TFAWS Active Thermal Paper Session

2-Phase Refrigeration Thermal Management for High Altitude Balloon Platforms

Evan Racine & Ryan Edwards

Presented By

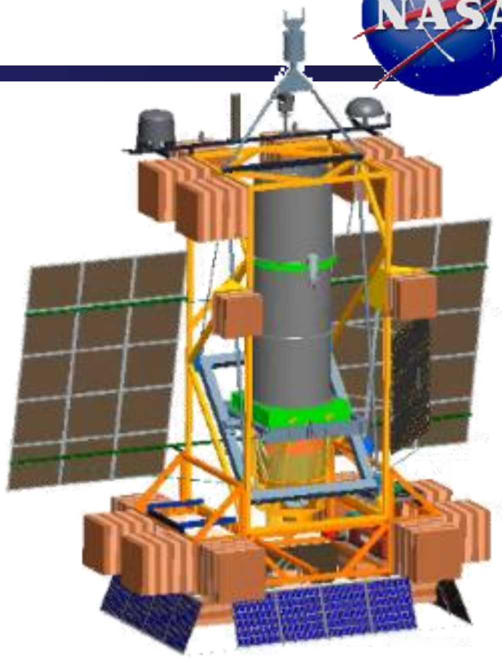
Evan Racine & Ryan Edwards

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL

GHAPS Overview

Gondola for High Altitude Planetary Science (GHAPS)

- Observation platform with 1 meter aperture telescope
  - UV/IR Planetary Science
  - Diffraction limited System
- Sub-arcsecond pointing capability (<1/3600 of a degree)
- Float between 100,000 and 120,000 feet
- 100 day mission duration
- Minimum 5 mission design
- Multiple launch site capability



GHAPS Gondola and Telescope

GHAPS Thermal Subsystem Requirements

- Remove 400W of heat from science instrument package
  - Requirement generated from historical data from BRRISON & BOPPS balloon flights, which used similar Science Instruments

- Do not adversely impact pointing capability
  - Any fluid lines crossing the gimbal hubs cannot introduce significant pointing disturbances
  - Any vibrations produced shall not impact science observation quality

Thermal Environments

Launch Site	Flight Duration	Solar Cycle	Ground Temperature	Float Temperature
Ft. Sumner, NM	<24 Hours	Day/Night	20°C	-35°C
McMurdo Station, AQ	<60 Days	24 Hour Sun	-5°C	-25°C
Wanaka, NZ	<100 Days	BOM: 9.5 Hours of Eclipse EOM: 16.5 Hours of Eclipse	20°C	-35°C
Kiruna, SWE	<7 Days	Day/Night	0°C	-35°C

Additional Thermal Environment Characteristics

- Ascent temperatures can reach -70ºC
- Antarctica
  - Up to 0.95 Albedo (Two Suns)
- New Zealand
  - Variable albedo based on land mass and storm/cloud formation

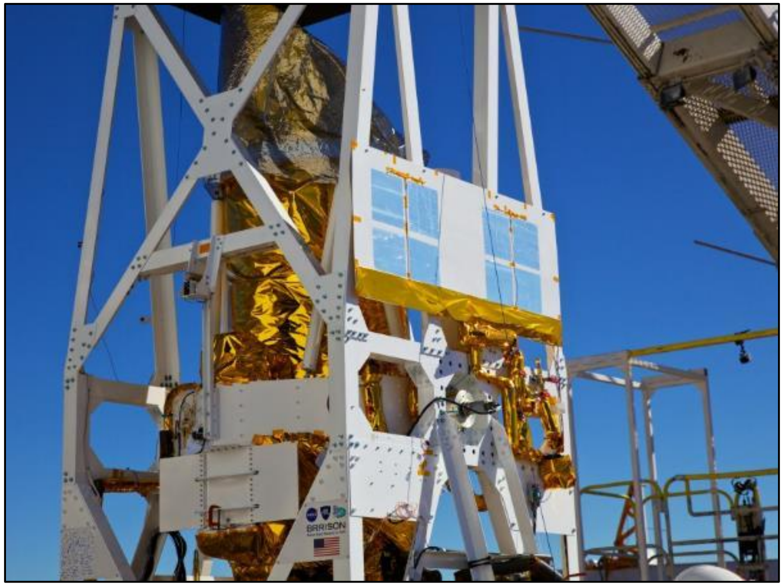
Design Challenges

- Environmental Variations
  - Diurnal Cycling
  - Earth IR
  - Albedo
- Mass Constraints
  - Balloon Platforms have limited flight mass to maintain altitude
  - All subsystems pushed to the limit on mass constraints
- Power Constraints
  - Due to mass constraints, battery mass and thus, power is limited for night time operations
- Gondola Pointing
  - Telescope pointing exclusion area 80º cone around sun
    - 280º of gondola rotation
    - **Radiator must operate facing the sun and in the shade**

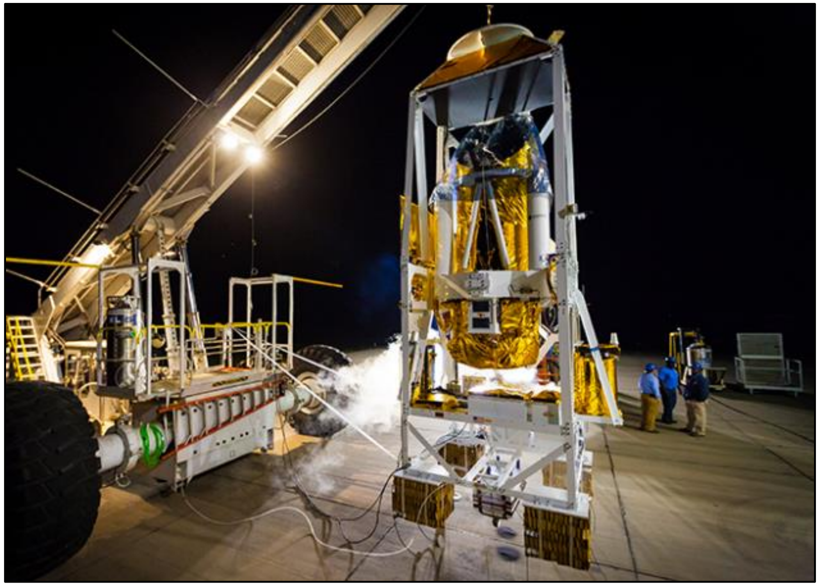
Historical Solutions

BRRISON/BOPPS Balloon Missions

- UV/IR Balloon Based Telescope Platform
- Single day missions with singular fixed targets (comets)
- Instruments similar to those expected to be used on GHAPS
- Thermal Management System
  - Single phase liquid loop and single 2m^2 radiator (Fluid: Galden HT)
  - 2 LN2 dewars for IR instrument cooling

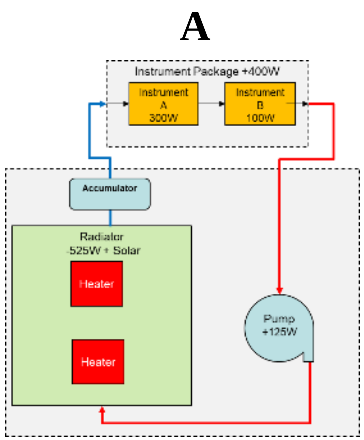


BRRISON Radiator and Heaters

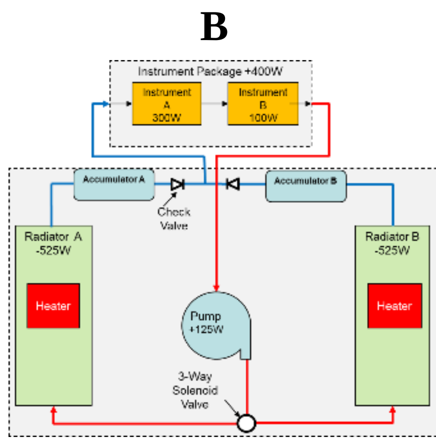


BRRISON Pre-Launch

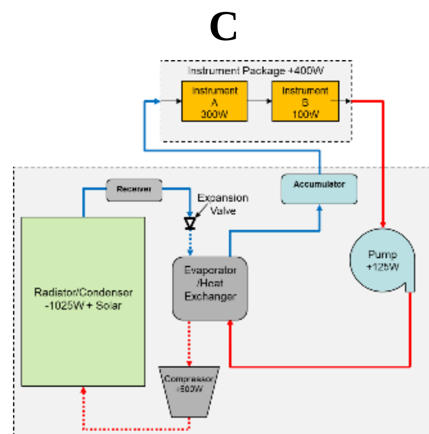
Design Evolution



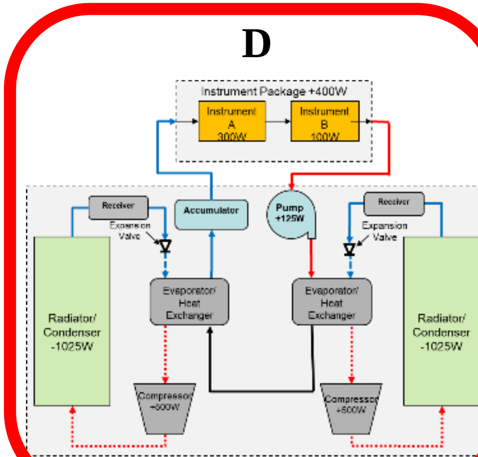
Single Radiator, Pump Loop



Dual Radiator, Pump Loop



Single Radiator, w/Refrigeration



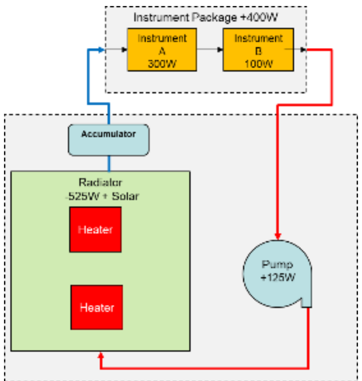
Dual Radiator, w/Refrigeration

Option:		Thermal Load (W)	Radiator Size (m^2)	System Mass (kg)	Total Radiator Mass (kg)	Average Power Consumption (W)			Battery Capacity for 17 hr Night (kW-Hr)	Battery Mass for 17 hr Night (kg)	Total Comparable Mass (kg)	Rank
						DIURNAL	DAY	NIGHT				
Single Radiator, Pump Loop	A	525	20	33	270	2276	1027	3525	59925	547	850	4
Dual Radiator, Pump Loop	B	525	3.5	32	95	218	151	285	4845	44	171	3
Single Radiator, w/ Refrigeration	C	525	4.1	38	55	317	266	367	6246	57	151	2
Dual Radiator, w/ Refrigeration	D	525	1.8	61	47	333	493	174	2962	27	136	1

With radiator coated with white paint (α: 0.19, ε: 0.92)

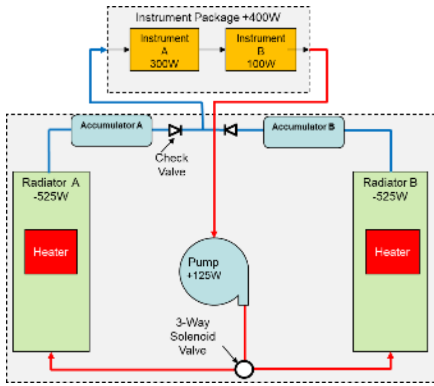
Design Evolution

A



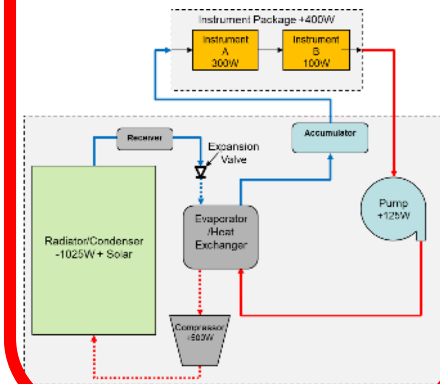
Single Radiator, Pump Loop

B



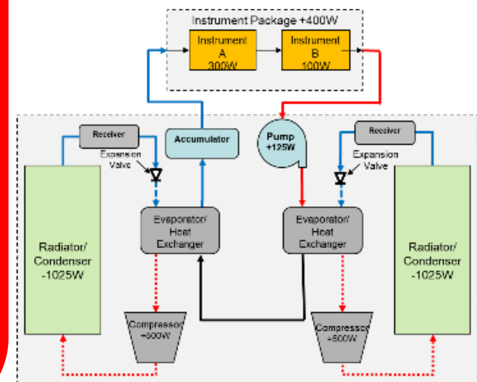
Dual Radiator, Pump Loop

C



Single Radiator, w/Refrigeration

D



Dual Radiator, w/Refrigeration

Option:		Thermal Load (W)	Radiator Size (m²)	System Mass (kg)	Total Radiator Mass (kg)	Average Power Consumption (W)			Battery Capacity for 17 hr Night (kW-Hr)	Battery Mass for 17 hr Night (kg)	Total Comparable Mass (kg)	Rank
						DIURNAL	DAY	NIGHT				
Single Radiator, Pump Loop	A	525	11	28	216	1219	475	1525	25925	237	481	4
Dual Radiator, Pump Loop	B	525	3.5	32	95	177	135	195	3315	30	157	3
Single Radiator, w/ Refrigeration	C	525	2.5	38	34	196	269	166	2826	26	98	1
Dual Radiator, w/ Refrigeration	D	525	1.8	61	51	257	430	186	3158	29	141	2

With radiator coated with silver Teflon (α: 0.06, ε: 0.80)

Other Designs Considered

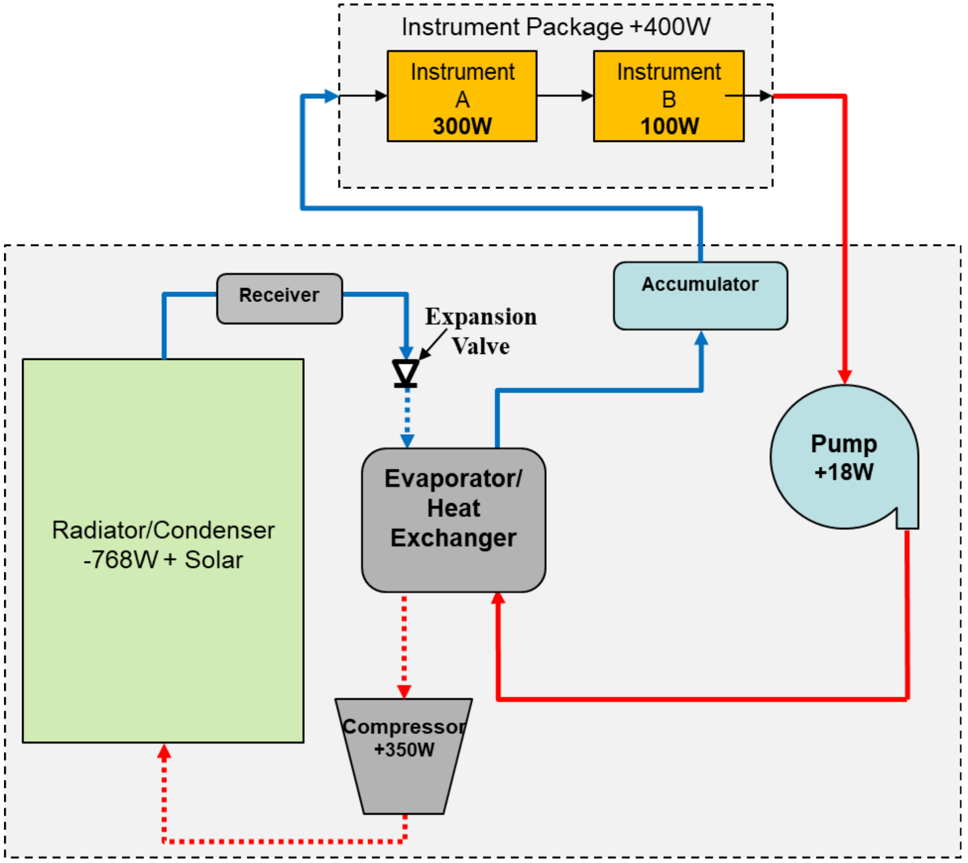
- Single Refrigeration Loop to the Instrument Loads
  - Prohibitive Characteristics
    - High pressure lines crossing the pointing gimbal
    - Two phase refrigerant in COTS components designed to be water cooled and not ideal for inducing refrigerant evaporation.
- All Passive Thermal Design
  - Prohibitive Characteristics
    - Not enough radiative power to cool instruments
      - No clear view to space
    - Reduces allowable instrument volume

Single Radiator, with Refrigeration System and Liquid Loop

Instrument Load → Liquid Loop → Heat Exchanger → Refrigeration Loop → Radiator

Liquid Loop
- Low power circulation pump
- Low freezing point heat transfer fluid
  - Galden HT-70
- 100% Duty Cycle throughout flight
- Flexible Tubing Crossing Pointing Gimbal

2-Phase Refrigeration Loop
- Variable Speed Compressor
  - Removes need for heaters on radiator to compensate for changing heat flux on radiator
  - Maintained constant liquid loop temperature
- Standard Refrigerant
  - R134a
- Radiator/Condenser
  - “Higher” Temperature increases radiative power
  - Silver Teflon Surface (α=0.06, ϵ=0.8)



Vapor-Compression Cycle

(1 → 2) A gas (R134a) is compressed to a superheated state.

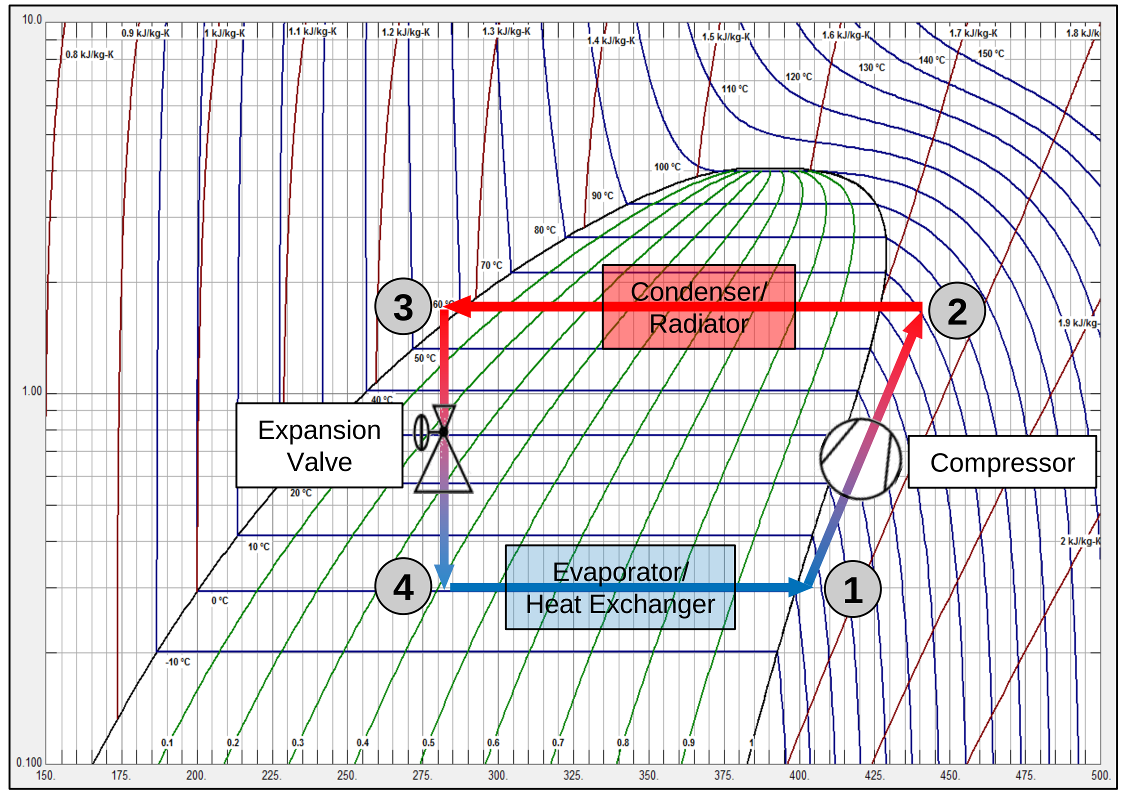
(2 → 3) The superheated gas is cooled and condensed in a radiator.

(3 → 4) A controlled expansion of the refrigerant in liquid phase creates a cold 2-phase flow.

(4 → 1) This is used to absorbed a heat load through evaporation.

Advantages

- By superheating a medium the quality of heat for the system is increased.
  - This allows for a smaller radiator, thus reducing weight.
- By controlling the mass flow rate of the refrigerant, the system can very precisely control the temperature of the heat exchanger.
  - This allows for the system to hold a precise heat exchanger temperature.
  - It also means the power consumption of the system can be scaled proportionally to the heat load.



R134a p-h Phase Diagram

Refrigeration Loop Modeling

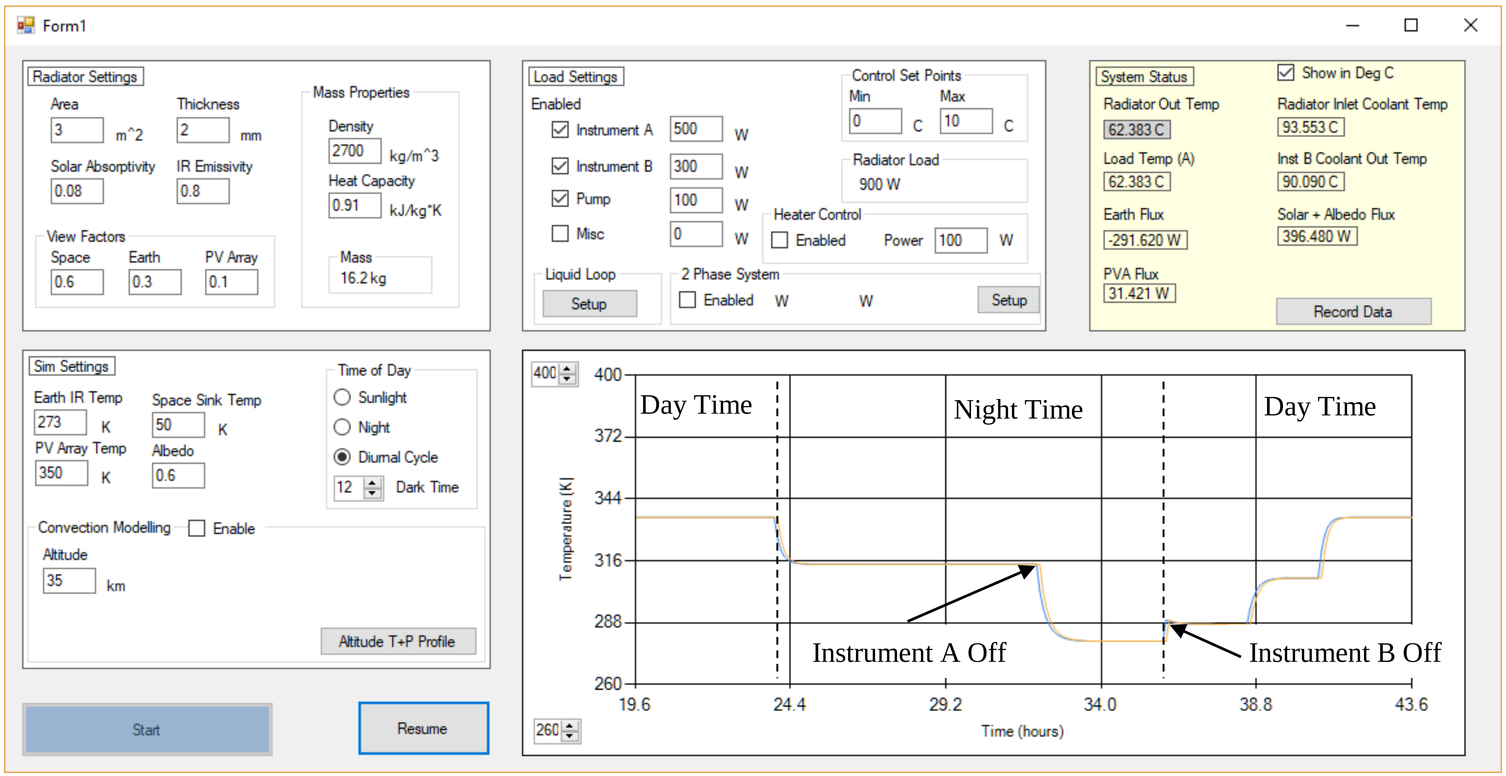
- Built in Microsoft Excel with REFPROP Add-on
  - NIST Reference Fluid Thermodynamic and Transport Properties Database
- Steady State Analysis

SUPERHEAT	h		T		Density		Flow Speed			
Compressor Outlet	489.3101	kJ/kg	112.6204985	C	61.46205367	kg/m3	0.983668529	m/s		
Sat Vap Point	426.4655	kJ/kg	59.39612916	C	85.93190107	kg/m3	0.703560461	m/s		
Delta	62.84454	kJ/kg	86.00831381	Ave C	73.69697737	Ave kg/m3	0.843614495	Ave m/s		
Rad desuperheat	0.311692	kJ/s*m2	0.000346324	kJ/s*cm tube		Max Radiative A	3	m2		
Superheat Watt Rej	0.18801	kJ/s				Max Rad Power	0.935075719	kJ/s		
Length of Superheat	5.428724	m	Radiator Area	0.603191504	m2	Remaining area	2.396808496	m2		
CONDENSING	h		T		Density		Flow Speed			
Sat Vap Point	426.4655	kJ/kg	59.39612916	C	85.93190107	kg/m3	0.703560461	m/s		
Sat Liq Point	286.454	kJ/kg	59.35348257	C	1056.245728	kg/m3	0.057238847	m/s		
Delta	140.0115	kJ/kg	59.37480586	Ave C	571.0888144	Ave kg/m3	0.380399654	Ave m/s		
Rad Condensing power	0.199233	kJ/s*m2	0.00022137	kJ/s*cm tube		Max Radiative A	2.396808496	m2		
Condensing Watt Rej	0.418868	kJ/s				Max Rad Power	0.477523097	kJ/s		
Req Length of condensi	18.92163	m	Req Radiator Area	2.102403226	m2	Remaining area	0.29440527	m2		
Refrigerant Subcooled?	1									
SUBCOOLING	h		T		Density		Flow Speed			
Sat Liq Point	286.454	kJ/kg	59.35348257	C	1056.245728	kg/m3	0.057238847	m/s		
Radiator Outlet	268.8107	kJ/kg	48.2736722	C	1114.313979	kg/m3	0.054256062	m/s		
Delta	17.64332	kJ/kg	53.81357739	Ave C	1085.279853	Ave kg/m3	0.055747454	Ave m/s		
Rad subcool	0.17891	kJ/s*m2	0.000198788	kJ/s*cm tube		Radiative Area	0.29440527	m2		
Subcool Watt Rej	0.052783	kJ/s								
Length subcool	2.655232	m	Radiator Area	0.295025808		SubCooling	11.07981036	C		
	h		T		Density		Flow Speed		Quality	
Radiator Outlet	268.8107	kJ/kg	48.2736722	C	1114.313979	kg/m3	0.054256062	m/s	0	% gas
Total Length Req	27.00558	m								
Total Rejection	0.659661	kJ/s								

Radiator Results Section from Refrigeration REFPROP Model

Radiator Modeling

- Written in C#
  - Basic Energy Balance Equations
- Ideal for Quick Transient Analysis
  - All parameters can be changed while running
  - Temperatures and View Factors Verified in Thermal Desktop



Standard Refrigeration System

Radiator

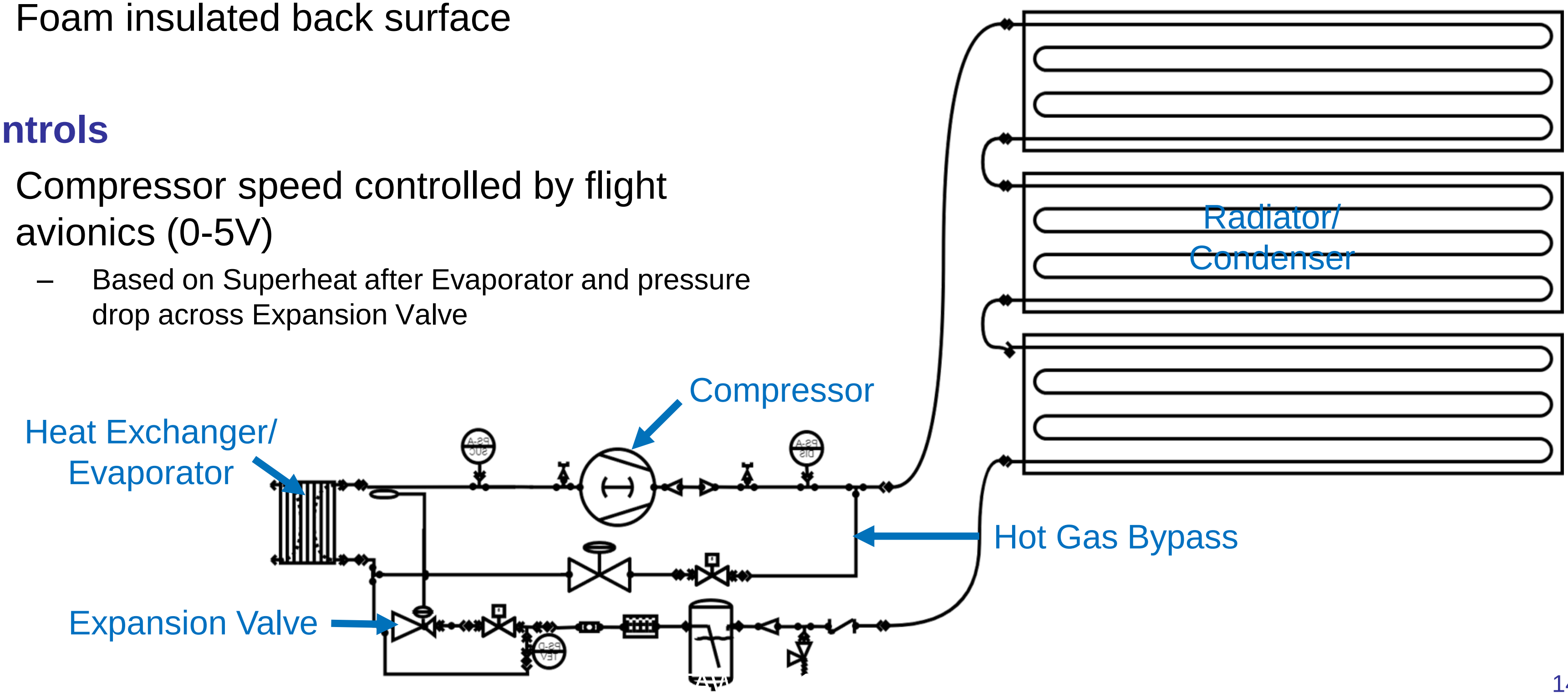
- 3m^2 total radiative area
  - Thee 0.5 x 2 m Radiators
- 60C Full Load Operating Temperature
- 2mm Thick Aluminum w/ Aluminum Tubing
- Silver Teflon tape radiative surface
- Foam insulated back surface

Variable Speed Compressor

- Up to 800W Cooling Capacity
- Hermetically Sealed
- Can reduce speed or duty cycled during night or periods of time with low instrument power consumption

Controls

- Compressor speed controlled by flight avionics (0-5V)
  - Based on Superheat after Evaporator and pressure drop across Expansion Valve



Advantages vs Single Phase System

Higher Radiator Temperature

- Increased radiative power per unit area
  - **Reduced Mass**
- Decreased impact from varying “ground” radiative environment

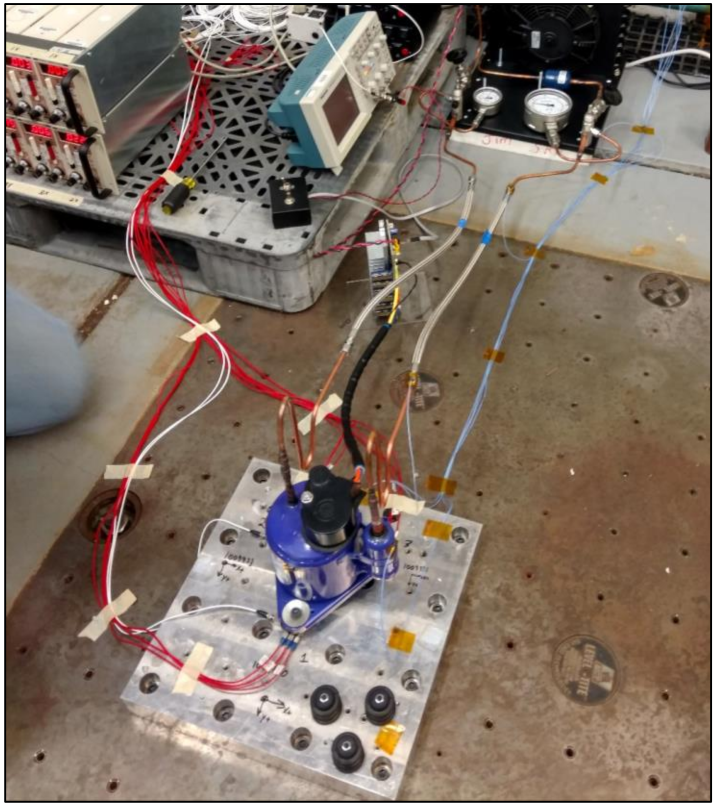
Radiator Heaters not required during nominal operation

- Variable speed compressor can adjust to varying loads and environments
- Saves power during night operations, low power modes, and cold cases.
  - **<u>Higher power consumption during daylight operations</u>**

	Single Phase Liquid Loop	**2- Phase Refrigeration**
Sun Pointing	0 W	240 W
Shade/Night	245 W	93 W

Power Comparison, 3m^2 Radiator Sized for Sun Pointing

Characterization Testing



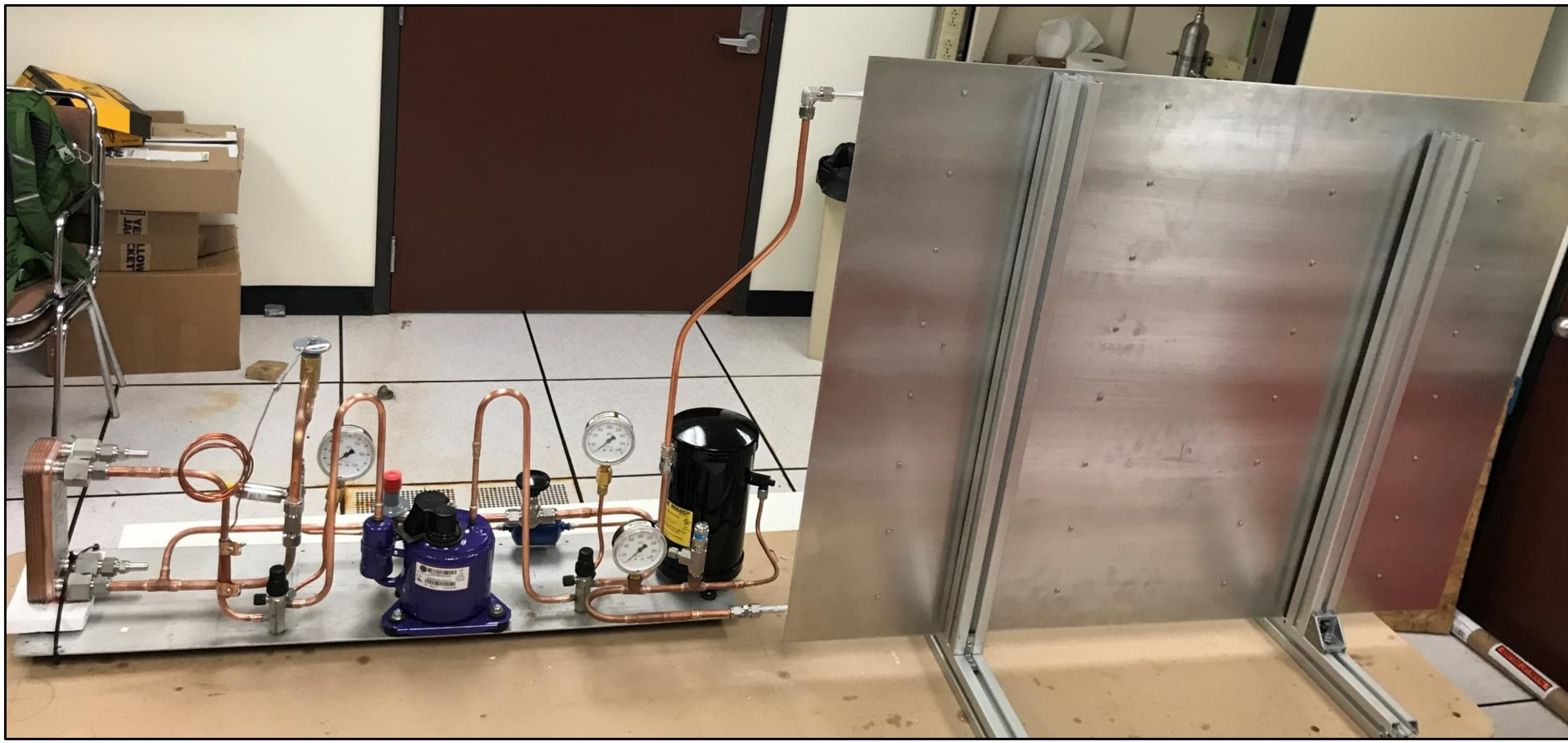
Compressor vibration was characterized at GRC Structural Dynamics Lab

Measured pointing error of the system with liquid lines and insulation at WFF

EDU Testing

Refrigeration Model Validation

- Subscale radiator manufactured in house at GRC
- Same components as flight design
- No TVAC Testing planned at this time

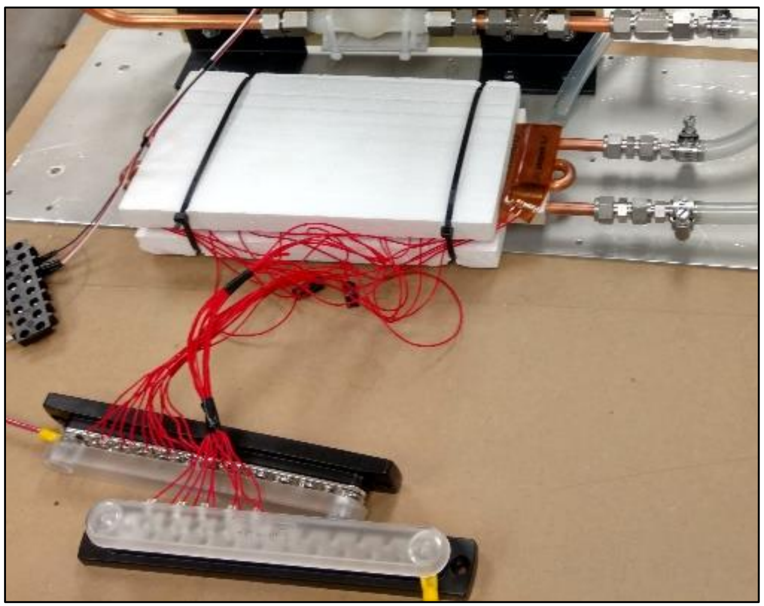


Refrigeration Loop EDU Layout with Radiator

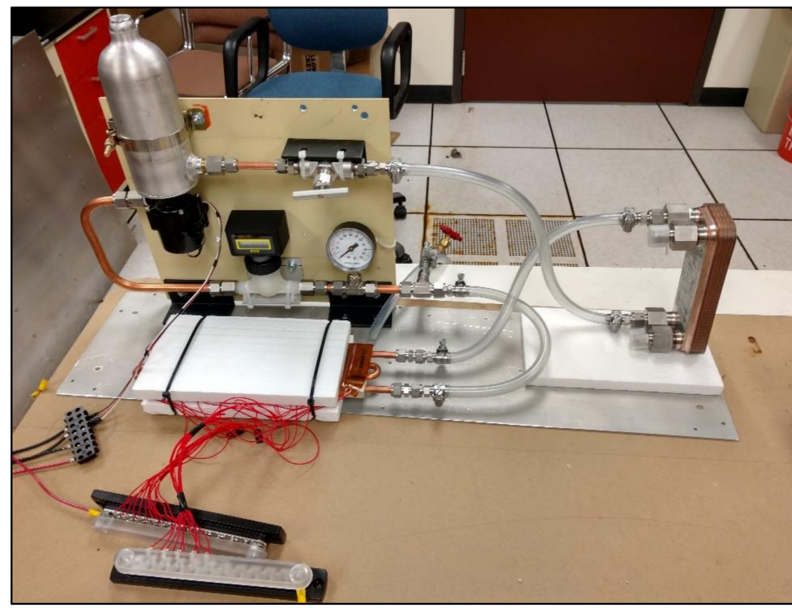
EDU Testing (Cont.)

Heat Load (Instrument Simulator)

- Lytron Cold Plate
- 480W Total Omega Flexible Polyimide Heaters
  - Load Simulator Power Supply to vary Load
- Brazed Plate Heat Exchanger



Heat Load



Liquid Loop Test Layout

Next Steps

- Complete Bench Testing of EDU
  - EDU testing is currently underway at GRC
- Compare Results to Model
  - Expected operating temperatures and pressures
  - Compressor Power Draw
- Document and Publish Results

Conclusions

- A 2-Phase Refrigeration System with a Radiator shows to be a viable means of reducing the radiator mass and night time power consumption for balloon payloads, with large heat loads.

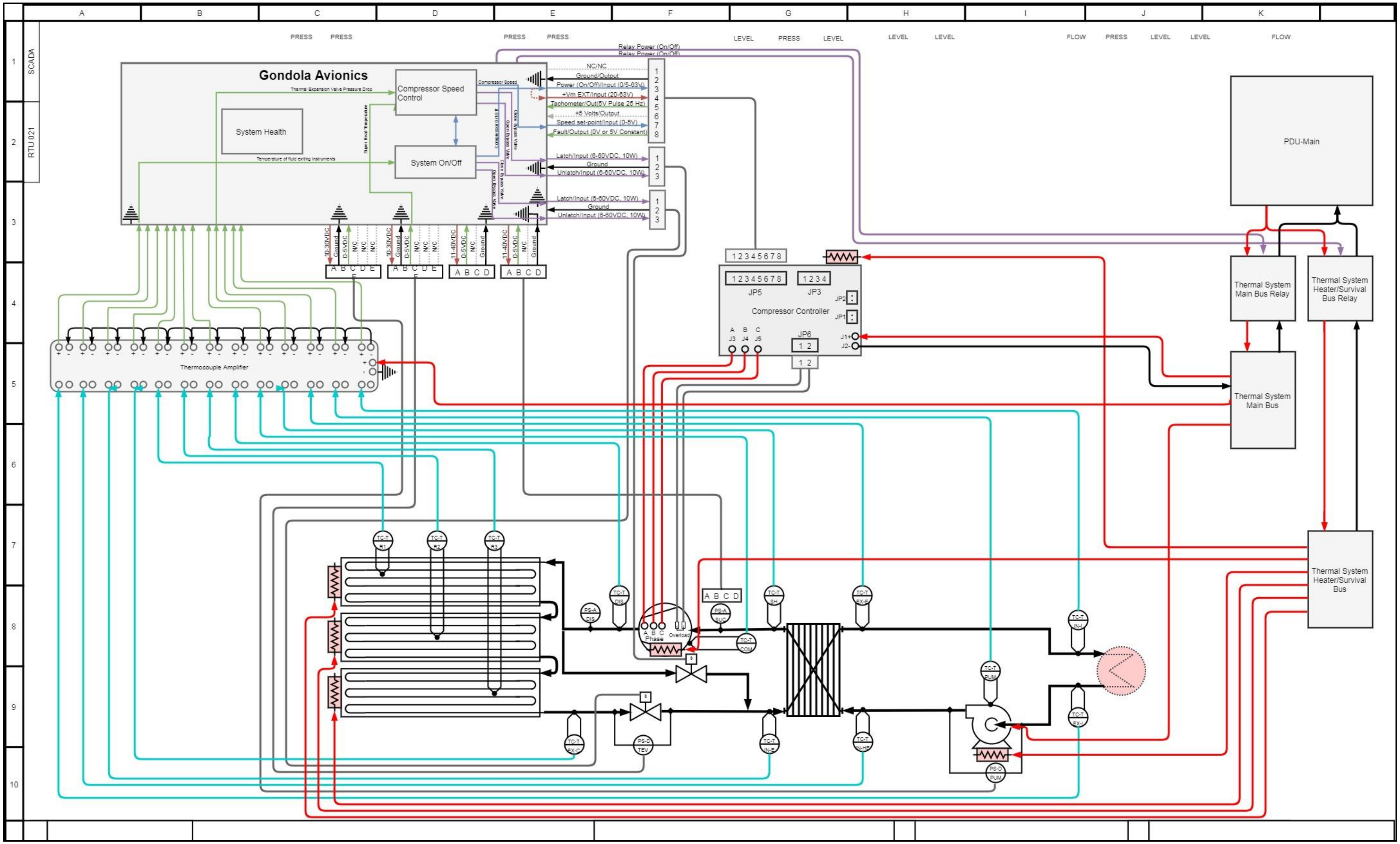
Questions…?

BACKUP

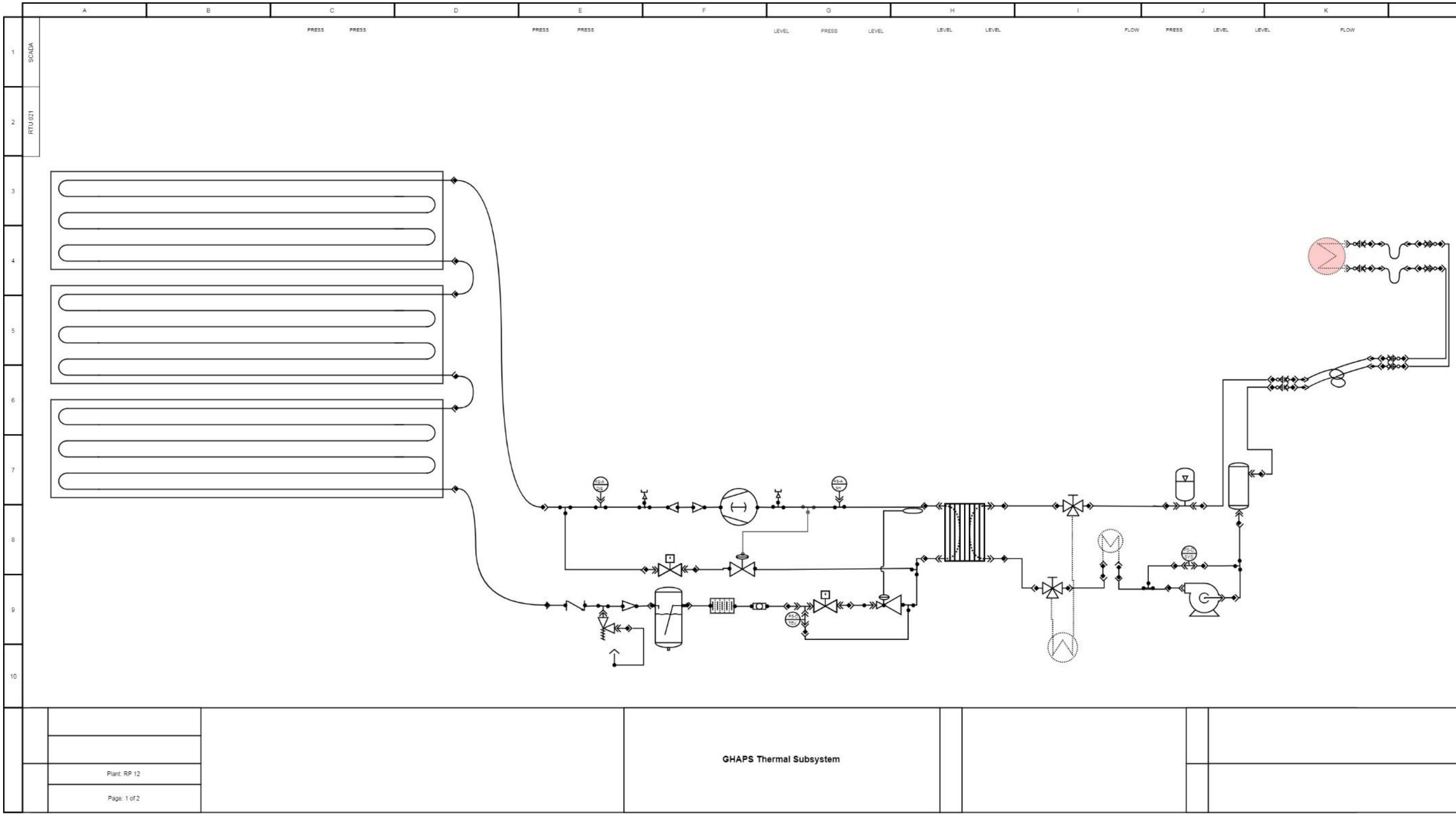
GHAPS Launch Site Matrix

Launch Site	Fort Sumner, NM	Palestine, TX	Alice Springs AUS	Kiruna SWE	McMurdo ANT	Wanaka NZ
Flight Season	Aug - Oct every year	May - July	March - May odd years [1]	May - July odd years	Dec - Jan every year	April - Aug even years
Campaign Duration	July - Oct	May - July	Feb - May	April - July	Oct - Feb	Feb - May
Launch Time	Morning	Morning / Afternoon	Morning	Anytime	Anytime	Morning
Lat/Long	34.4731° N, 104.2422° W	31.7786° N, 95.7144° W	23.80° S, 133.89° E	67.8833° N, 21.1167° E	77.8500° S, 166.6667° E	44.7222° S, 169.2455° E
Trajectory	West / Turnaround	West	West / East / Turnaround	West	West	East
Latitude Range	32 N - 40 N	30 N - 33 N	17 S - 29 S	60 N - 80 N	Continent	29 S - 65 S (nominal) 25 S - 80 S (possible)
Longitude Range	100 W - 114 W	95.71 W - 102 W	116 E - 140 E	23 E - 120 W	Continent	South Hemisphere
Float Wind Speed Range	0 - 40kts	10 - 45kts	0 - 40kts	10 - 30kts	5 - 30kts	10 - 120kts
Balloon Type	Zero Pressure	Zero Pressure	Zero Pressure	ZP / SPB	ZP / SPB	Super Pressure
Max Science Mass	6000 lbs	6000 lbs	6000 lbs	6000 lbs (ZP) 3674 lbs[2] (SPB)	6000 lbs (ZP) 3674 lbs[2] (SPB)	3674 lbs [2]
Comm Package [3]	CIP	CIP	CIP	SIP	SIP	SIP
Ready to Ship	August	May	January	March	August	December
Building door constraints	30' h x 15' w (Hook Height 29.5 ')	29.5' h x 18' w (Hook Height 30 ')	31.5 ' h x 23.6' w (Hook height 27.4 ')	See attached	30' h x 18' w (Hook Height 25.5 ')	13.7' h x 20' w (Hook Height 11.2 ')
Launch vehicle envelope	Suspension ht is 40', ground clearance is 6 '	Suspension ht is 40', ground clearance is 6 '	Suspension ht is 40', ground clearance is 6 '	Suspension ht is 40', ground clearance is 6 '	Suspension ht is 40', ground clearance is 6 '	Suspension ht is 40', ground clearance is 6
Pre-flight Testing [4]						
Duration	up to 24 hrs	up to 12 hrs	up to 36 hrs	up to 7 days	up to 50 days	up to 100 days
Average Temp	-35 C	-35 C	-35 C	-25 C	-25C	-35 C
Min Temp (10mb-5mb)	-50C to -25C	-50C to -25C	-50C to -25C	-40C to -10C	-30C to -5C	-75C to -30C
Min Temp (ascent)	-75 C	-78 C	-85 C	-55 C	-50 C	-70 C
Average Pressure	7mb	7mb	7mb	7mb	7mb	7mb
Time to complete recovery	hrs to a few days	hrs to a few days	hrs to a few days	multiple trips, several days to weeks	multiple trips, several days to weeks	multiple trips, severa days to weeks
Typical Recovery Vehicle [5]	Truck / Mobile Crane / Helo	Truck / Mobile Crane / Helo	Truck / Mobile Crane / Helo	Small Aircraft / Truck	Small Aircraft	Small Aircraft / Truck
Size constraints for components	20' L x 8' W x 10 ' H	20' L x 8' W x 10 ' H	20' L x 8' W x 10 ' H	20' L x 8' W x 10 ' H	56" x 50" plane cargo door	20' L x 8' W x 10 ' H
Mass constraints for components	1800 lbs helicopter sling	1800 lbs helicopter sling	1800 lbs helicopter sling	1800 lbs helicopter sling	2200 lbs plane, 1800 lbs helo sling	1800 lbs helicopter sling
Average Temp	10 to 32 C 50 to 90F	21 to 38 C 70 to 100 F	10 to 21 C 50 to 70 F	-1 to 16 C 30 to 60 F	-18 to 4 C 0 to 40 F	4 to 21 C 40 to 70 F
Average Pressure	875 mb	1000 mb	955 mb	1020 mb	950 mb	1000 mb

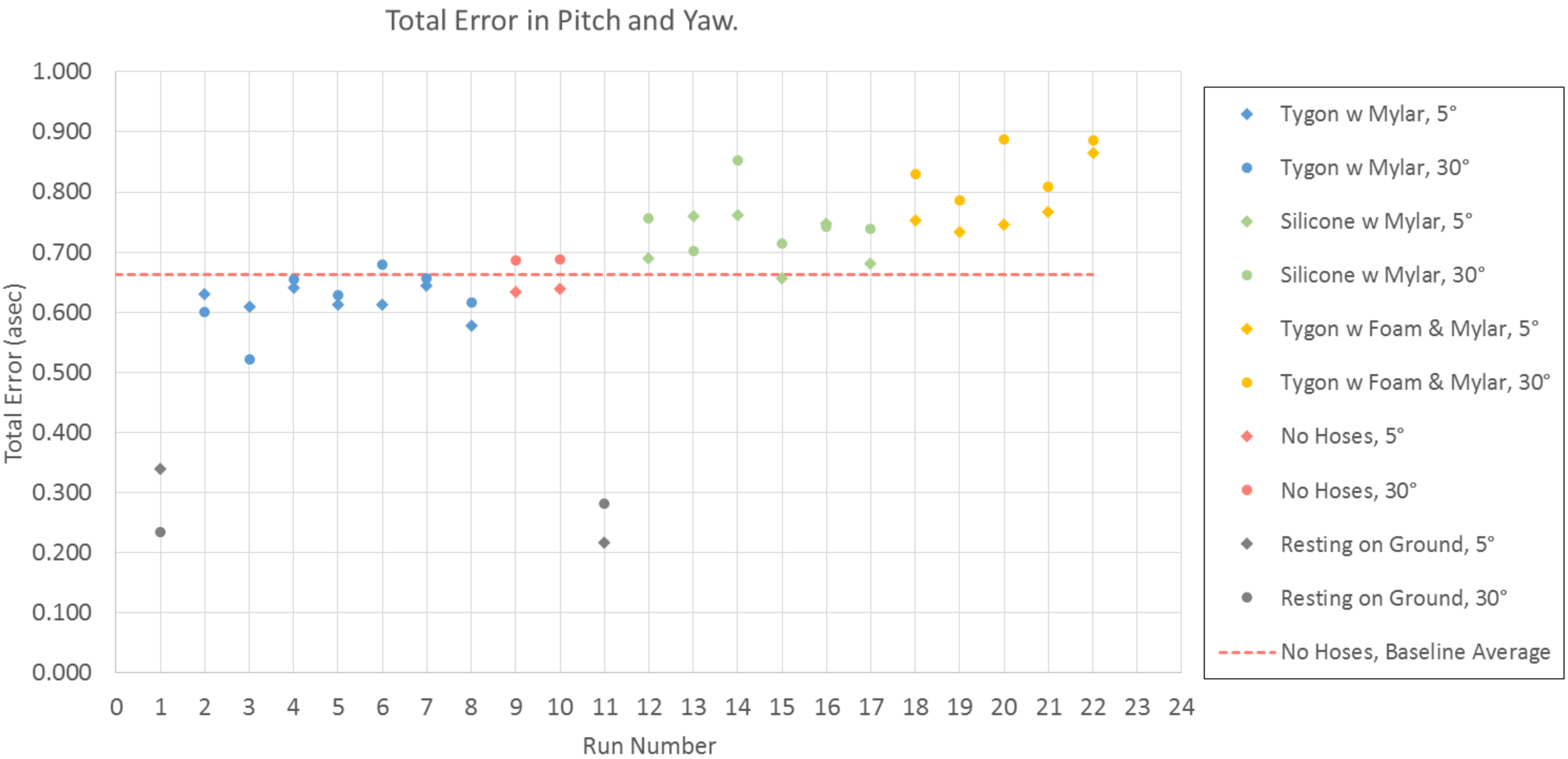
Thermal System Wiring Diagram



GHAPS Thermal System Full P&ID



WASP Fluid Line Test Results



- The chart displays the combined pitch and yaw RMS error for each run and elevation angle.
- The red dotted line is the average of the baseline runs, with no hoses on TF2

Compressor Vibration Testing

Summary and Observations

- The internal posts in these isolators are short circuiting their isolation capability. The Customer needs to look at isolators that do not have this feature.
  - Could potentially remove the internal posts from the isolators that were tested, however a force link setup would have to be used vs preloading the entire joint which was done in this test for simplicity.
- For the isolator to be effective, the highest frequency suspension mode needs to be at least a factor of 5 below the fundamental excitation frequency of the Compressor Pump.
  - The small isolator was not soft enough for any of the Compressor Pump operating speeds. The rocking suspension mode is around 19 Hz, which is not the highest frequency suspension mode, but even if it was it is only a factor of 3 below the fundamental excitation frequency of the Compressor Pump when operating at 3,600 rpm.
- The isolation system for this compressor pump needs to be ideally designed to isolate at no greater frequency of 5 Hz if the pump is to be run at 1800 RPM.