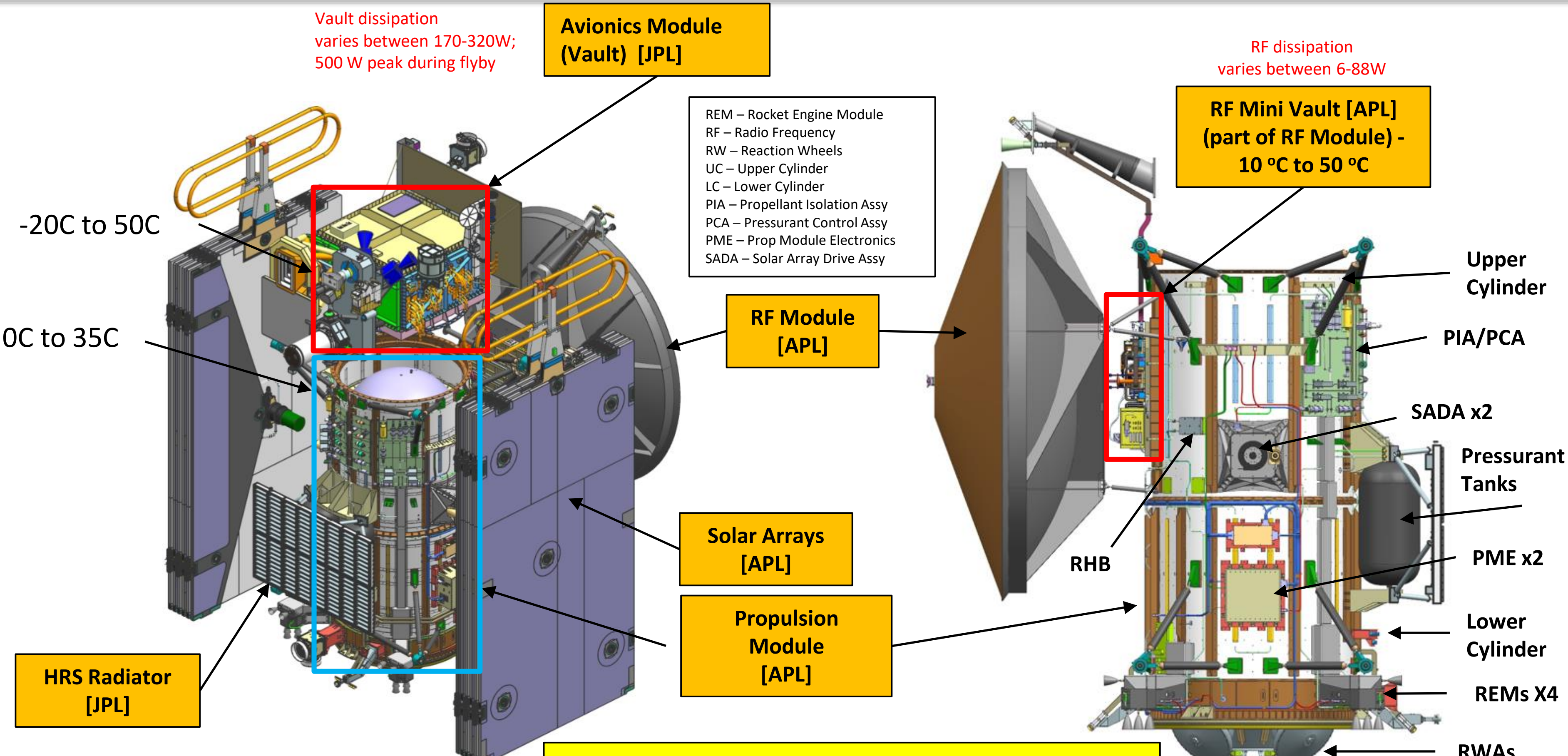
# The Cause → Effect Linkage



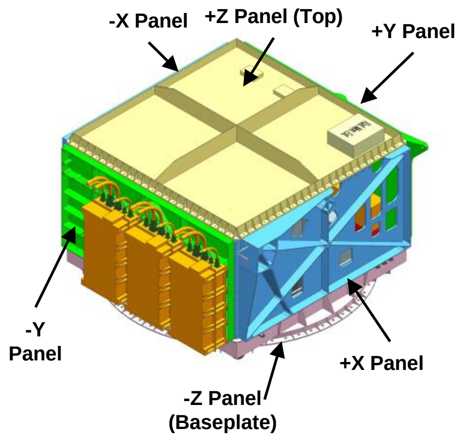

- **So higher pressure drops would lead to warmer interface temperatures**
- **If interfaces are close to their allowable limits, larger ΔPs could potentially result in temperature violations**
- ***Hence a sensitivity study of temperature predictions to pressure drop is warranted, and is the thrust of this presentation***

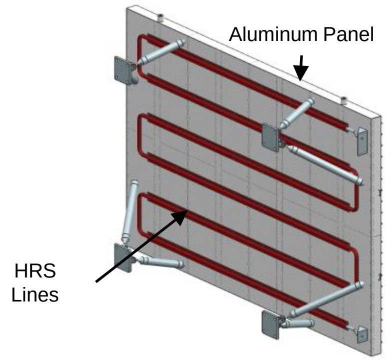
# Case Study: Europa Clipper

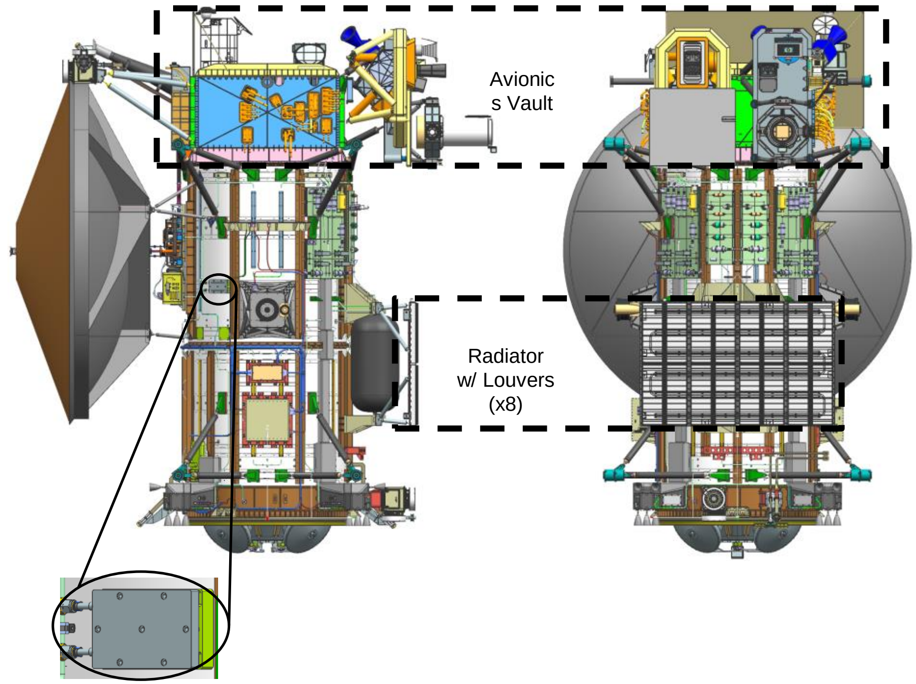


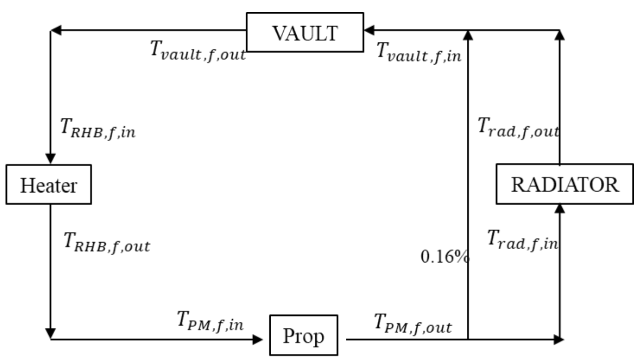

**HRS MISSION ENABLING ATTRIBUTE:** Heat harvesting functionality is required to maximize electrical power available to instruments during flybys

# Europa Clipper HRS



# Pressure Drop Estimation

- List all contributors to ΔP

- Use known references for each item above to estimate nominal conservative ΔPs for any flow rate

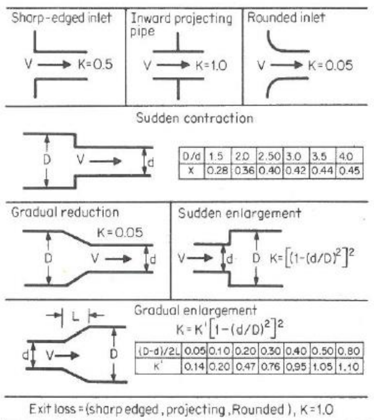
- **Inflate the ΔPs so estimated by a variable (increased) error of 10% to 100% in steps and tabulate**

**Table 11. Representative Equivalent Length in Pipe Diameters (L/D) of Various Valves and Fittings**

| | |
|---|---|
| Globe valves, fully open | 450 |
| Angle valves, fully open | 200 |
| Gate valves, fully open | 13 |
| ¾ open | 35 |
| ½ open | 160 |
| ¼ open | 900 |
| Swing check valves, fully open | 135 |
| In line, ball check valves, fully open | 150 |
| Butterfly valves, 6 in and larger, fully open | 20 |
| 90° standard elbow | 30 |
| 45° standard elbow | 16 |
| 90° long-radius elbow | 20 |
| 90° street elbow | 50 |
| 45° street elbow | 26 |
| Standard tee: | |
| Flow through run | 20 |
| Flow through branch | 60 |

Compiled from data given in "Flow of Fluids," Crane Company Technical Paper 410, ASME, 1971.

**Table 10. Representative Values of Resistance Coefficient K**



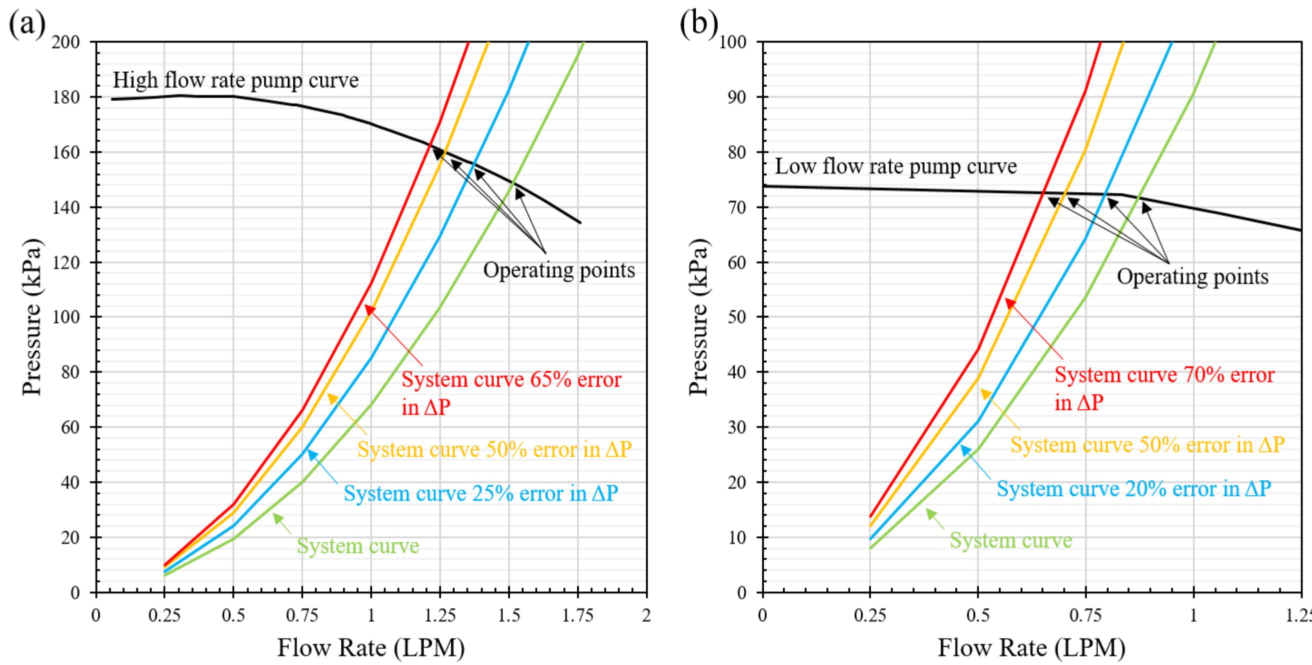

Compiled from data given in "Pipe Friction Manual," 3d ed., Hydraulic Institute, 1961.

| Minor Components | K Factor | L/D | L/D based on Vault Friction factor |
|---|---|---|---|
| 90deg street elbow | 1.85 | 47 | Reference 1: Marks' Standard Handbook for Mechanical Engineers for street elbows |
| 90deg standard elbow | 1 | 26 | Reference 1: Marks' Standard Handbook for Mechanical Engineers for standard elbows |
| 90deg standard elbow: screwed R/a = 2 | 1.820 | 47 | Reference 4: Check; Equation 10.9 has typo, should be 0.5/r instead of 0.5*r; also not good approx. for turbulent flow |
| 90deg standard elbow: Long Radius R/a = 3 | 0.993 | 25 | Reference 4: Check; Equation 10.9 has typo, should be 0.5/r instead of 0.5*r; also not good approx. for turbulent flow |
| 90deg smooth bend in circular pipe | 0.340 | 9 | Reference 5: Turbulent flow Re>4000, moderate bends R/D >=1.8, >360 |
| 180deg bends | 3.7 | 95 | Reference 1: Double of the 90deg street elbow k factor? |
| 180deg standard elbow: Long Radius R/a = 3 | 1.448 | 37 | Reference 4: check; Equation 10.9 has typo, should be 0.5/r instead of 0.5*r |
| 180deg standard elbow: screwed R/a = 2 | 2.688 | 69 | Reference 4: check; Equation 10.9 has typo, should be 0.5/r instead of 0.5*r |
| 180deg smooth bends in circular pipe | 0.521 | 13 | Reference 5: Turbulent flow Re>4000, moderate bends R/D >=1.8 |
| Tee Fittings - line flow | 0.8 | 20 | Reference 1: to match L/D of 20 @ 0.75 lpm |
| Tee Fittings - branch | 2.35 | 60 | Reference 1: to match L/D of 60 @ 0.75 lpm |
| Mechanical Fittings | 0.8 | 20 | Reference 2: Expansion and Contraction - doubled from k = 0.4 for 0.028" walls |

| | | |
|---|---|---|
| **Total Pressure drop external to IPA** | **psid** | **10.916** |
| **Total Pressure drop due to IPA only** | **psid** | **7.860** |
| **TOTAL HRS SYSTEM DELTA P** | **psid** | **18.776** |
| **TOTAL DELTA P + 50% Error** | **psid** | **28.164** |
| **TOTAL DELTA P + 60% Error** | **psid** | **30.041** |
| **TOTAL DELTA P + 70% Error** | **psid** | **31.919** |

# Operating Point Determination

1. Create line ΔP vs. flow rate curve (almost parabolic)
2. Plot pump curve provided by vendor from test or extrapolated data
3. **Find intersection of these two curves to represent *operating point* of overall system (ΔP and flow rate)**



# Process for Estimating Component Temperatures

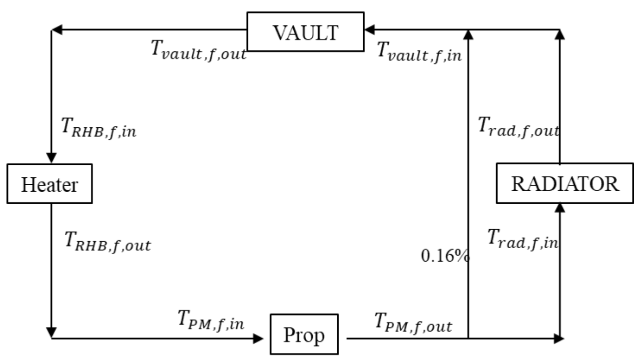
- **Use this resultant flow rate to compute fluid temperature distribution in the HRS at all key components**
  - Using predicted heat inputs and outputs from each key module

$$\dot{m}c_p\left(T_{f,out} - T_{f,in}\right) = Q = \varepsilon\sigma A_s T^4$$

$$G = \frac{1}{R} = \left(\frac{1}{hA} + \frac{1}{G_{tube}}\right)^{-1}$$

$$T_i = T_{f,out} + Q/G$$

- **Compare this against the Max Temperature Limits**

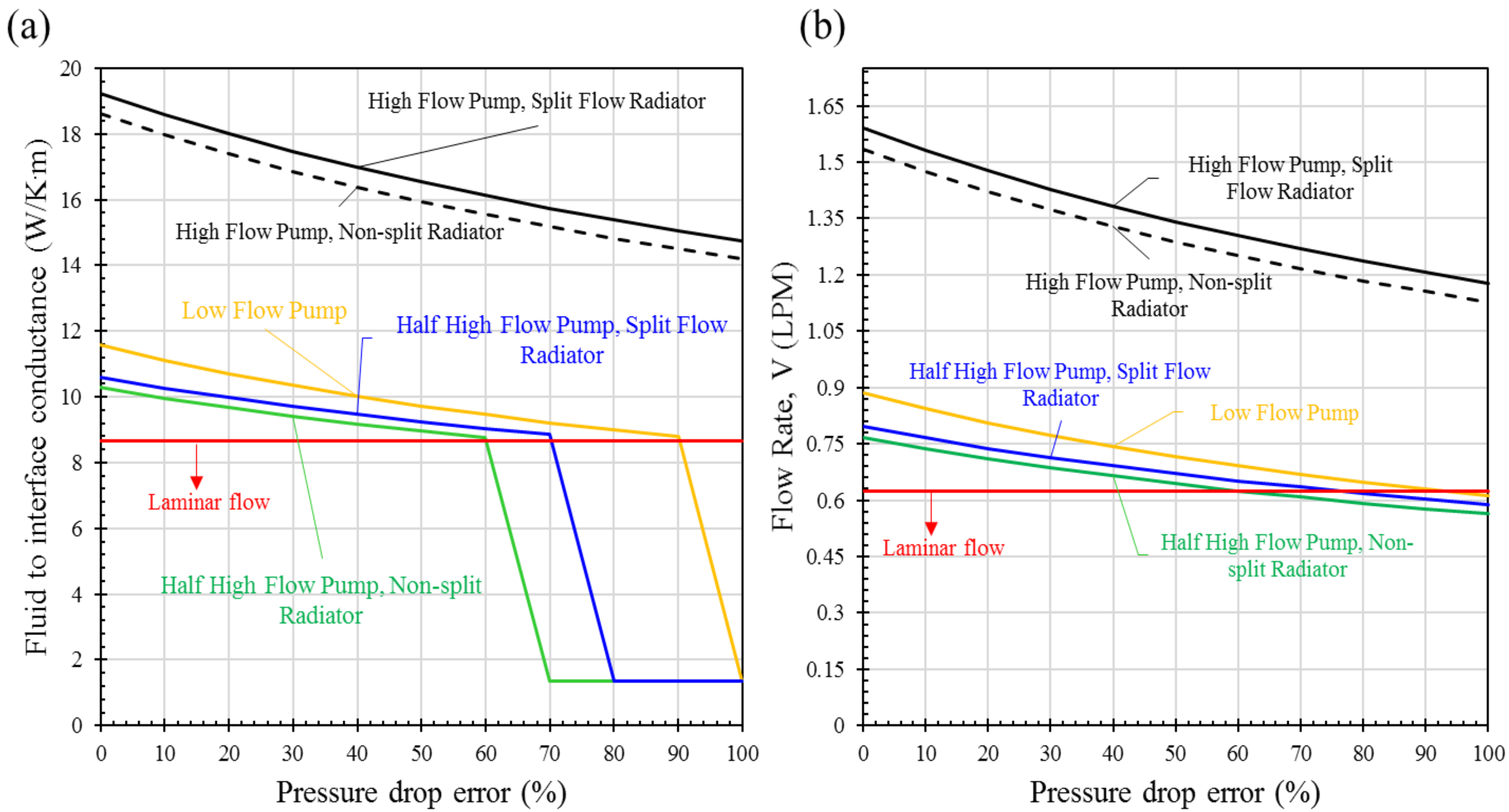


# Examples Of Impact of ΔP Error on Flow Rates & Thermal Conductance (I)

| | Operating Cases | % ΔP Error | Flow Rate V | Conductance G |
|---|---|---|---|---|
| a | Low flow rate pump | 0% | 0.89 LPM | 11.6 W/m-C |
| | | 90% | 0.63 LPM | 8.8 W/m-C |
| b | High Flow rate pump with split PM | 0% | 1.53 LPM | 18.6 W/m-C |
| | | 60% | 1.25 LPM | 15.5 W/m-C |
| c | High flow rate pump with split PM and radiator | 0% | 1.59 LPM | 19.2 W/m-C |
| | | 70% | 1.27 LPM | 15.7 W/m-C |

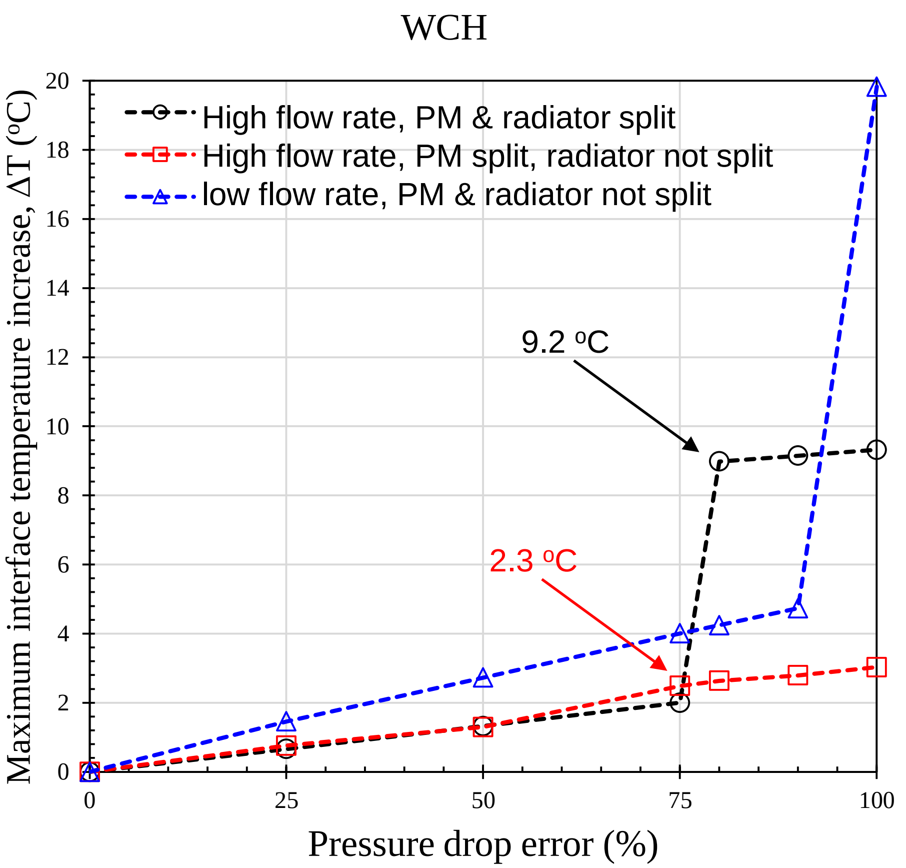
- Low Flow Pump (no splitting):
  - 90% increase in ΔP leads to only 30% reduction in flow & 24% in G
- High Flow Pump (Split PM, Radiator Un-Split):
  - 60% increase in ΔP leads to only 20% reduction in flow & 17% in G
- High Flow Pump (Split PM & Radiator):
  - 70% increase in ΔP leads to only 20% reduction in flow & 20% in G

# Examples Of Impact of ΔP Error on Flow Rates & Thermal Conductance (II)



# Worst Case Hot ΔT Impact

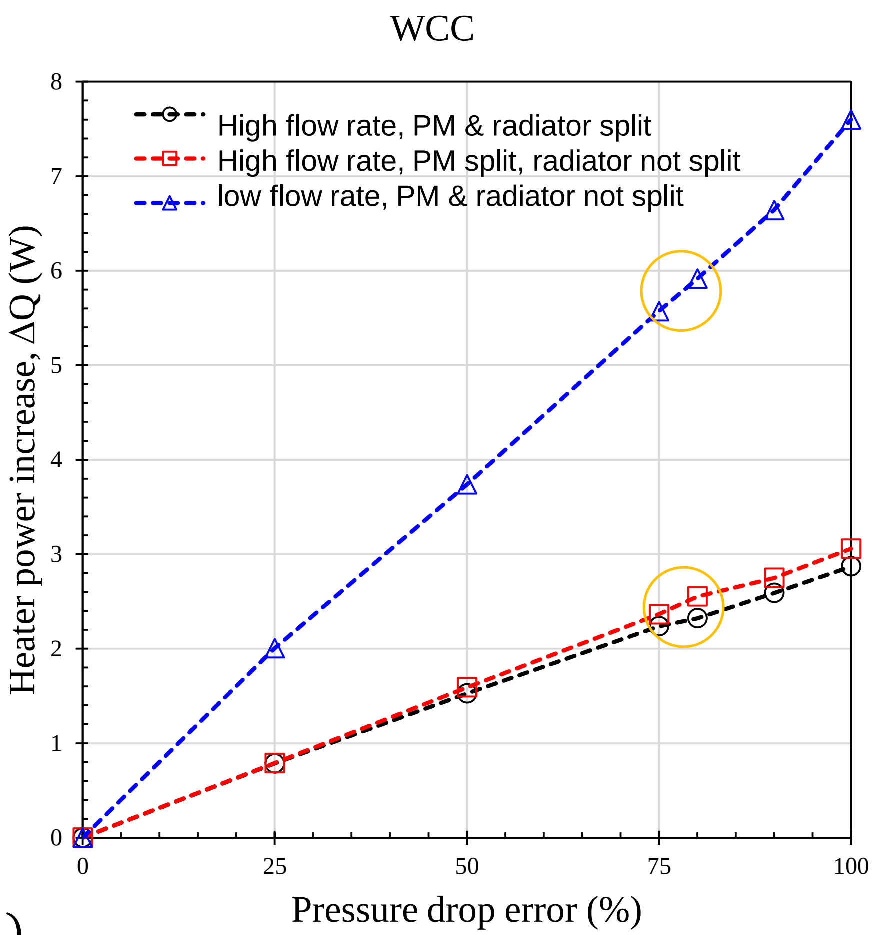
- Clipper Design is robust with respect to pressure drop (split or no split radiator)
  - <2°C increase in T due to 75% error in ΔP for high flow system
  - <5°C increase in T due to 90% error in ΔP for low flow system
- Linear increase in ΔT vs pressure drop in turbulent flow regime
  - Sharp increase in ΔT when flow becomes laminar for low & high flow rate split radiator case



# Worst Case Cold Survival Power Impact

- **High flow rate design is robust with respect to ΔP (regardless of radiator routing)**
  - <3 W (<2.5%) increase in $Q_{heater}$ due to 75% increase in pressure drop
  - Linear increase in heater power required to maintain AFTs with ΔP

- **Low flow rate design requires more heater power compared to high flow rate for same ΔP error**




$$\Delta Q = Q_{heater}(0\%\ \Delta P_{error}) - Q_{heater}(\Delta P_{error})$$

# Summary

- A comprehensive study of sensitivity of max temp. violations (WCH) & Survival power increases (WCC) to ΔP increases in an HRS was undertaken
- Most up to date pump curves provided by pump vendor were employed
- All components in flow path were accounted
- Errors of up to 100% in estimated HRS ΔP were analyzed
- Critical flow rates required to avoid laminar flow in tubing was estimated to ensure that thermal conductances remain acceptably high

# Key Conclusions

- A major finding was that Clipper HRS is very robust to accommodating ΔP increases above the most conservative estimated values
- ΔP increases of as much as 60% to 90% above the most conservative values lead to relatively small reductions in margins against max temp. limits & relatively small increases in required survival powers
- Hence this study gives confidence in robustness of Clipper HRS to ΔP increases due to estimating processes or change in configuration maturation
- It also dispels the notion that pressure drop is generally a “wall” which is impermeable or cannot be crossed without very adverse impacts
- Flow being laminar - because of excessive pressure drops - is more drastic in consequence (more of a “wall”) due to the large increase in interface temperatures
- Even though this study was done for a specific HRS, the methodology presented in this paper can be utilized for different configurations utilizing single phase fluid loop HRS for thermal control

# Acknowledgements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- Government sponsorship acknowledged

# Questions & Answers?