Design and Modeling of a Variable Heat Rejection Radiator

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Background

- Variable Heat Rejection Radiator technology needed for future NASA human rated & robotic missions

- Primary objective is to enable a single loop architecture for human-rated missions
  - Radiators are typically sized for maximum heat load in the warmest continuous environment resulting in a large panel area
  - Large radiator area results in fluid being susceptible to freezing at low load in cold environment and typically results in a two-loop system
  - Dual loop architecture is approximately 18% heavier than single loop architecture (based on Orion thermal control system mass (09ICES-0353))
  - Single loop architecture requires adaptability to varying environments and heat loads
Example Mission Profile

Environmental Sink Temperature and Energy Rejection Requirements
($\alpha = 0.1$, $\epsilon = 0.85$)

*Time-Averaged*
Digital Radiator Concept
The concept is based on using valves to turn ‘on’ or ‘off’ the fluid flow through parallel fluid lines imbedded in the radiator.

Extensive analytical work was performed using Thermal Desktop/Fluint to investigate the feasibility of this concept.

Several bench-top tests were performed to verify the fluid evacuation from closed tubes and to verify circulation in the tubes after they have experienced temperatures below the fluid freeze point.

Several fluids were investigated to understand performance.

Based on results from test and analysis, a scaled Digital Radiator design will be developed and tested.
Digital Radiator Concept Tests

- Bench top testing performed early on for proof of concept (2006-07)
- Results fed into further testing and thermal model development (2008-10)
Thermal Model Description

Four panels of 2m x 3m in parallel with bypass line.

- **Aluminum Facesheet (Out)**
  
  \[ t = 0.011" \]
  
  Radiation to Sink

- **Aluminum Finned Tubing per Panel**
  
  Qty = 23, OD = 3/8", \[ t = 0.028" \]
  High Bondline Conductance
  Contactor to Inside of Top Facesheet

- **Contactor** from Top to Bottom
  Facesheets: 300 W/m-K
  Represents ½” Honeycomb

- **Aluminum Facesheet (In)**
  
  \[ t = 0.011" \]

Future Improvements: Non-infinite bondline, transient cases, control feedback loop, pressure drop concerns
Key Model Assumptions

- Working fluid is 50/50 PGW
- Manifold designed to provide equal mass flow to each tubing segment
- Requirements time-averaged over specific portions of the mission profile
- Bypass line completely insulated
- Embedded tubing thermally shorted to front panel
# Trade Space

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Tube Diameter Study

- No significant increase in heat rejection found for various tube diameters
- Evacuation shown to work in tests on 3/8” tubing

*23 Finned Tubes, 2m x 3.3m Panel, 205K Sink, 0.058kg/s Mass Flow
Tube Quantity Study

- Increase in tube quantity per panel results in an increase in heat rejection due to fin efficiency.
- A “knee” occurs at approximately 23 tubes.
- Tube quantity and associated fluid found to have significant effect on mass.

*Finned Tubes, 2m x 3m Panel, 210K Sink, 0.06kg/s Mass Flow*
Panel Size Study

- Data shown for internally finned and smooth wall tubing
- Finned tubing shows increase in heat rejection
- Panels sized for LSO (worst case hot). A panel size of 6m² (2m by 3m) is shown to reject the required minimum of 6040W to a 210K sink.

*23 Finned/Smooth Tubes, 210K Sink, 0.06kg/s Mass Flow
**Mass Flow Study**

- An increase in mass flow results in an increase in heat rejection as well as an increase in outlet temperature.

- A mass flow of 0.06 kg/s provides maximum heat rejection while meeting the 10°C desired outlet temperature for cabin feedback.

*23 Finned Tubes, 2m x 3m Panel, 210K Sink*
Mission Profile: LEO

Required $Q_{REJ} = 1080W$

$T_{IN} = 288K$
Total $m_{DOT} = 0.06kg/s$

Bypass
$m_{DOT} = 0kg/s$

$T_{SINK} = 190K$
$Q_{REJ} = 1084W$

$T_{SINK} = 190K$
$Q_{REJ} = 0W$

$T_{SINK} = 190K$
$Q_{REJ} = 0W$

$T_{SINK} = 190K$
$Q_{REJ} = 0W$

$T_{OUT} = 282.6K$
Total $Q_{REJ} = 1084W$

$\Delta T \sim 5K$

* Average sink temperatures and heat rejection
Mission Profile: LEO

Required $Q_{REJ} = 936\text{W}$

$T_{IN} = 288\text{K}$
Total $m_{DOT} = 0.06\text{kg/s}$

$T_{OUT} = 283.4\text{K}$
Total $Q_{REJ} = 936\text{W}$

$\Delta T \sim 5\text{K}$

*T* Average sink temperatures and heat rejection
Mission Profile: TLC

Required \( Q_{\text{REJ}} = 3535 \text{W} \)

\( T_{\text{IN}} = 301 \text{K} \)
Total \( m_{\text{DOT}} = 0.06 \text{kg/s} \)

\( T_{\text{OUT}} = 283.6 \text{K} \)
Total \( Q_{\text{REJ}} = 3552 \text{W} \)

\( \Delta T \approx 17 \text{K} \)

Average sink temperatures and heat rejection
Mission Profile: TLC

Required $Q_{REJ} = 4800\text{W}$

$T_{IN} = 307\text{K}$
Total $m_{DOT} = 0.06\text{kg/s}$

$T_{SINK} = 222\text{K}$
$Q_{REJ} = 1336\text{W}$

$T_{OUT} = 283.5\text{K}$
Total $Q_{REJ} = 4810\text{W}$

$\Delta T \sim 23\text{K}$

*Average sink temperatures and heat rejection
Mission Profile: LSO

Required $Q_{REJ} = 6040W$

$T_{IN} = 313K$
Total $m_{DOT} = 0.06kg/s$

Δ$T \sim 30K$

Total $Q_{REJ} = 6207W$

* Average sink temperatures and heat rejection
Point Design Metrics

Point design metrics for the digital radiator include:

- **Mass:**
  - Radiator Panel
  - Fluid in the Tubes
  - Mass of the Tube Material
  - Latch Valves to Control Tube Flow*
  - Heaters (Start-Up)
  - Check Valves
  - Evacuation pump*
  - Accumulator*

- **Power:**
  - Evacuation pump
  - Start-up Heater

- **Volume:**
  - Available space

- **Reliability:** High (Latch valves have been used in flight, so also pumps)

- **Scalability:** Excellent (mass of radiator and valves scale directly, mass of pump and accumulator scales at a reduced levels)

- **TRL:** 5-6 (currently it is at TRL 4-5)

* Key additional elements in DR compared to Apollo stagnation radiator
Several challenges exist in the development of full-scale Digital Radiator for future NASA missions:

- The development of lightweight two-way and three-way latch valves for flight radiator
- Evaluation of evacuation for smaller diameter tubes (both finned and smooth) for mass savings
- Obtaining reliable components with the mass estimates used
- Reliable operation of the completely integrated single panel with the pumps, accumulator, and radiator
Performance Challenge

- LLO will provide a highly variable sink temperature yet require steady heat rejection.

- A sublimator may be implemented to handle the high temperatures but freezing may occur at the low end.

- Knowledge of thermal mass associated with spacecraft required to determine transient performance.

- Heaters, heat exchanger, or alternative fluids may be necessary to handle reaction times.
Design Summary

- Design capable of maintaining outlet temperature throughout the mission.
- All panels identical and within area constraints.
- Two tube evacuations required for mission profile.
- Pressure drop across panels less than 10 psi.
- Multiple configurations (such as various tube quantities per panel) capable of meeting mission profile.
- Design for optimal mass and power involves iterations on model trades and laboratory tests.