The January 2015 Repressurization of ISS ATCS Loop B – Analysis Limitations and Concerns

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In January 2013 a false ammonia leak alarm resulted in the shutdown and partial depressurization of one of the two International Space Station (ISS) External Active Thermal Control System (EATCS) loops. The depressurization resulted in a vapor bubble of 18 liters in warm parts of the stagnant loop.

To repressurize the loop and regain system operation, liquid would have to be moved from the Ammonia Tank Assembly (ATA) into the loop. This resulted in the possibility of moving cold (as low as -30°C) ammonia into the water-filled Internal Active Thermal Control System (IATCS) interface heat exchangers. Before moving forward, the freezing potential of the repressurization was evaluated through analysis – using both a Thermal Desktop SINDA/FLUINT model and hand calculations. The models yielded very different results, but both models indicated that heat exchanger freezing was not an issue. Therefore, the repressurization proceeded.

The presentation describes the physical situation of the EATCS prior to repressurization and discusses the potential limits and pitfalls of the repressurization. The pre-repressurization analytical models and their results are discussed. The successful repressurization is described and the results of a post-event model assessment is detailed.

The January 3015 Repressurization of ISS ATCS Loop B – Analysis Limitations and Concerns

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Overview

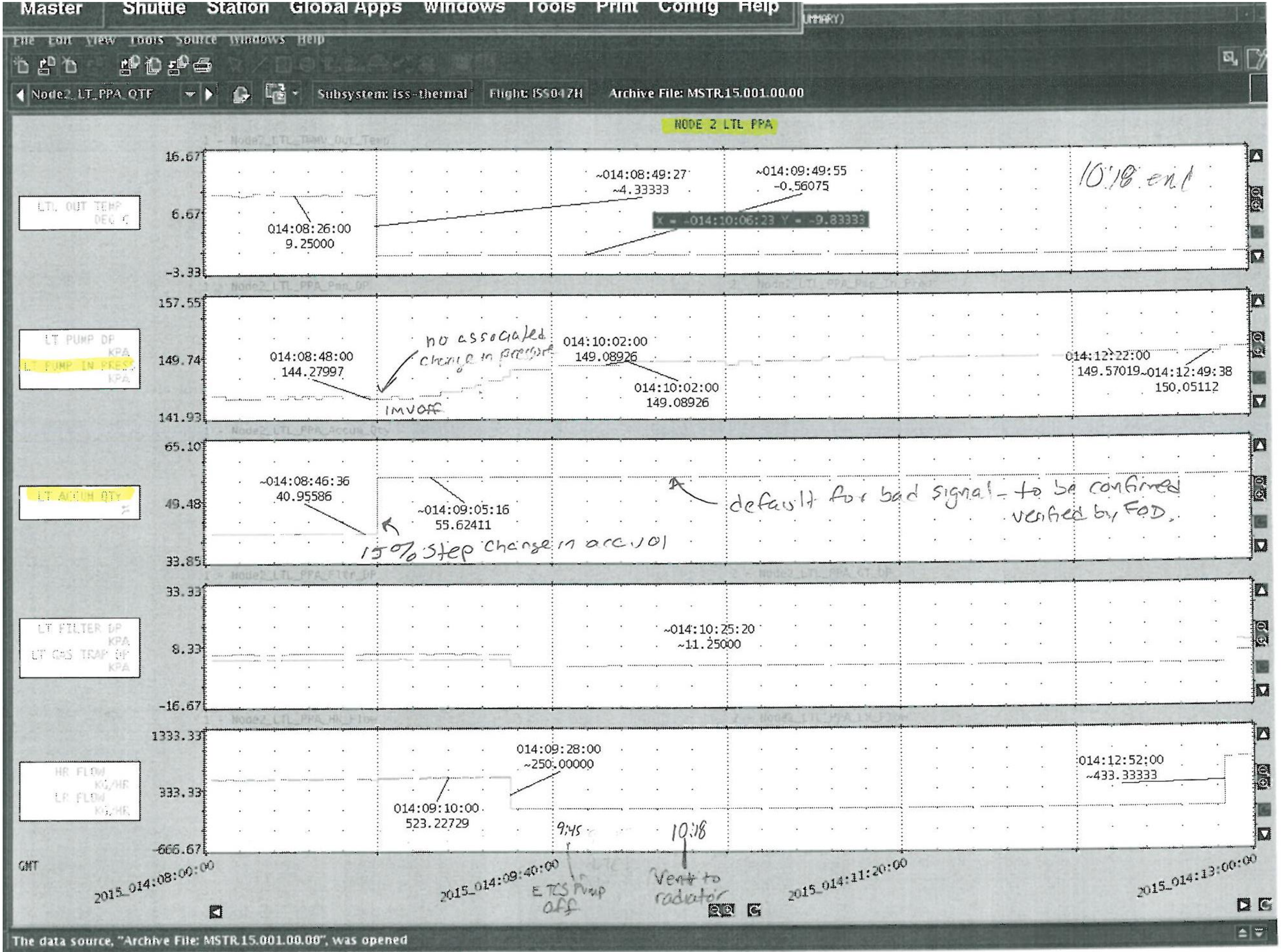
- Acknowledgements
- The event
- The starting condition for the system fill
- Limitations
- Initial idea
- Follow-on idea
- Analysis results
- Execution

Acknowledgements

- ATCS System
  - Gary Rankin
  - Tim Bond
  - Mike Holt
- Boeing Active Thermal
  - Mary Schaff
  - Marcelino Figueroa
- Boeing Passive Thermal
  - Mrugen Patel
- Boeing Passive Thermal Team

The Event

- On January 14, the Node 2 LTL (low temperature internal water loop) accumulator volume increased instantaneously by 15% to 55.62%
- The resulting accumulator volume measurement was high enough to trigger an ammonia alarm
  - an ammonia leak into the internal thermal control system (ITCS) would increase the accumulator quantity
- After some time, it was noted that the loop pressure was increasing so the ammonia leak protocol was triggered



Subsystem: iss-thermal

Flight: ISS047H

Archive File: MSTR.15.001.00.00

10:18 end

no associated change in pressure

IMV off

15% step change in acc vol

default for bad signal - to be confirmed verified by FOD.

9:45

ETCS Pump off

10:18

Vent to radiator

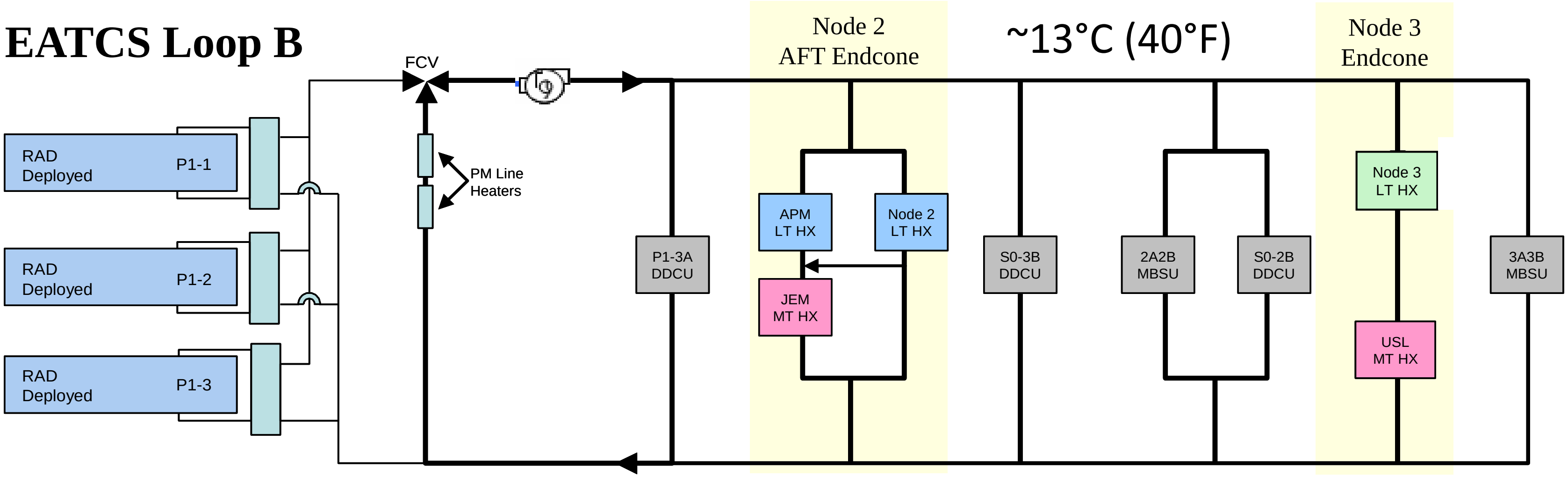
The data source, "Archive File: MSTR.15.001.00.00", was opened

The Leak Protocol

- Stop external active thermal control system (EATCS) ammonia pump
  - reduces pressure at the heat exchangers
- Isolate ammonia tank assembly (ATA) which is used as a system accumulator
  - isolates the large (~130 kg or 300 lb) reservoir of ammonia
- Vent nitrogen from one of the isolated radiator flow paths
- Open system to the now-vented radiator flow path
  - creates ullage in the system
- System becomes two-phase and will reach the saturation pressure associated with the temperature of the warmest fluid

Normal Operating Conditions

EATCS Loop B



~13°C (40°F)

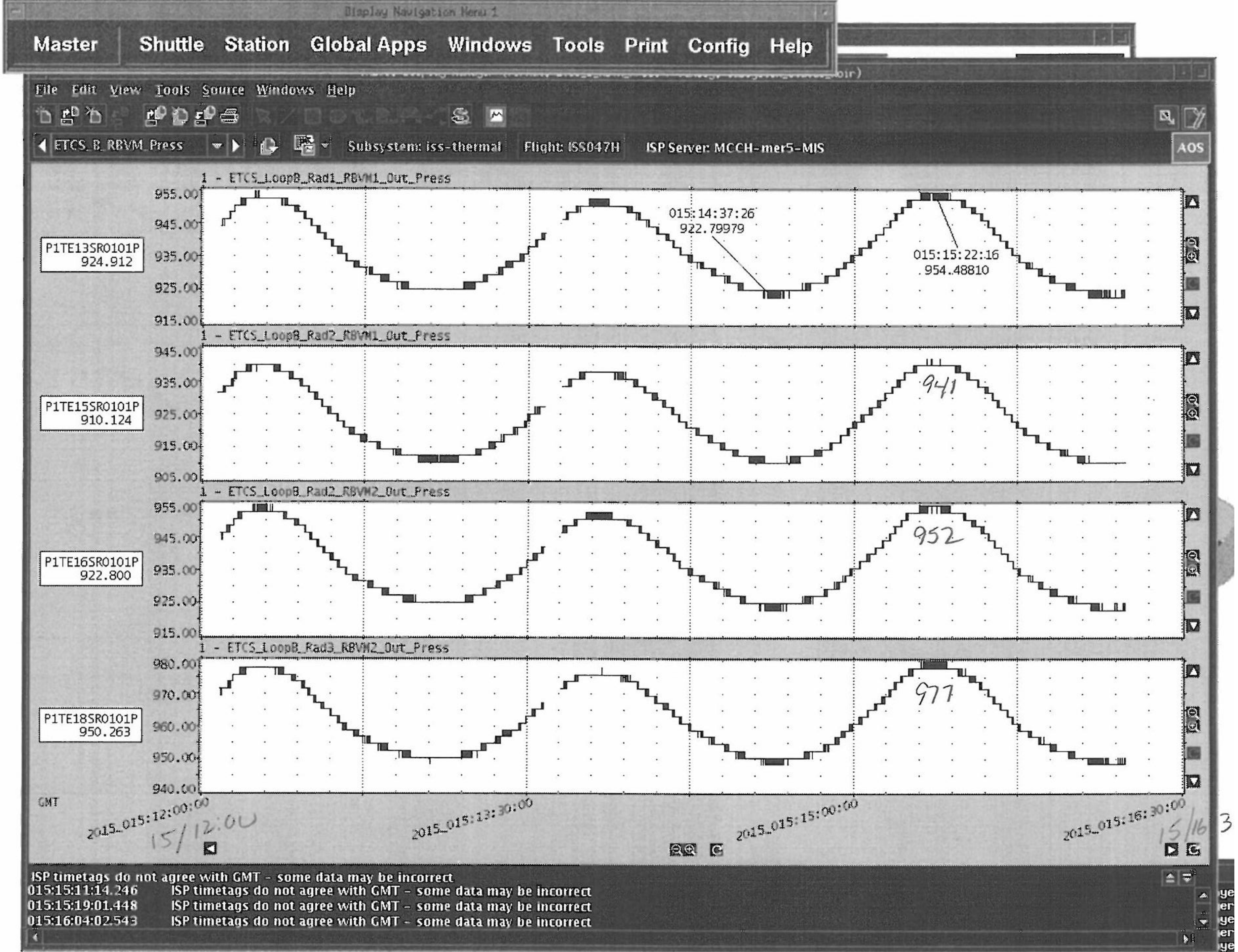
~13°C (56°F)
to very low temperatures

~13°C (56°F)

ITCS water temperatures are even warmer

Aftermath

- All ITCS HXs continued to flow except for the APM LT HX which was bypassed and the core heater was enabled
- Volume calculations (the volume of the radiator passage – the pump accumulator Δ volume) showed that 18 liters (0.64 ft^3) of ammonia vapor had been formed
  - 0.1 kg (0.21 lbm) of vapor
  - requires 120 kJ (110 BTU) of energy
    - raise 1 liter of water 28°C
  - energy is available in the fluid itself and in the lines and fittings
- Over time the fluid pressure adjusted to the highest temperature in the loop (endcone lines)
  - the liquid/vapor interface was located there
  - the local temperature set the pressure
- The pressure beat over the orbit as the average loop temperature (and average liquid density) cycled - moving the fluid between cooler and warmer parts of the endcone)
  - 905 to 950 kPa >> 21.7 to 23.3°C (71-74°F)



Subsystem: iss-thermal

Flight: ISS047H

ISP Server: MCCH-mer5-MIS

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015:15:19:01.448      ISP timetags do not agree with GMT - some data may be incorrect
015:16:04:02.543      ISP timetags do not agree with GMT - some data may be incorrect
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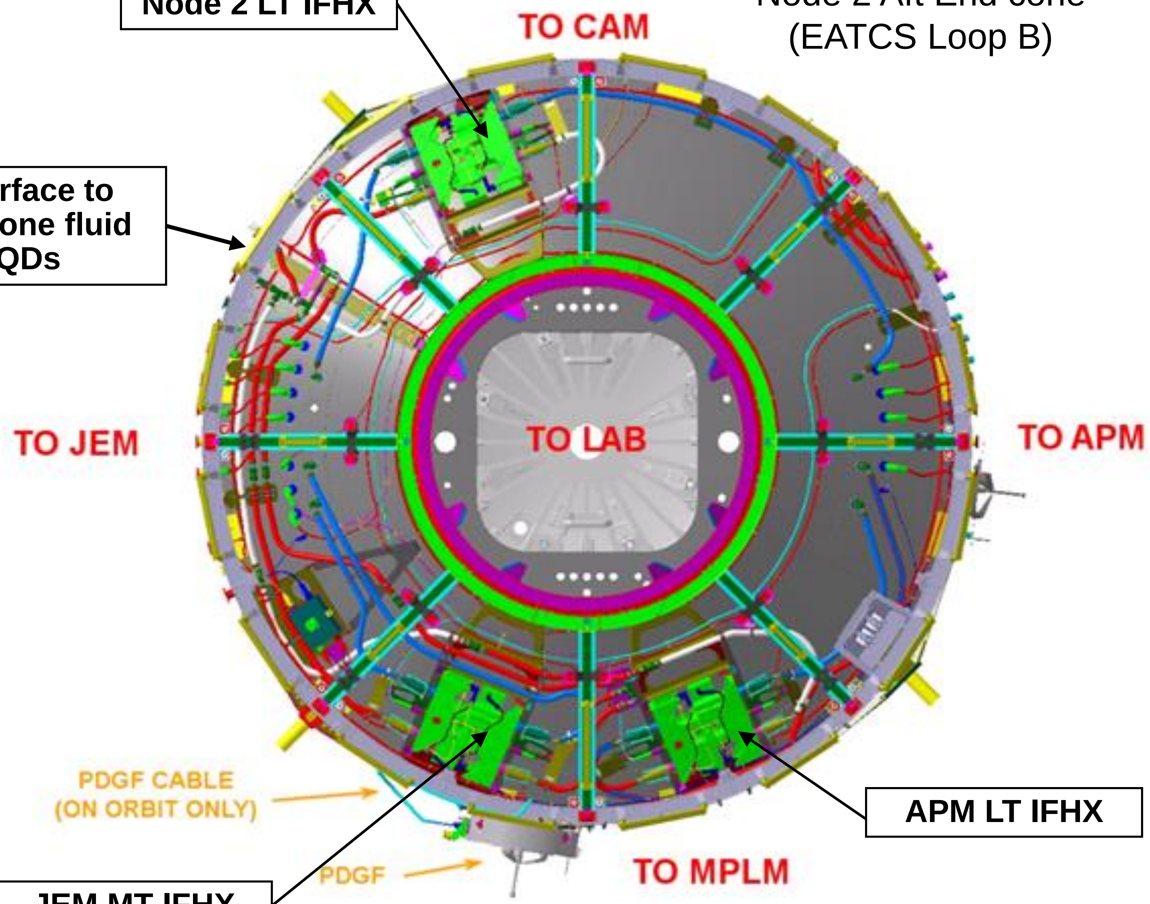
Aftermath

- Because Loop B was stagnant, the liquid in the lines outside of the heated endcones was free to drop to the local environment temperature
- Of most concern was the boom tray temperature, which is the fluid closest to the endcones (where the heat exchangers reside)
  - during repressurization, this fluid would fill the endcones, then the heat exchangers
- Passive thermal analysis of boom tray temperatures
  - fluid upstream of Node 3 heat exchanger was -30°C (-22°F)
  - fluid upstream of Node 2 heat exchangers was 0°C (32°F)
- 18 liters (0.64 ft^3) of vapor would fill 40 m (135 ft) of 1 inch tubing
  - not enough to completely fill the endcones
  - we could not know which endcone lines were filled and which were empty

Node 2 Endcone Layout / IFHX Locations

Node 2 Aft End cone (EATCS Loop B)

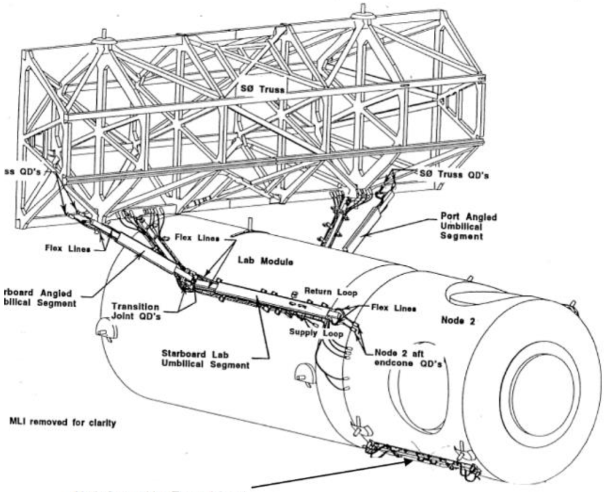


Node 2 LT IFHX

Interface to endcone fluid QDs

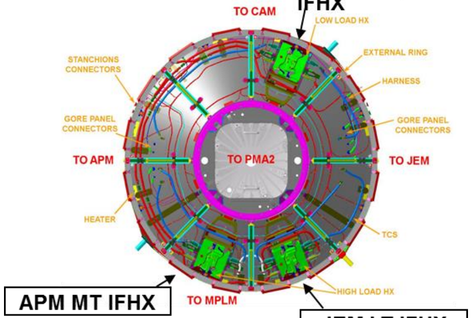
APM LT IFHX

JEM MT IFHX



Node 2 Fluid Line Tray - deleted.

Figure 17.4-6 NH3 Umbilical Trays Deployed from S0 to Node 2



Node 2 MT IFHX

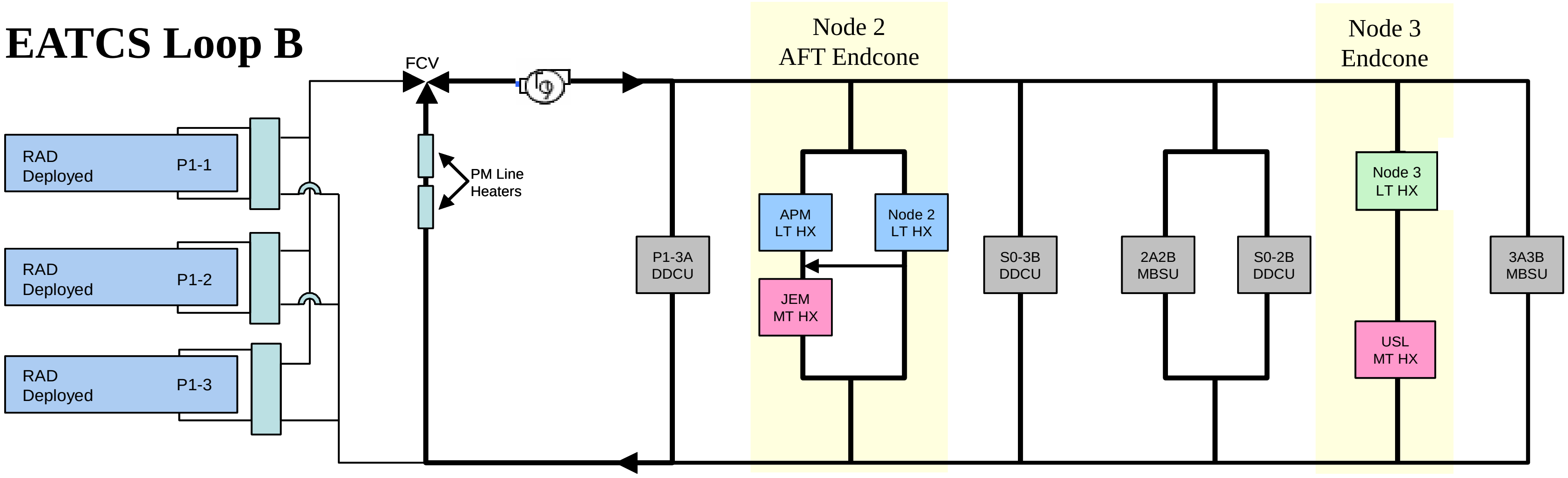
APM MT IFHX

JEM LT IFHX

Node 2 Fwd End cone (EATCS Loop A)

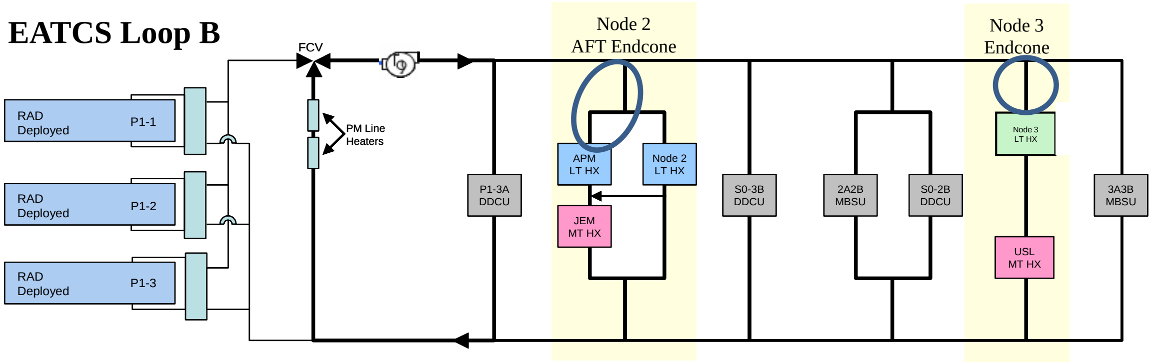
Starting Conditions for Refill

- Node 3 LT HX was flowing and was warm
- Node 2 LT HX was flowing
- JEM MT HX was flowing
- APM LT HX was isolated and its heaters were on



Limitations

- We did not want to send subfreezing ammonia to the heat exchangers mounted on Node 2 (Node 2 LT, JEM MT and APM LT)
  - 0°C fluid in boom trays
  - 2.8 liters (0.1 ft^3) of volume in shortest leg to APM LT
  - required dwell time of four hours to increase temperature to 5.5°C 42°F (required margin)
- We did not want to send subfreezing ammonia to the Node 3 LT heat exchanger
  - -29°C (-20°F) fluid in boom trays
  - 0.8 liters (0.03 ft^3) of volume in shortest leg to APM LT
  - required dwell time exceeded 12 hours to increase temperature to 5.5°C 42°F



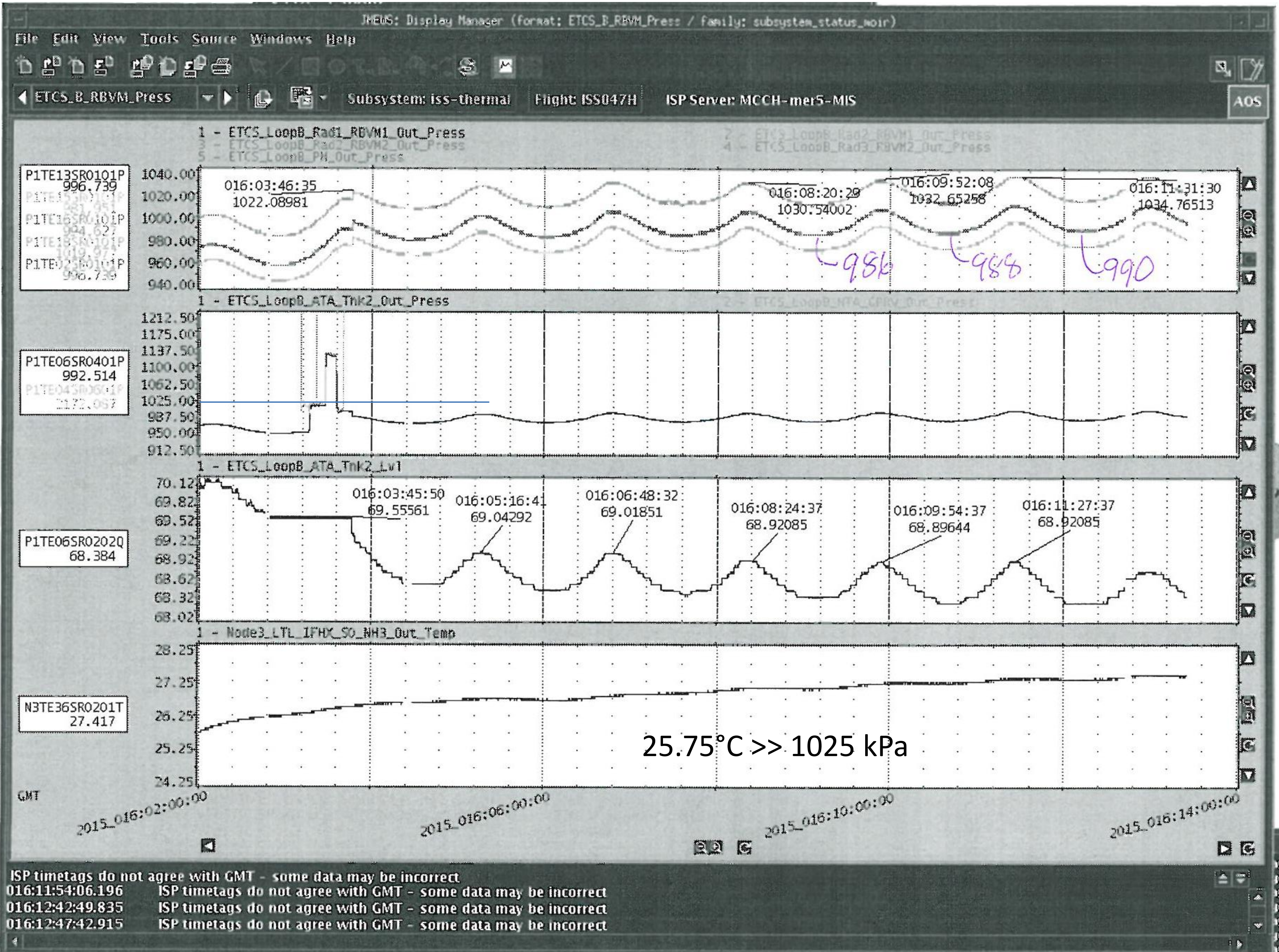
Previous PMA Recovery Procedure

- Open ATA to system
- Pressurize enough to introduce enough liquid into system to fill the shortest leg (from boom tray to HX)
- Dwell to allow fluid to warm to endcone temperature
- Repeat

- With 0.8 liters (0.03 ft^3) critical volume and dwell time >12 hours, this would have required more than 10 days

Initial Idea

- Since Node 3 LT was flowing and warm,
  - pressurize accumulator to a pressure below one that would force liquid into the Node 3 LT HX
  - observe the Node 2 endcone volume limit of 2.8 liters (0.1 ft^3)
  - wait for required dwell time
  - repeat
- One successful push was obtained but it was clear that we would soon run out of pressure headroom
  - as we pushed more liquid into the system, the liquid/vapor interface would be forced into warmer areas, creating higher pressures
  - Node 3 LT-induced saturation pressure limit would be reached



25.75°C >> 1025 kPa

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ISP timetags do not agree with GMT - some data may be incorrect
016:11:54:06.196     ISP timetags do not agree with GMT - some data may be incorrect
016:12:42:49.835     ISP timetags do not agree with GMT - some data may be incorrect
016:12:47:42.915     ISP timetags do not agree with GMT - some data may be incorrect
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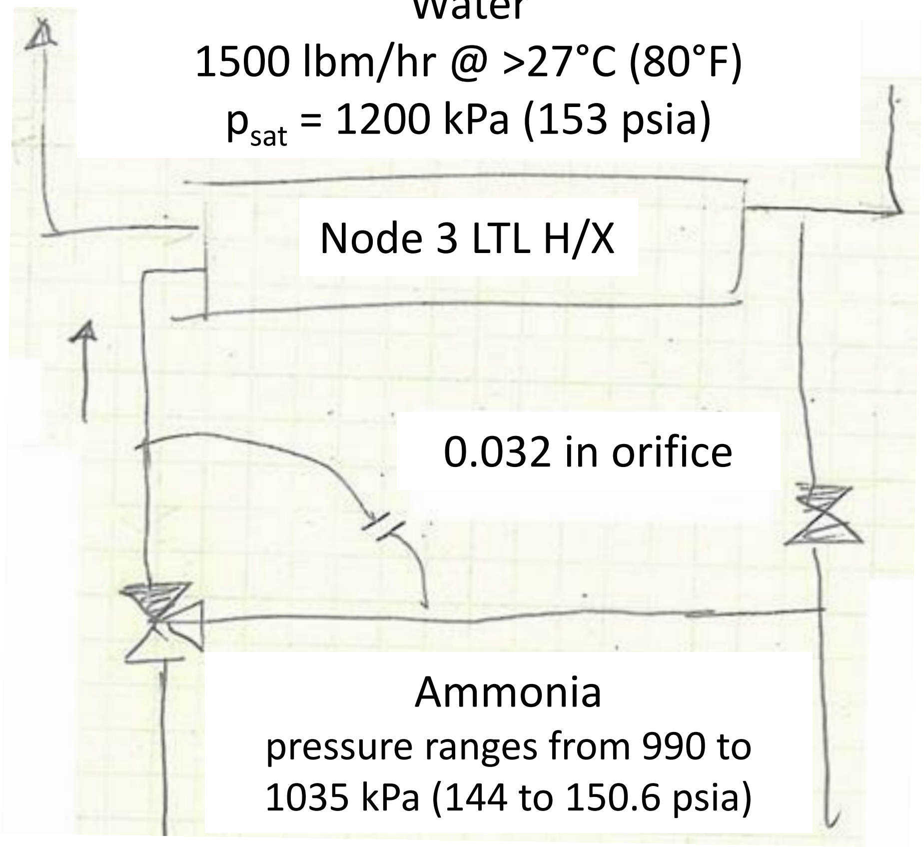
Follow-on Idea

- Could we show that freezing would not occur even if cold ammonia entered the Node 3 heat exchanger?
- That would allow us to use
  - only the limit of the Node 2 endcone volume - 2.8 liters (0.1 ft^3)
  - a shorter dwell
    - 4 hours since the boom tray upstream of Node 1 was at 0°C

Current Configuration



Water
1500 lbm/hr @ >27°C (80°F)
p_{sat} = 1200 kPa (153 psia)

Node 3 LTL H/X

0.032 in orifice

Ammonia
pressure ranges from 990 to 1035 kPa (144 to 150.6 psia)

-20°F Ammonia

contemporaneous chart

Pressure Increase Scenario

- Consider the loop pressure to be constant at 1000 kPa
- If the loop pressure is increased
  - Once p>1200 kPa condensation will occur
    - condensation can be limited by available heat transfer or vapor inflow
  - Once all vapor is condensed, liquid ammonia will be pulled into the heat exchanger core
    - 19:1 density ratio

contemporaneous chart

Pressure Increase Scenario

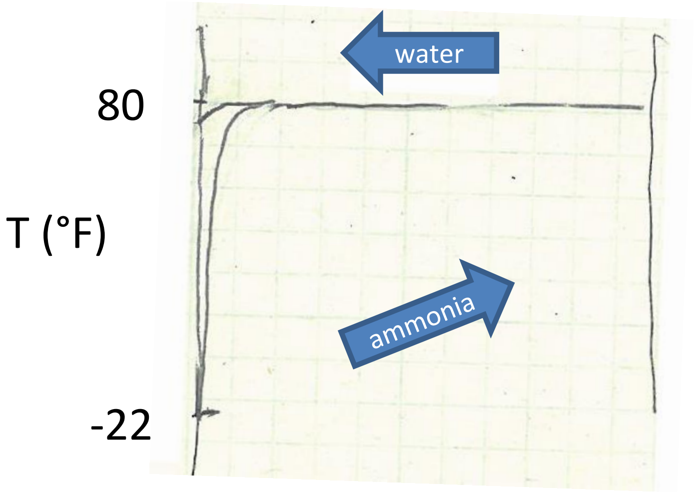
- Liquid inflow will be limited by the 0.032 inch orifice

orifice Δp (psid)	orifice Δp (kPa)	m dot (lbm/hr)	minutes to fill core
1	6.9	7	9
5	34.5	16	4
10	69.0	23	3

orbital cycle Δ is ~45 kPa

contemporaneous chart

In the Heat Exchanger

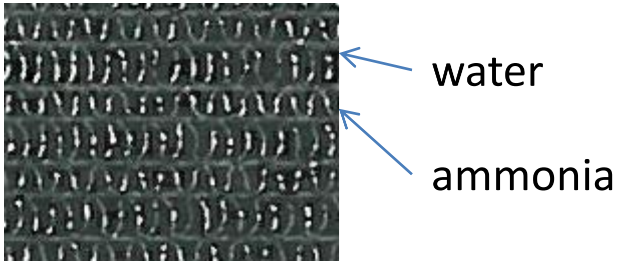


- Heat exchanger effectiveness is near unity
- When cold inflow begins, the water temperature at the exit (LHS) is 80°F
- As cold flow has passes through the core, the water exit temperature drops
- Minimum water exit temperature occurs when entire core has experienced cold flow

contemporaneous chart

At the Heat Exchanger Water Exit

- Ammonia is as cold as -20°F
- Water is colder than 80°F

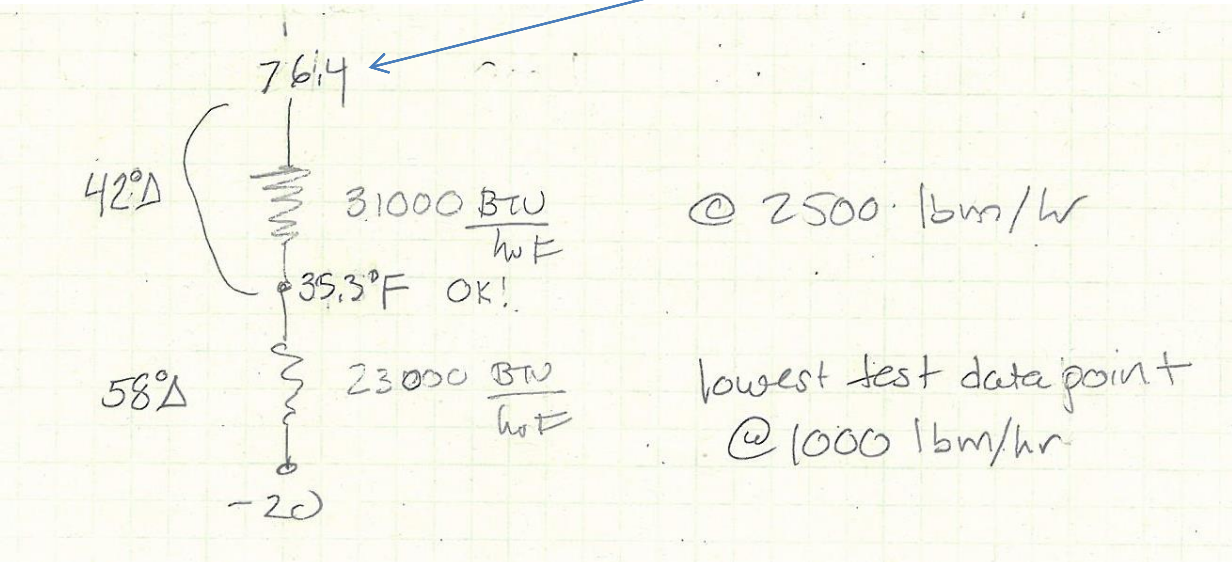


- Core metal temperature will be determined by relative magnitude of water and ammonia heat transfer
  - $UA_{water} > UA_{ammonia}$ so core temperature will be closer to the water temperature than to the ammonia temperature

contemporaneous chart

Two Results

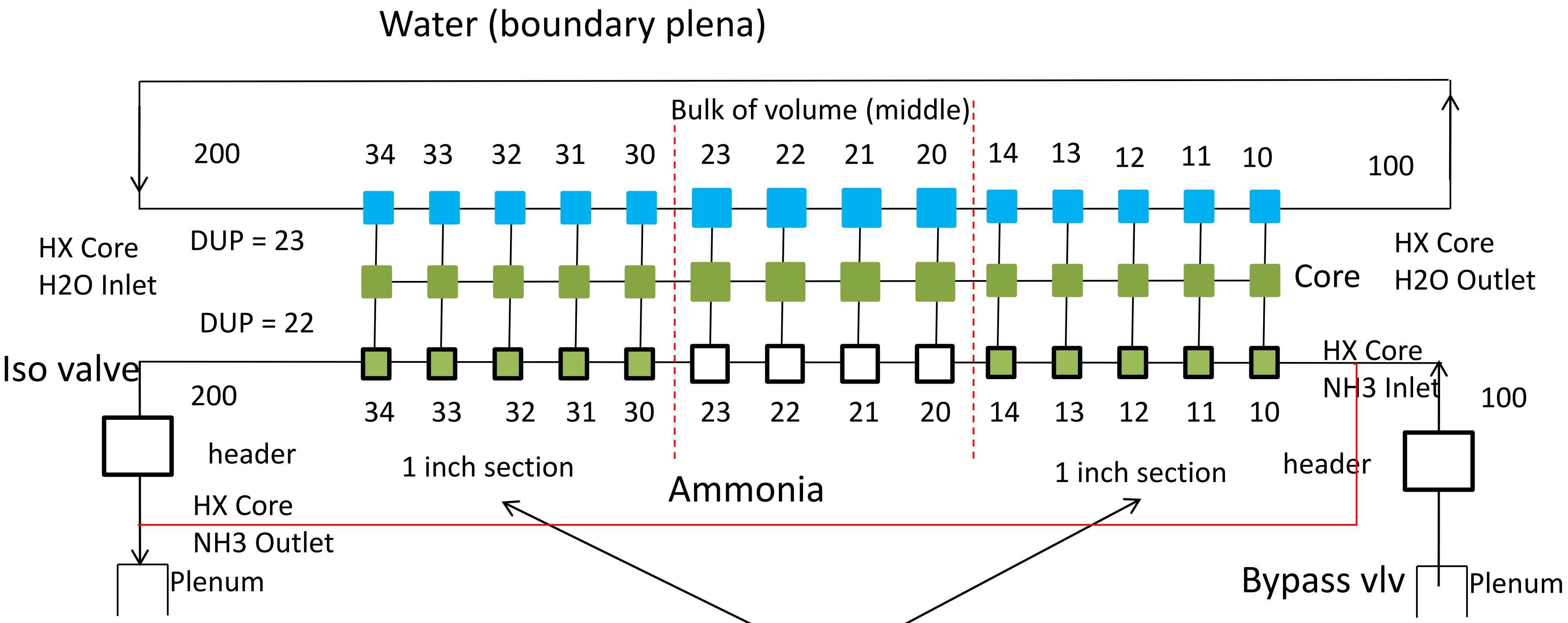
- Detailed SINDA/FLUINT model indicated that the minimum metal temperature was >15°C (60°F)
- Hand calculation



measured water temperature

35.3°F = 1.8°C

Flowing IFHX Model Schematic
Normal operation



Water (boundary plena)

Bulk of volume (middle)

200 34 33 32 31 30 23 22 21 20 14 13 12 11 10 100

HX Core
H2O Inlet

DUP = 23

DUP = 22

Core

HX Core
H2O Outlet

Iso valve

200

34 33 32 31 30 23 22 21 20 14 13 12 11 10

HX Core
NH3 Inlet

100

header

1 inch section

Ammonia

1 inch section

header

HX Core
NH3 Outlet

Plenum

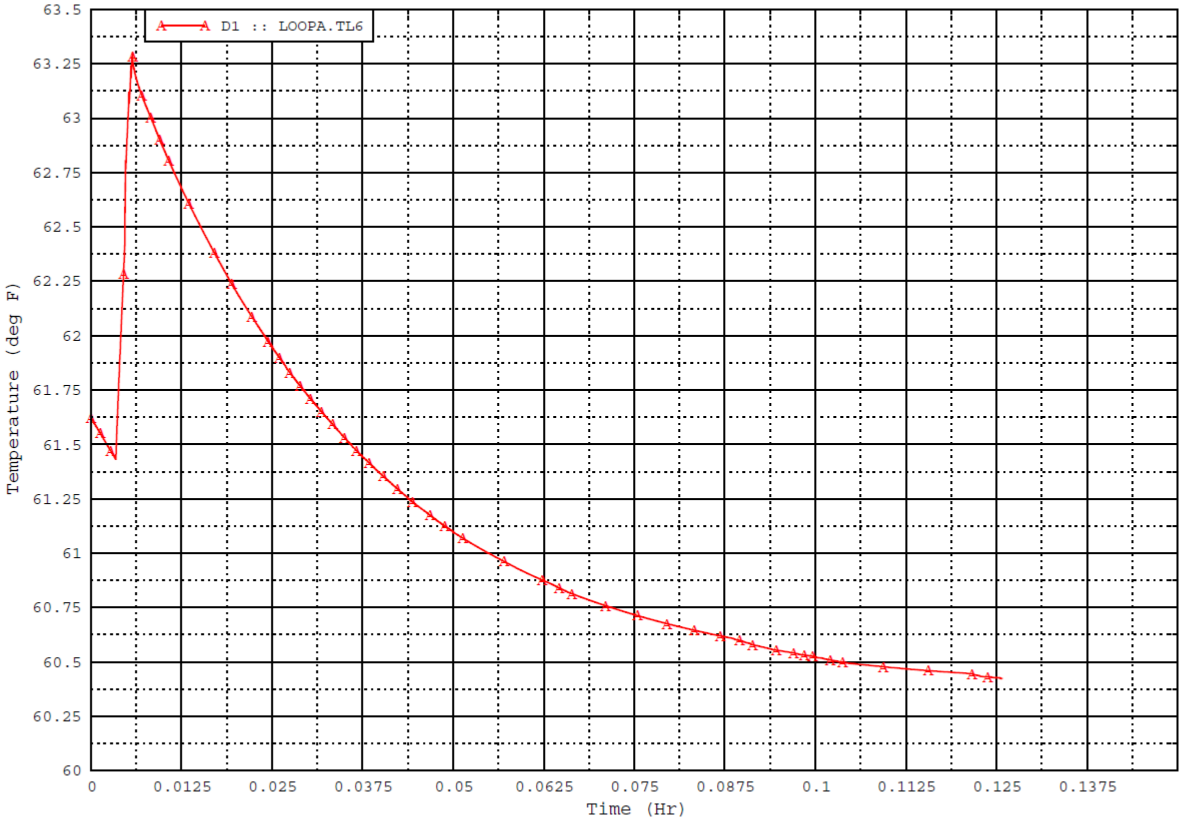
Bypass vlv

Plenum

🟦 Water
🟩 Core
☐ Ammonia

Nodes are smaller at the inlet and outlet where flashing/freezing is most likely to occur – We'll see it here first.

1st Node Metal Temperature

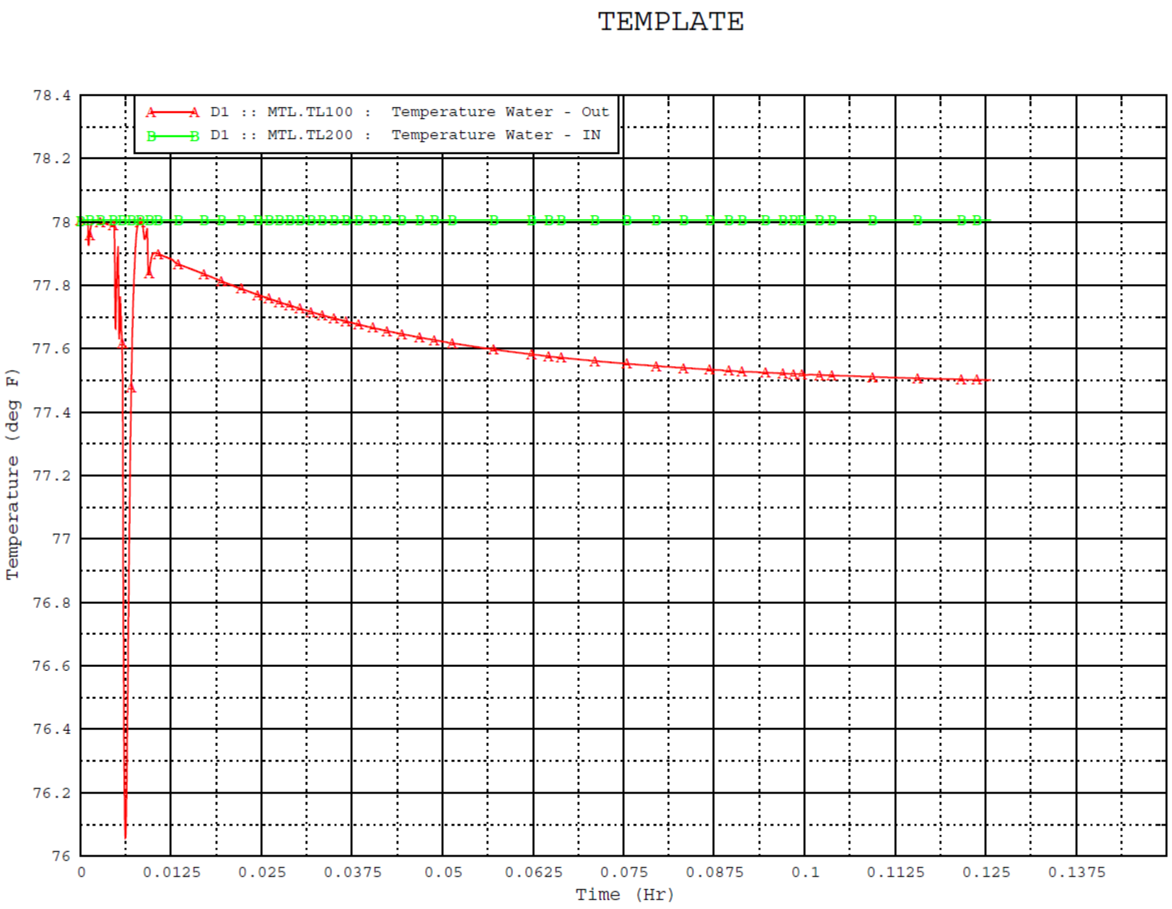


Why The Difference? (in Hindsight)

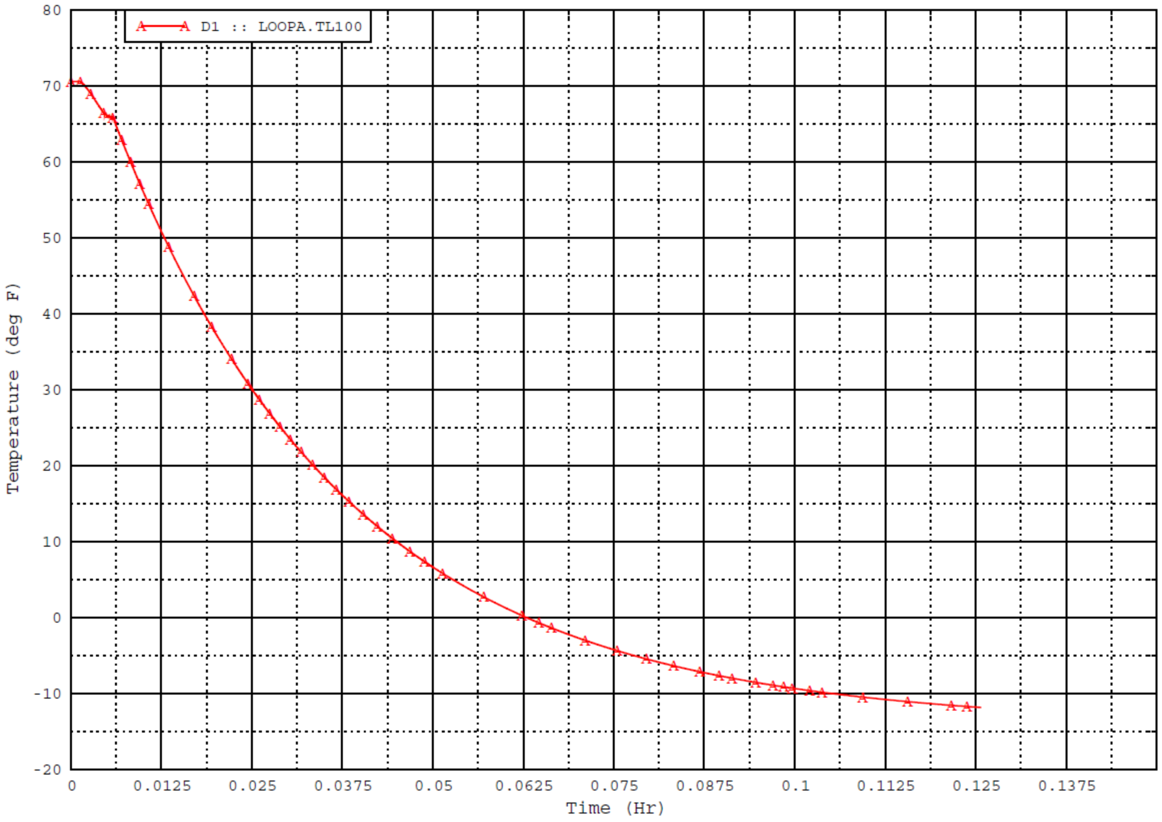
- The SINDA/FLUINT model took the heating from warm metal into account
  - ammonia was warmed to -25°C (-13°F)

  but that was not the largest effect
- The model element size was 0.2 inches
  - because the ammonia flow was so low (about 100:1 ratio), all the heat transfer took place in the first element or two
- The model was returning the <u>average</u> metal temperature within the first element, not the <u>minimum</u> temperature (which would occur at the entrance)
- We were safe to proceed despite the difference in the results because even the conservative hand calculation showed positive margin

Water Temperatures

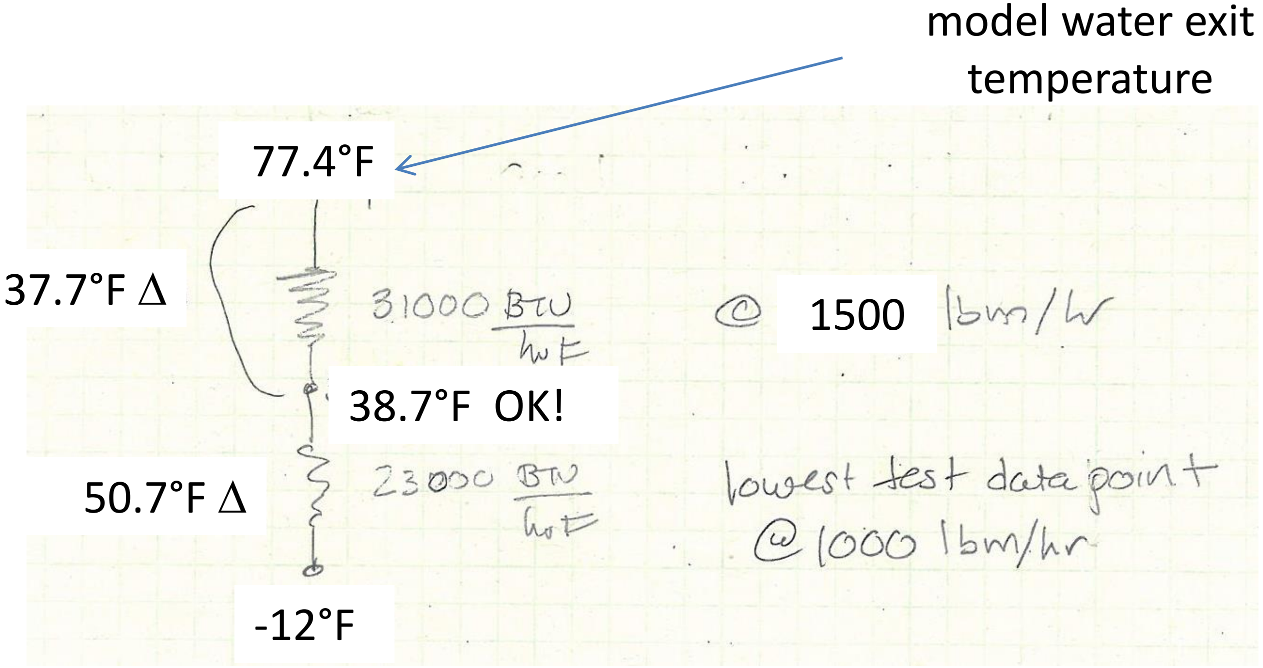


Ammonia Inlet Temperature



The Right Answer

- Hand calculation



model water exit temperature

77.4°F

37.7°F Δ

38.7°F OK!

1500

50.7°F Δ

-12°F

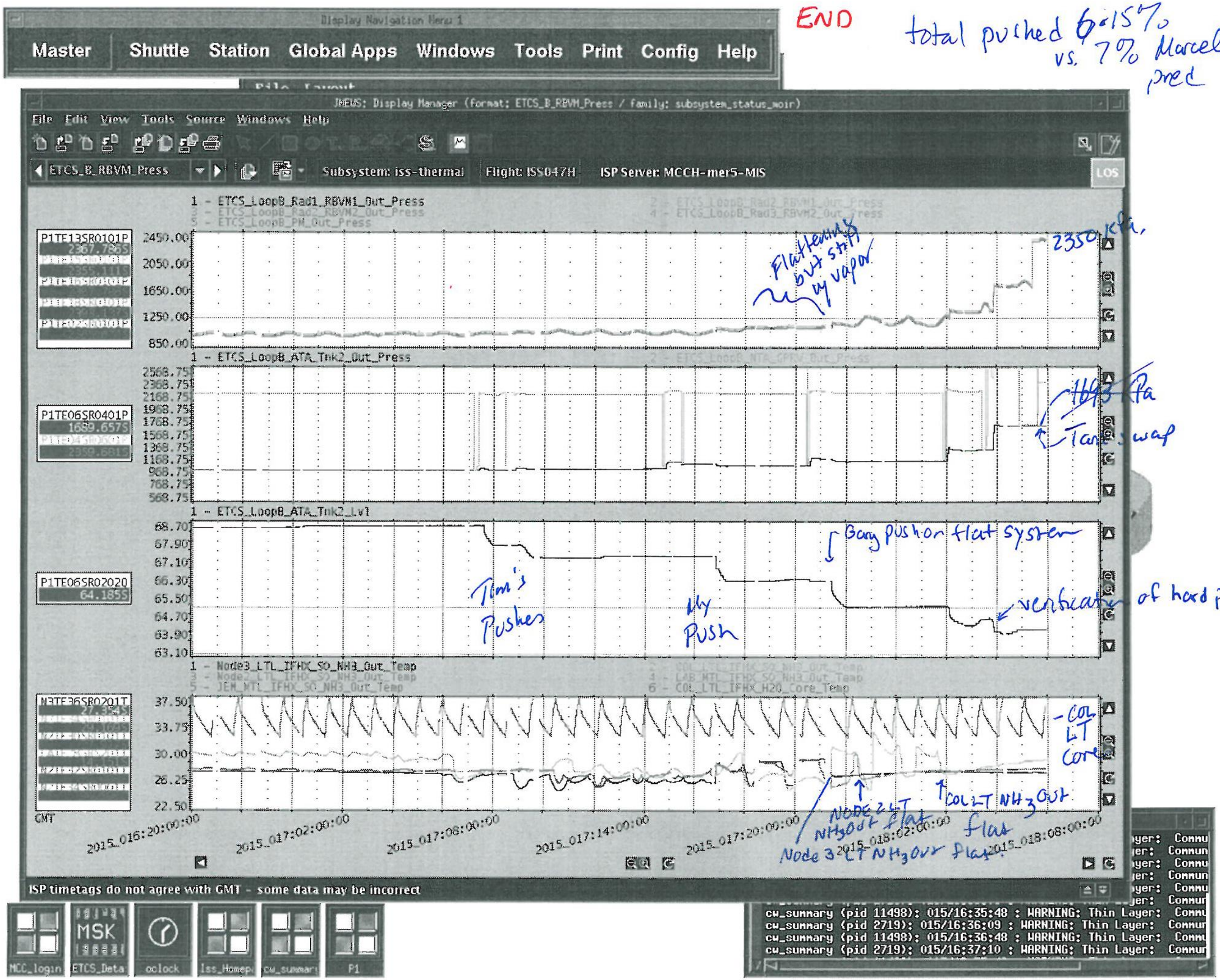
38.7°F = 3.7°C

The Home Stretch

- Since we were no longer concerned about freezing in the flowing Node 3 LT HX, the stagnant APM LT HX became the limiting factor
- Upstream of APM LT HX
  - 0°C fluid in boom trays
  - 2.8 liters (0.1 ft^3) volume in shortest upstream leg
  - required dwell time of four hours
- 2.8 liter (0.1 ft^3) insertions on 4 hour centers were begun

END

total pushed ~~6~~ 6.15%
vs. 7% Marcellino
pred



Flattening but still ω vapor

2350 kPa

~~1693~~ kPa

Tank swap

Gary push on flat system

Tim's Pushes

My Push

verification of hard pack

- COL LT Core

NODE 2 LT NH3out flat

COL LT NH3 Out flat

Node 3 LT NH3 Out flat

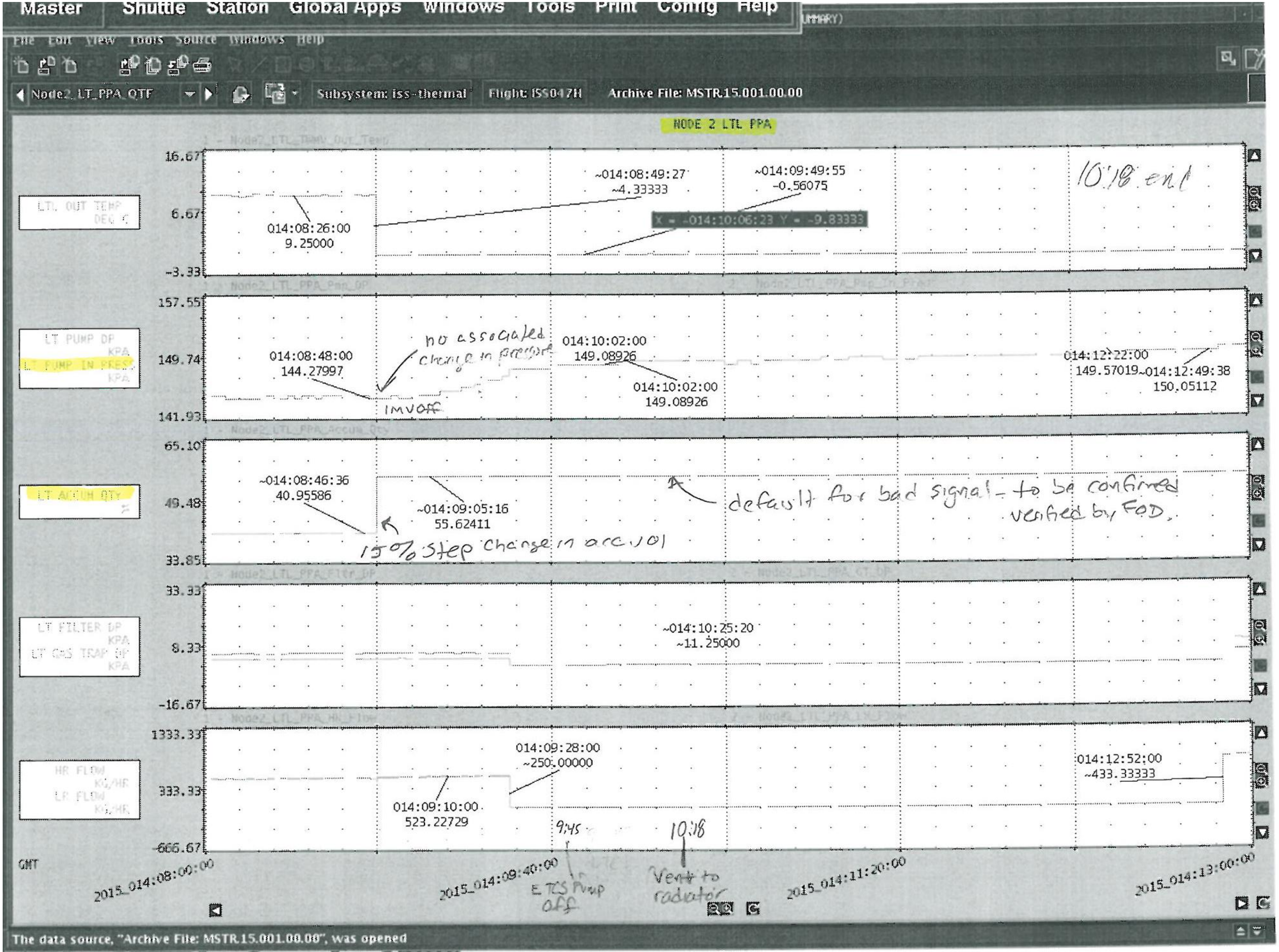
ISP timetags do not agree with GMT - some data may be incorrect

```
cw_summary (pid 11498): 015/16:35:48 : WARNING: Thin Layer:  Commu
cw_summary (pid 2719): 015/16:36:09 : WARNING: Thin Layer:  Commun
cw_summary (pid 11498): 015/16:36:48 : WARNING: Thin Layer:  Commu
cw_summary (pid 2719): 015/16:37:10 : WARNING: Thin Layer:  Commun
```

The Denouement

- System hard packed after 15.7 liters (0.56 ft^3) of ammonia inserted (vs. 17.9 liter - 0.64 ft^3 initial estimate)
  - based on ATA quantity change
- System was ready to be restarted 4 days after ammonia alarm event

Backup



Subsystem: iss-thermal

Flight: ISS047H

Archive File: MSTR.15.001.00.00

10:18 end

no associated change in pressure

IMV off

15% step change in accum ql

default for bad signal - to be confirmed verified by FOD.

9:45

ETCS Pump off

10:18

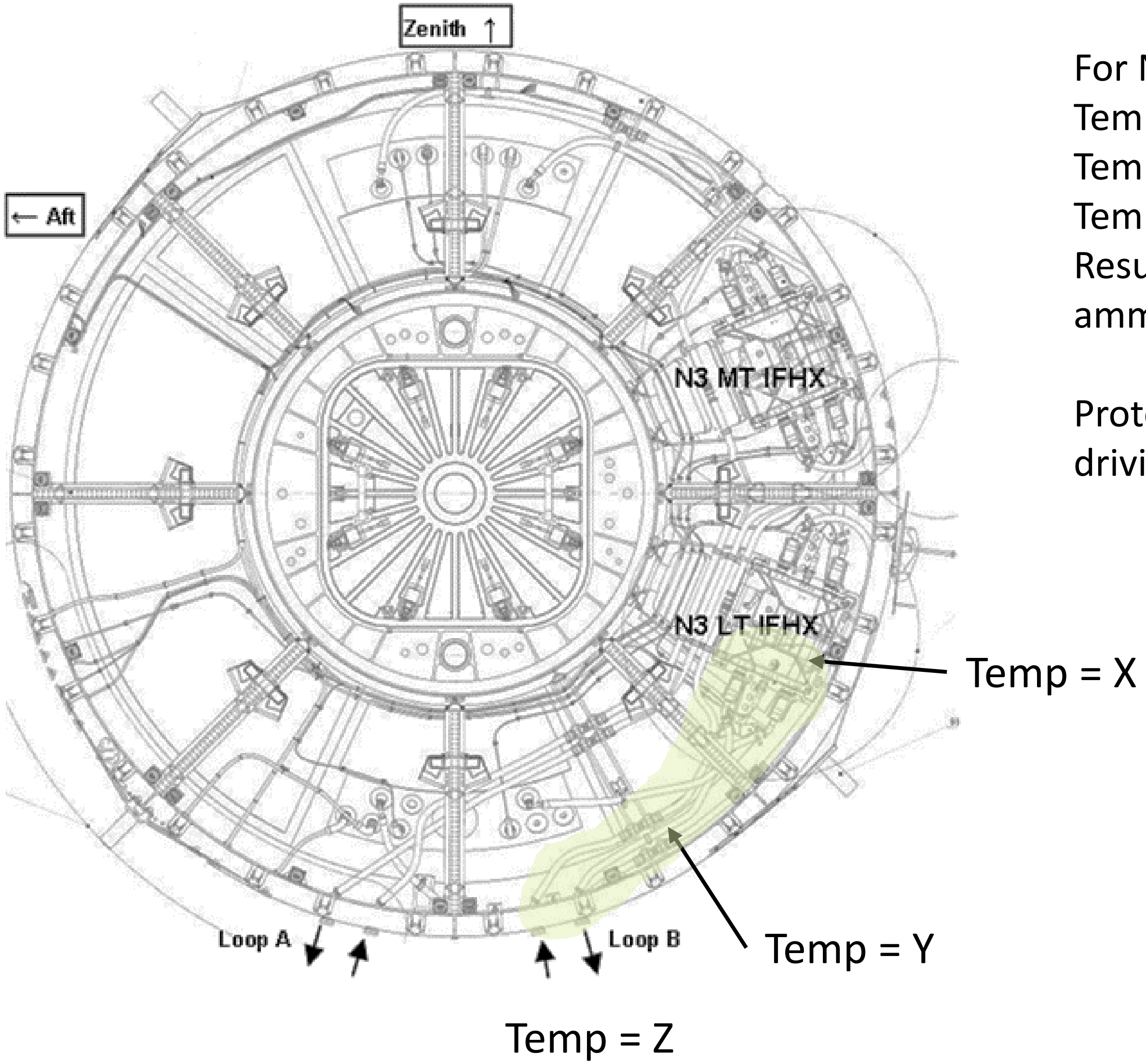
Vent to radiator

The data source, "Archive File: MSTR.15.001.00.00", was opened

How Did We Know That There Was No Leak?

- Accumulator spike was not right
  - instantaneous accumulator level change is indicative of a large leak
  - a large leak would have stroked the accumulator fully
    - $p_{ATCS} >> p_{ITCS}$
- There was no instantaneous change in loop pressure
  - changes in gas cap accumulator quantity always result in changes in loop pressure

Node 3 Endcone and Heat Exchangers



Temp = X

Temp = Y

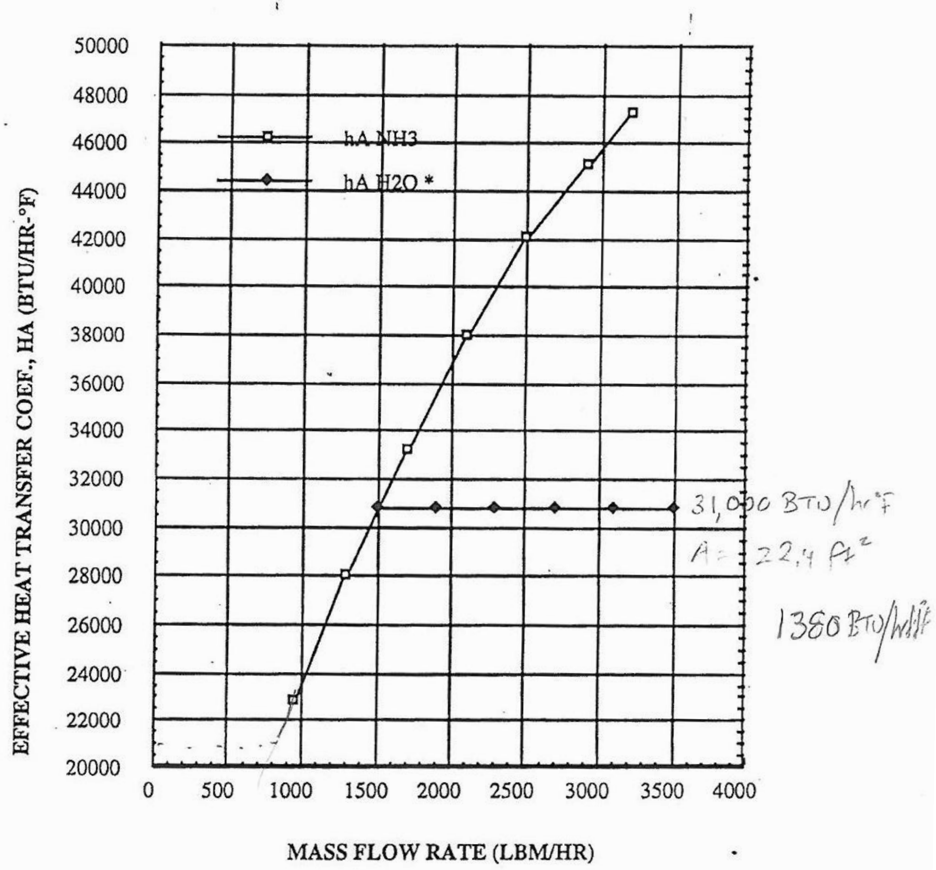
Temp = Z

For Node 3:
Temp X ~ 26 C (telemetry)
Temp Y ~ 18-20 C (est. shell temp)
Temp Z ~ -29C (analysis)
Result: NH3 vapor in IFHX, cold ammonia not too far away

Protection of the Node 3 LTL IFHX was driving timeline

HEAT EXCHANGER PERFORMANCE

- water values used directly from vendor data
- ammonia values developed from basic principles
  - pure laminar flow does not allow for UA enhancement from serpentine nature of flow path



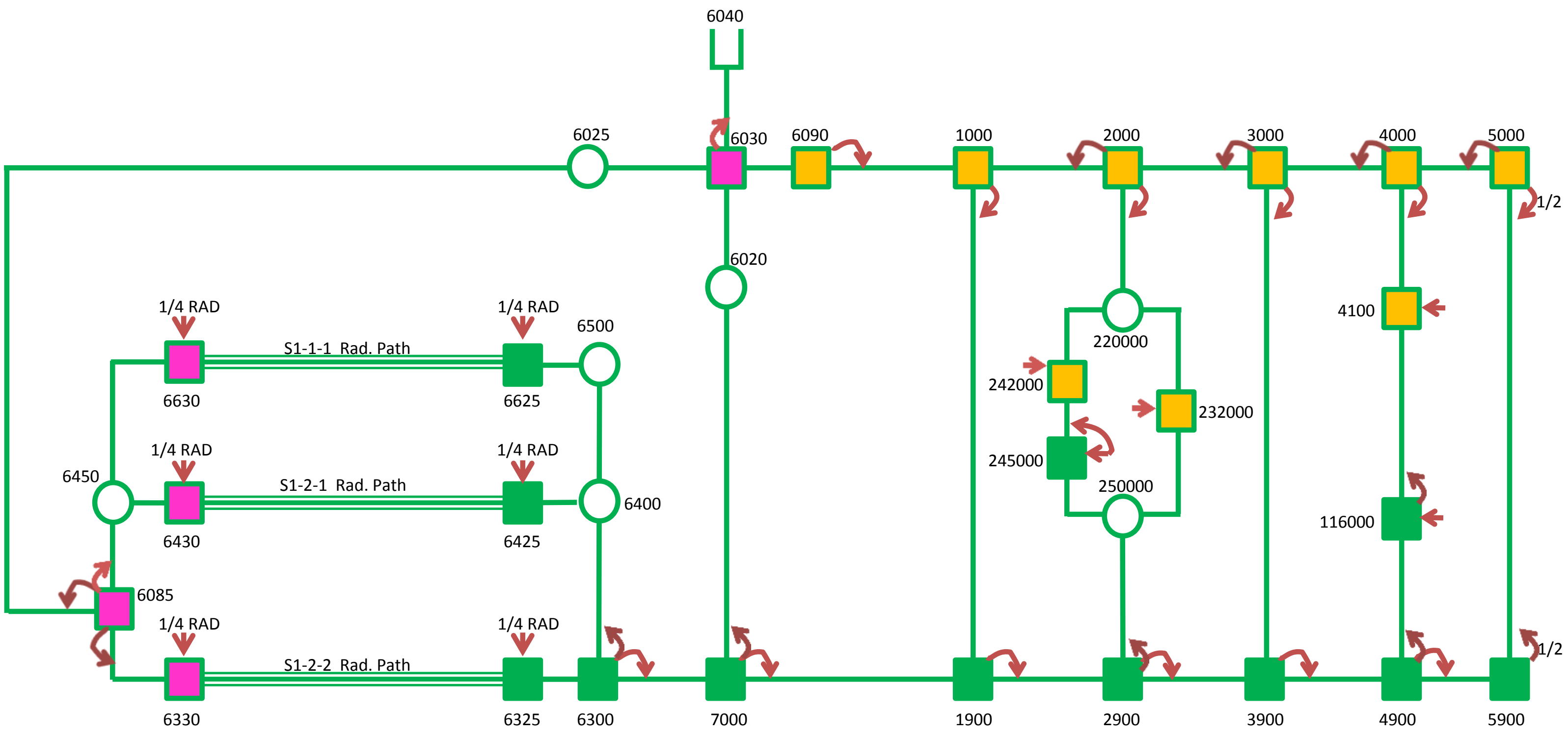
31,000 BTU/hr°F

A = 22,4 ft²

1380 BTU/hr ft²

* Minimum Nussert number operation
hA = constant over given flow range

Simplified Model Schematic



🟨 Lump – PM to IFHX

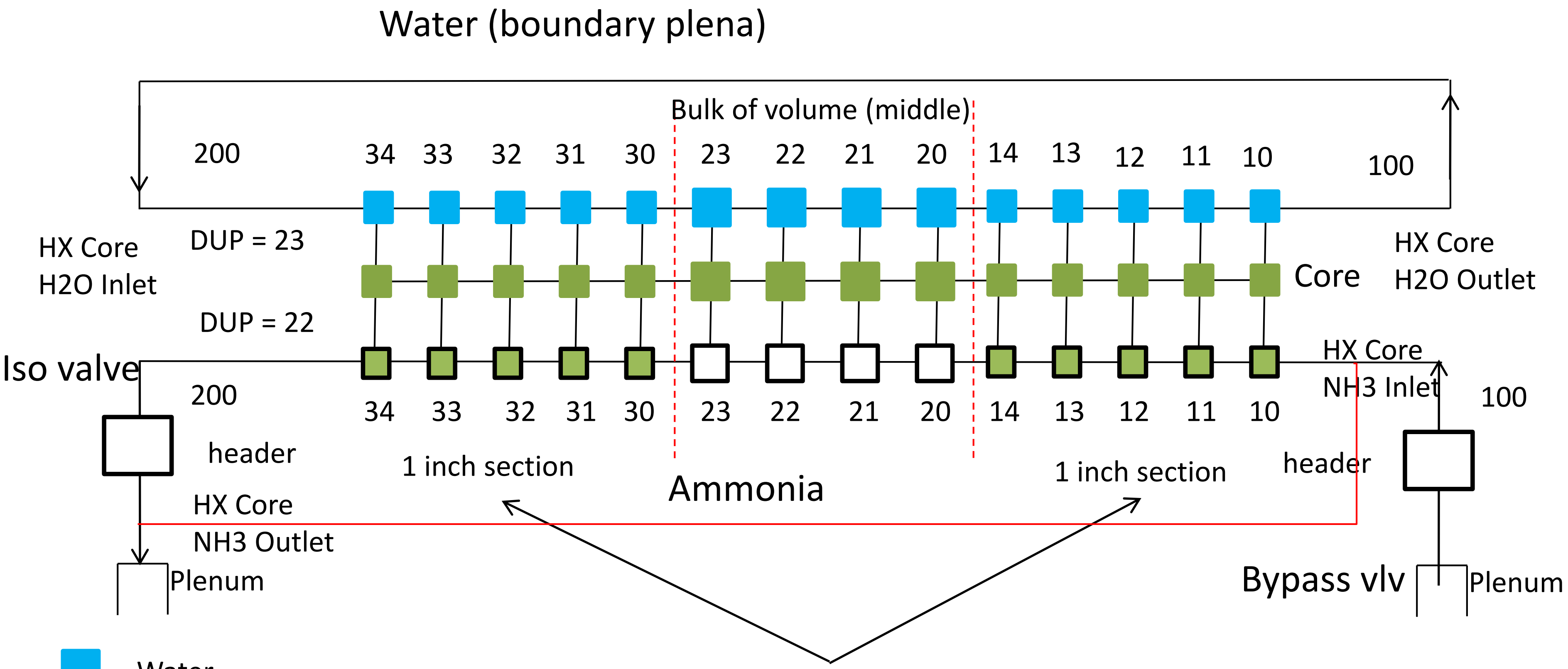
🟪 Lump – RAD to PM

🟩 Lump – IFHX to Rad

○ Lump w/o volume

↷ Path used to create Volume

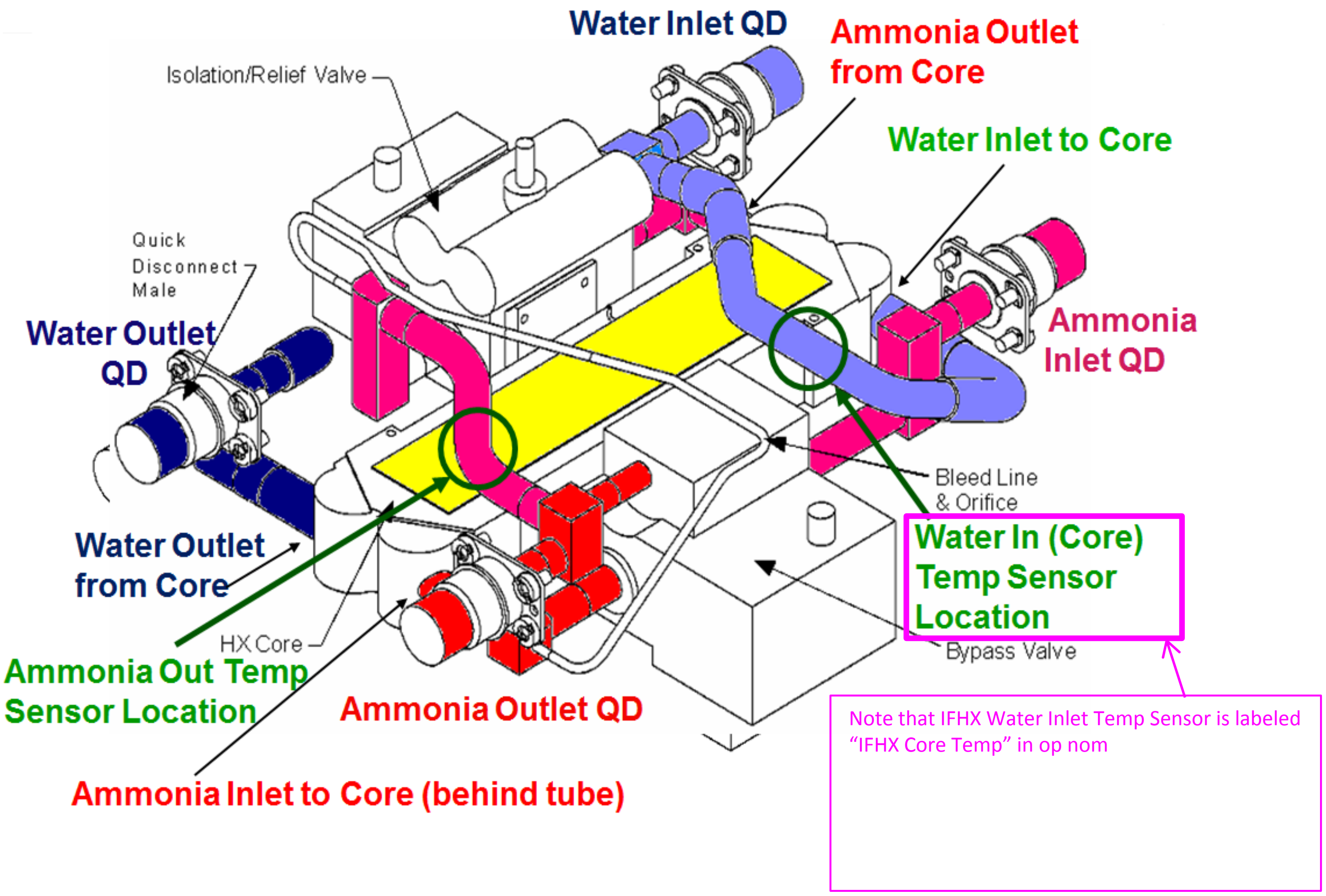
Flowing IFHX Model Schematic
Normal operation



Nodes are smaller at the inlet and outlet where flashing/freezing is most likely to occur – We'll see it here first.

🟦 Water
🟩 Core
☐ Ammonia

IFHX



Note that IFHX Water Inlet Temp Sensor is labeled "IFHX Core Temp" in op nom

Loop Configurations