Analytical Investigation of Pumped Fluid Loop Radiators for Orion Spacecraft

Gretchen Reavis
Paragon Space Development Corporation
greavis@paragonsdc.com

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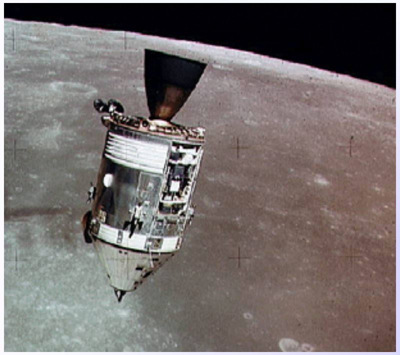
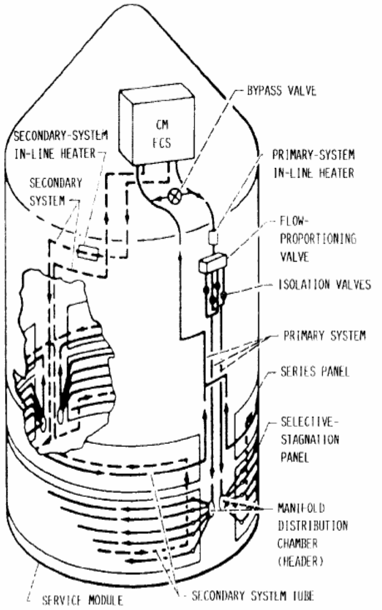
Historical Perspective: Apollo Stagnating Radiator

Apollo 15 (Source: NASA)





Radiator Concept (Ref 1.)

- Pumped fluid loop system using selective stagnation to proportion flow in radiators for accommodation of varying mission heat load
- Two panels in parallel with circumferential tubes each with a smaller series panel downstream
- Controlled stagnation accomplished through varied tube length between manifold to panel

Design Characteristics (Ref 1.)	
Peak Fluid Inlet Temperature	107.6 F (42 C)
Radiator Area	95.8 ft2 (8.9 m2)
Flow Regime	Laminar
Working Fluid	Glycol / Water
Fluid Path	Parallel
Flow Rate	238.1 lb/hr (0.03 kg/s)
Heat Load	2.0 KW
Radiator Coating	Z 93 White Paint

Apollo Radiator Design Challenges

From Interview with Frank H. Samonski (Ref 2.)

Chief, Command Module Environmental Control System Office, Apollo Support Office, Crew Systems Division (1965-1969)

If one panel is hot and one panel is cold, the fluid will flow toward the hot panel due to the higher viscosity in the cold panel …

“The radiator, the design of the radiator itself, you might think you just take this panel of metal and maybe braze on a bunch of tubes and flow the fluid through it, and that would do it, but it’s not that easy. First of all, maybe one side of the spacecraft is exposed to deep space, and it’s radiating heat away like crazy. But the other side of the spacecraft, where you have the other radiator, is maybe seeing the Earth, and it’s not radiating away so much. So the side that’s seeing deep space, the fluid within the radiator, because it’s getting colder, it becomes more viscous, and the flow rate sort of slows down. The resistance of the passage on that radiator is higher, so more flow is diverted to [the Earth-side] one, where you don’t want it, because it’s not in a good environment for rejecting heat.

If a panel freezes, it can’t be unthawed …

“So we had to find a way to, first of all, balance the flow to the two panels on opposite sides of the spacecraft that would compensate for the environment that they were seeing. Then we had to figure out a way to, if the fluid got very cold and viscous within a particular radiator, how is it that you recover from that, that the flow doesn’t stagnate, and then you can never get heat out there in order to thaw it to get it to go again.

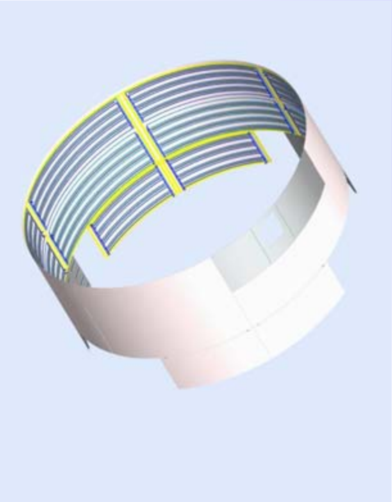
Selective stagnation was complex and required sophisticated testing …

“So that was a pretty tricky job, and what we ended up with was a technique called selective stagnation. We had, I forget, maybe five or six parallel tubes in that radiator, and there was a manifold that supplied the fluid to those tubes, and one that collected it. By adjusting the restrictions in the manifolds for each tube, you could predict with some certainty what the temperature range would be in each of the tubes. So, the one furthest from the manifold would be the coldest, so you would want it to have the least pressure drop. Then come in one, and it would be a little more resistance maybe. So within certain ranges, the radiator could kind of stagnate and then recover itself. That took some testing, sophisticated testing, in our big chambers here, Chamber A, the space environment simulator, and the like, to get that all correct.”

Orion Spacecraft: Requirements and Challenges

CEV (Source: Lockheed Martin)

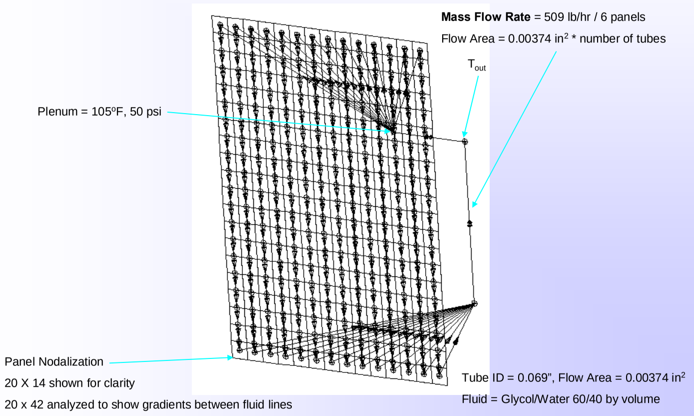
- Pumped fluid loop system
- Six primary panels, four secondary panels
- Circumferential flow
- Redundant flow paths
- Investigation of parallel and series flow configuration



Design Characteristics	
Peak Fluid Inlet Temperature	105 F
Radiator Area	310 ft2
Flow Regime	Laminar
Working Fluid	Glycol / Water
Fluid Path	TBD
Flow Rate	509 lb/hr
Heat Load	5.7 KW
Radiator Coating	Z 93 White Paint

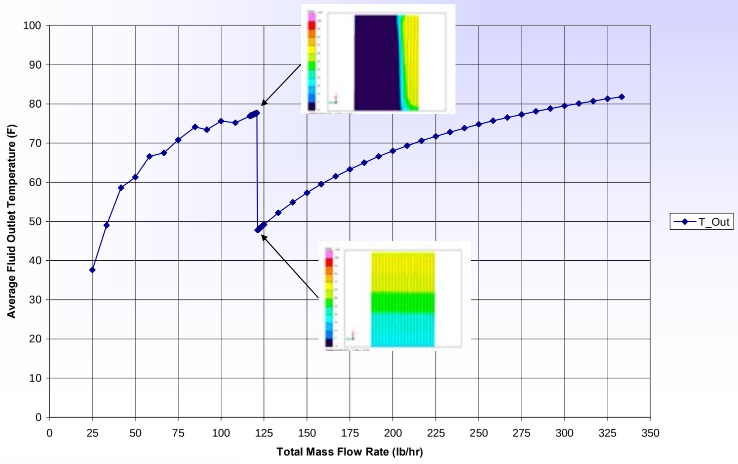
Investigation: Single Panel System

Single Panel Model with 20 flow tubes



Radiator Stagnation Occurs Suddenly

Average Fluid Outlet Temperature vs Total Mass Flow Rate for T_Env = 0K



Design Parameters

- Panel: 70" x 105" by 0.06" thick Al 6061-T6
- Tubes: Al 6061-T6 with 0.069" ID
- 20 Al tubes with 3.5" spacing
- Common manifold
- Feeder Tubes: 6" long with 0.069" ID
- Fluid: Propylene Glycol Water, 60/40 mix
- Fluid inlet temperature: 105 ºF
- Surface Coating: Z-93, α=0.17, ε=0.92
- Sink Temperature: 0 K

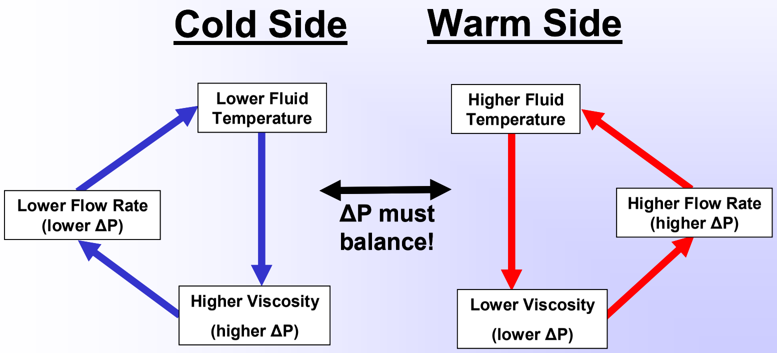
Nominal vs Stalled Operation

- Nominal operation
  - Flow Rate $\geq$ 121.2 lb/hr
  - Lowest fluid outlet temperature: 47.8 oF
  - Maximum heat rejection: 1543.4 W
- Stalled operation
  - Flow Rate $\leq$ 120.8 lb/hr
  - Fluid outlet temperature: 77.7 oF
  - Heat rejection: 744.1 W

- ***Stall occurs suddenly: 15 of 20 tubes shut down with a change in flow rate of less than 0.4 lb/hr***

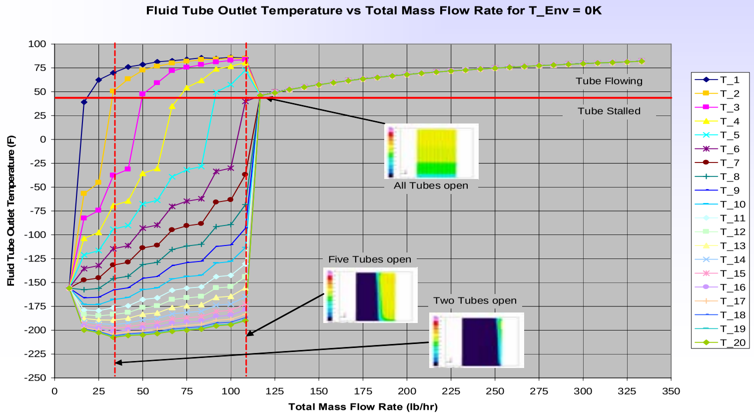
Flow Stagnation

Initial Conditions Determine Stability of Fluid Flow in a Radiator System (Ref 3.)



Depending upon the initial conditions, this can result in a stable situation, or complete stalling of the cold side.

Flow Stagnation by Tube in 20 Tube Panel Model as a Result of Flow Rate Reduction

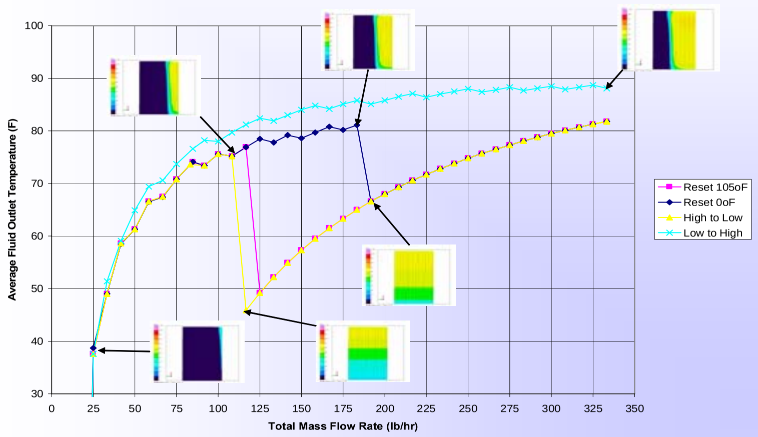


- Effect of Stalled Radiator
  - Increase in radiator outlet temperature
  - Reduction in heat rejection.
- Driving Factors in Flow Stagnation
  - Viscosity characteristics of the fluid
  - Temperature drop across a single radiator (function of flow rate and tube length)
  - Magnitude of the cooling differential across radiator panel
- There is a limit to the amount of temperature drop that can be achieved across a single radiator.
- Geometry of the radiator fluid tubes does not impact susceptibility to flow stagnation, provided that all the tubes are identical.

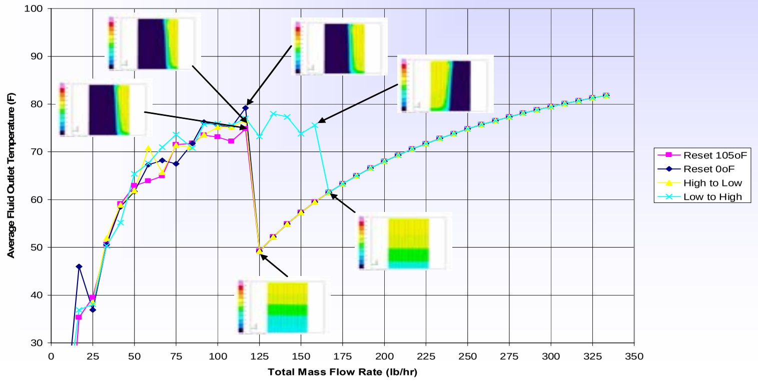
(Ref 3.)

Investigation: Single Panel System Flow Stability and Initial Temperature

Different Initial Conditions Produce Different Stagnation Solutions with FASTIC



Different Initial Conditions Produce Different Stagnation Solutions with STDSTL



- ***Four different initial conditions were used for a mass flow rate parametric***

1. Reset initial temperatures for fluid elements before each call to solution subroutine
   - Reset to 105° F
   - Reset to 0° F
2. Use temperatures from previous flow rate solution for initial conditions for fluid elements
   - Sweep from high to low flow rate
   - Sweep from low to high flow rate

- ***FASTIC Solution***
  - ***Results show four different solutions for stagnation.***
  - ***When radiator freezes completely prior to increasing flow rate, radiator does not recover.***
- ***STDSTL Solution***
  - ***Results show two different solutions for stagnation.***
  - ***Does not converge when stagnation is present. DRLXCC and ARLXCC appear to oscillate.***
  - ***Freezing radiator completely prior to increasing flow rate affects stability solution***

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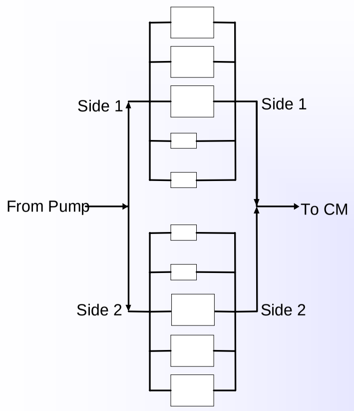
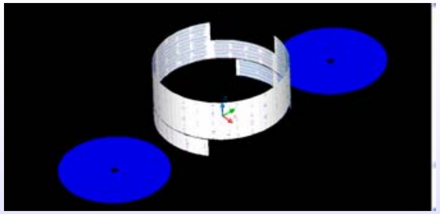
Investigation: Multi-Panel System



Panels in Parallel
(One Fluid Loop with Two Legs Shown)

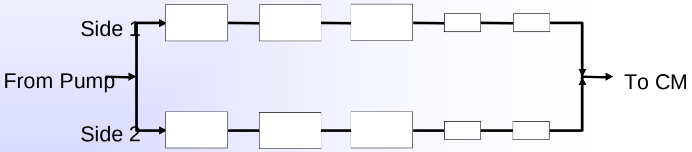


Six Primary Panels

Four Secondary Panels

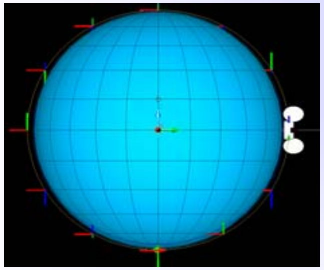
Redundant Fluid Loops (A & B)

Two legs per Loop (A1, A2, B1, B2)



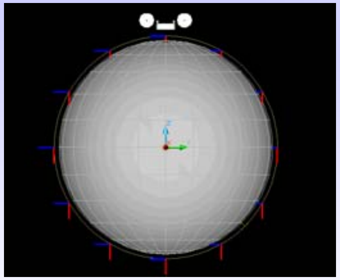
Panels in Series
(One Fluid Loop with Two Legs Shown)

ISS, LEO, Broadside to Sun, Hot Case *with Spin, β=75*



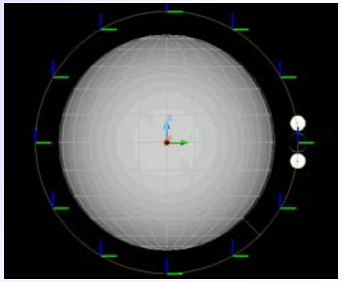
LEO Orbit Parameters	
Beta angle (b)	75
Altitude	188.985 nm
Period	1.52564 hrs
Spin	4.6 rev/orbit
Hot Environment	**Parameters**
Albedo	0.30
Planetshine	83.95 Btu/hr-ft2
Solar	448.27 Btu/hr-ft2

Lunar, LLO, Broadside to Sun Hot Case *β=90*



LLO Orbit Parameters	
Beta angle (b)	90
Altitude	48.5961 nm
Period	1.94846 hrs
Hot Environment	**Parameters**
Albedo	0.20
Planetshine	
Dark:	3.73 Btu/hr-ft2
Sun:	381.03 Btu/hr-ft2
Solar	450.77 Btu/hr-ft2

Lunar, LLO, Nose to Sun Cold Case *β=90*



LLO Orbit Parameters	
Beta angle (b)	0
Altitude	215.983 nm
Period	2.4645 hrs
Cold Environment	**Parameters**
Albedo	0.07
Planetshine	
Dark:	0.735 Btu/hr-ft2
Sun:	356.30 Btu/hr-ft2
Solar	416.88 Btu/hr-ft2

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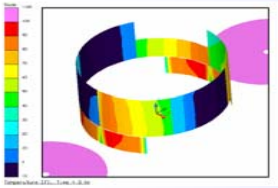
Multi-Panel Stall Analysis

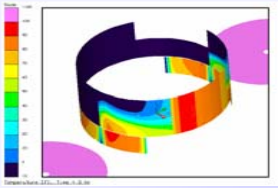
Orbit Average Steady State Results

Panels in Parallel

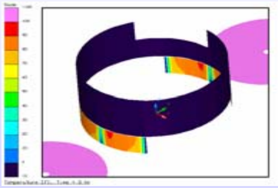
One Pump for each loop (A & B)



ISS, LEO, Broadside to Sun
Hot Case, spin



Lunar, LLO, Broadside to Sun
Hot Case, β=90

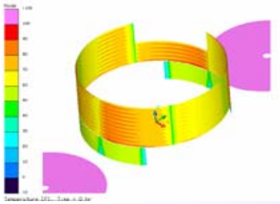


Lunar, LLO, Nose to Sun
Cold Case, β=90

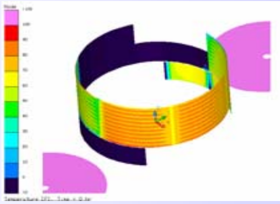
Case	Environment	Fluid	
	Q_{in} (W)	T_{out} (F)	Q_{out} (W)
ILBHs	4949.5	78.2	3081.9
LLOBH90	2988.4	81.1	2750.4
LLONC90	124.0	88.2	1943.8

Panels in Series

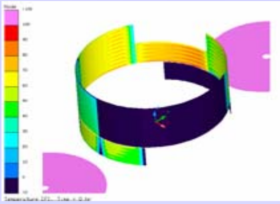
One Pump for each loop (A & B)



ISS, LEO, Broadside to Sun
Hot Case, spin



Lunar, LLO, Broadside to Sun
Hot Case, β=90

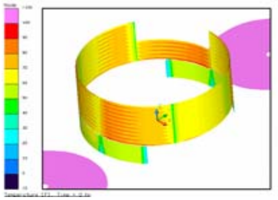


Lunar, LLO, Nose to Sun
Cold Case, β=90

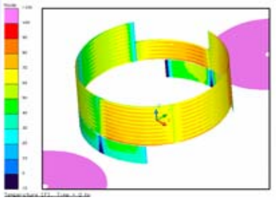
Case	Environment	Fluid	
	Q_{in} (W)	T_{out} (F)	Q_{out} (W)
ILBHs	4949.5	60.0	5132.6
LLOBH90	2988.4	70.2	3999.1
LLONC90	124.0	56.0	5590.9

Panels in Series

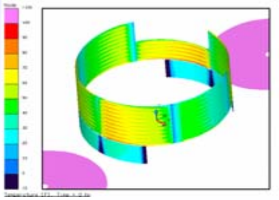
One Pump for each leg (A1, A2, B1 & B2)



ISS, LEO, Broadside to Sun
Hot Case, spin



Lunar, LLO, Broadside to Sun
Hot Case, β=90



Lunar, LLO, Nose to Sun
Cold Case, β=90

Case	Environment	Fluid	
	Q_{in} (W)	T_{out} (F)	Q_{out} (W)
ILBHs	4949.5	60.2	5127.1
LLOBH90	2988.4	50.6	6233.5
LLONC90	124.0	33.0	8118.1

References:

- 1) NASA Technical Memorandum 100972, A Solar Dynamic Radiator with a Historical Perspective, McLallin, Fleming, Hoehn and Howerton. Prepared for the 23rd Intersociety Energy Conversion Engineering Conference, Denver, Colorado, July 31--August 5, 1988
- 2) NASA Johnson Space Center Oral History Project: Oral History Transcript Frank H. Samonski Interviewed by Jennifer Ross-Nazzal, Houston, Texas – 30 December 2002.
- 3) AIAA-2007-0529, Investigation into the Understanding of Flow Stagnation in Fluid Tube Radiators, Hahn and Reavis, Prepared for 45th AIAA Aerospace Sciences Meeting and Exhibit 8 - 11 January 2007, Reno, Nevada