COMPARISON OF ANALYTICAL AND NUMERICAL PERFORMANCE PREDICTIONS FOR A REGENERATIVE HEAT EXCHANGER IN THE INTERNATIONAL SPACE STATION NODE 3 INTERNAL ACTIVE THERMAL CONTROL SYSTEM

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ABSTRACT

The complexity of International Space Station (ISS) systems modeling often necessitates the concurrence of various dissimilar, parallel analysis techniques to validate modeling. This was the case with a feasibility and performance study of the ISS Node 3 Regenerative Heat Exchanger (RHX). A thermo-hydraulic network model was created and analyzed in SINDA/FLUINT. A less complex, closed form solution of the system dynamics was created using Excel. The purpose of this paper is to provide a brief description of the modeling processes utilized, the results and benefits of each to the ISS Node 3 RHX study.

INTRODUCTION

The Node 3 pressurized element enhances the crew capacity of the International Space Station (ISS) from three to seven by providing dedicated resources and utilities supporting crew habitability functions at station level. Of these dedicated resources and utilities, the most critical are the Environmental Control and Life Support (ECLS) systems which condition the internal atmosphere. To provide for continuous operation, the Node 3 Internal Active Thermal Control System (IATCS) Low Temperature Loop (LTL) and Moderate Temperature Loop (MTL) collect and reject waste heat from the ECLS racks. Requirements exist to ensure that during a single failure of a External Active Control Thermal System (EATCS) ammonia loop or a Electrical Power System (EPS) power domain, the IATCS will continue to provide cooling to the critical ECLS systems. In order to sustain operation for this contingency, the IATCS must accommodate a Loop Crossover Assembly (LCA) to allow the two loops (nominally configured in dual loop mode) to operate in series (single loop mode), utilizing the MTL to provide coolant for LTL heat rejection.

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS) DESCRIPTION

The Environmental Control and Life Support Systems (ECLSS) control the atmosphere of the internal pressurized volume in terms of air pressure, temperature, humidity, particulate and microbial concentrations. Additionally, the ECLSS provides for crew waste management and hygiene. The following rack assemblies achieve these ECLSS functions:

- Atmosphere Revitalization System (ARS) rack
  - Sample Delivery System (SDS) – allows proper air flow distribution inside the rack
  - Trace Contaminant Control Subassembly (TCCS) – processes the cabin air to remove the gaseous trace contaminants that could be hazardous for the crew
  - Major Constituent Analyzer (MCA) – continuously monitors the partial pressures of the major atmospheric constituents in the Node 3 cabin and from other modules of the ISS
  - Area smoke detection and fire indication
  - Carbon Dioxide Removal Assembly (CDRA) – processes the cabin air to remove carbon dioxide
  - Avionics Air Assembly (AAA) – provides air circulation for fire detection and provides air cooling for rack components
- Oxygen Generation System (OGS) rack – contains the Oxygen Generator Assembly (OGA) which produces oxygen for atmospheric supply
- Water Recovery System (WRS) #1 & #2 racks – waste water processing to potable water and pre-treated urine to urine distillate processing
- Waste & Hygiene Compartment (W&HC) #1 & #2 racks – crew personal hygiene and crew urine and fecal collection
- Common Cabin Air Assembly (CCAA) – air/water heat exchanger that transfers environmental heat loads to the LTL for rejection

NODE 3 INTERNAL ACTIVE THERMAL CONTROL SYSTEM (IATCS) DESCRIPTION - NOMINAL OPERATION

The Node 3 IATCS consists of two separate single-phase, water coolant loops. The function of the IATCS is to provide heat rejection for subsystem avionics equipment, for the environmental control system and for subsystems and payloads within elements attached to Node 3. The two IATCS loops consist of a Low Temperature Loop (LTL) which provides coolant in the temperature range between 38-43 °F and a Moderate Temperature Loop (MTL) which provides coolant in the temperature range between 61-65 °F. The Node 3 IATCS is schematically shown in Figure 1.

The collected heat load is rejected by means of two separate single-phase ammonia loops (A and B), via two dedicated NH_3/H_2O Heat Exchangers (HX) mounted externally on the Node 3 Zenith Cone. The collected heat is transferred from the ammonia loops to the EATCS radiators for rejection to space.

The LTL provides cooling for Multi-Purpose Logistics Module (MPLM), Node 1/Airlock and Habitation Module (HAB), the ECLSS CCAA and ARS – CDRA racks. The MTL provides cooling for an MPLM scar, Node 1/Airlock and Cupola, the ECLSS ARS – AAA rack, WRS#1 and #2, W&HC#1 and #2 and OGS racks and coldplate cooled electronics equipment located in Avionics Racks #1 and #2.

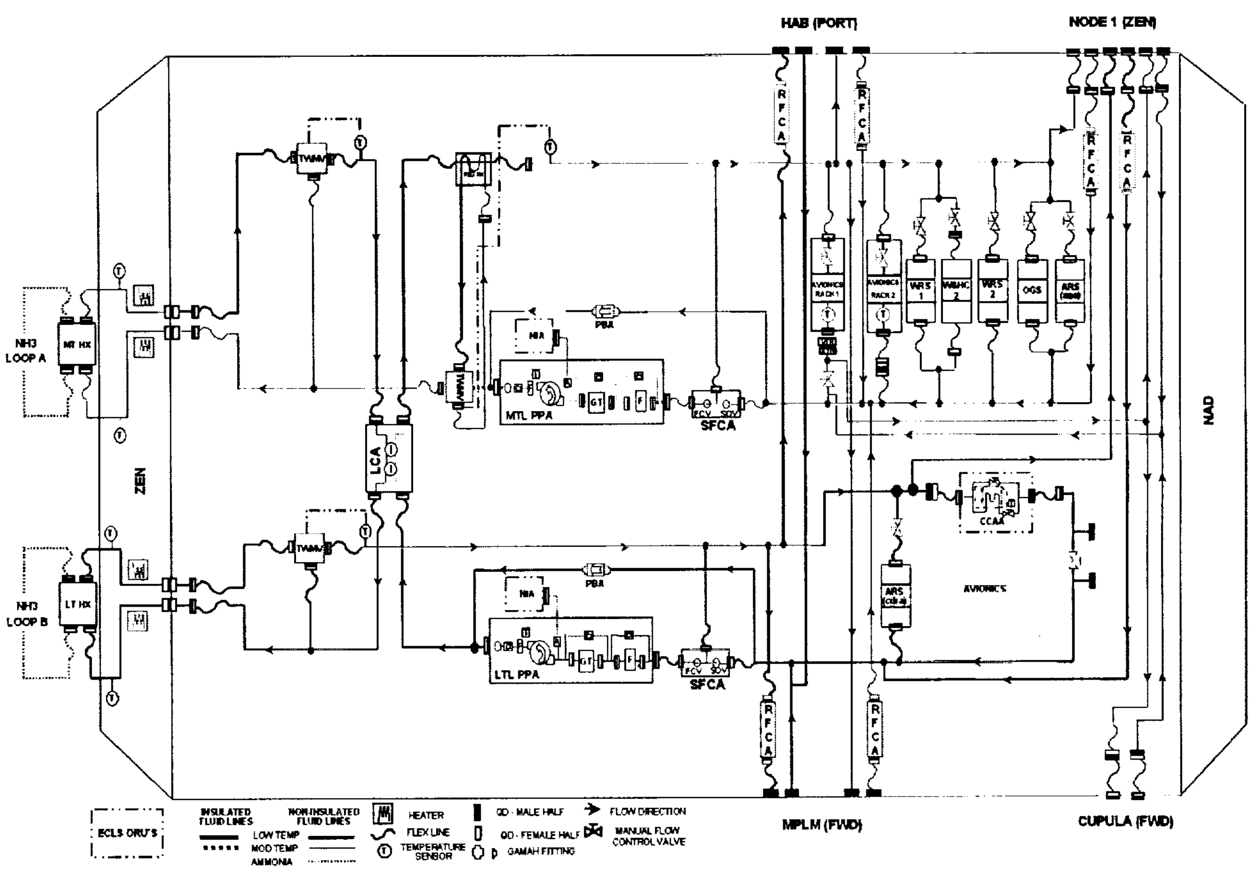

Figure 1. Node 3 IATCS

NODE 3 INTERNAL ACTIVE THERMAL CONTROL SYSTEM (IATCS) DESCRIPTION - CONTINGENCY OPERATION

A single failure of the EATCS loop B or EPS power domain 2/3 would result in the loss of LTL coolant flow, creating a condition where CO_2 removal capability would be lost in both the United States Laboratory (USL) module and Node 3. To eliminate the effects of this critical failure, the Node 3 IATCS will accommodate a LCA to connect the two loops in series to operate as a single loop, utilizing the MTL to provide coolant for LTL heat rejection.

In view of the fact that the MTL will be providing coolant for LTL use, the temperature of the MTL coolant must be adjusted to satisfy the needs of systems and equipment on the LTL. This is accomplished by lowering the setpoint of the MTL Three Way Mix Valve (TWMV) from a nominal setpoint of 63.0 °F to 50.0 °F. Consequently, as the coolant re-enters the MTL, the LTL heat load may not have been sufficient to raise the coolant above the cabin dew point temperature (60.0 °F). Therefore, the system ensures the coolant temperature is above the dew point with an RHX in conjunction with an RHX TWMV (65.0 °F set point) to preclude condensation on MTL coolant lines and equipment.

REGENERATIVE HEAT EXCHANGER (RHX) FEASIBILITY AND PERFORMANCE

As previously stated, the RHX must ensure the temperature of the MTL coolant is above the cabin dew point temperature to preclude condensation. A study was performed to determine if the condensation preclusion requirement could be satisfied under a "low load" scenario (no attached modules). The basis of this analysis is estimated heat dissipation values ascertained from the Node 3 Design Review Thermal Budget [1]. The heat loads utilized for the analysis are shown in Table 1. The estimates were derived for equipment that were considered to be operational after a single failure of the EATCS loop B or EPS power domain 2/3. The analysis also shows the allowable performance envelope for condensation preclusion and heat rejection.

Table 1. Node 3 IATCS Single Loop Mode Thermal Budget

SOURCE OR COMPONENT	THERMAL LOAD [Watts]	
	LTL	**MTL**
ARS / CDRA	**725.0**	-
ARS / AAA	-	**229.0**
OGA	-	**2320.0**
MTL PPA	-	**470.0**
TWMV	-	**1.0**
SFCA	-	**2.0**
Environment (cold biased attitude with 80 °F cabin)	*-720.0	-
Crew (2)	*270.0	-
Avionics Rack #1	*17.3	**557.7**
CCAA Water Separator	*44.7	-
CCAA Temperature Control Valve	*1.0	-
CCAA EIB	*6.5	-
Smoke Detector	*6.0	-
Harness	*20.0	-
THC Cabin Fan	*191.0	-
General Luminare Assembly	*300.0	-
ELPS	*10.0	-
UOP – 1, 2, 3, & 4	*36.0	-
Pressure Control Panel	*20.0	-
Nitrogen Introduction Assembly	*14.4	-
IMV Fan	*110.0	-
IMV Valve	*4.0	-
PCS	*100.0	-
CCAA	**430.9**	-
	1155.9	**3579.7**

* air load: total value incorporated for CCAA

CLOSED FORM SOLUTION

A closed form solution was developed to ascertain RHX performance based on Node 3 single loop mode architecture. Figure 2 shows the layout and nomenclature used for the closed form solution.

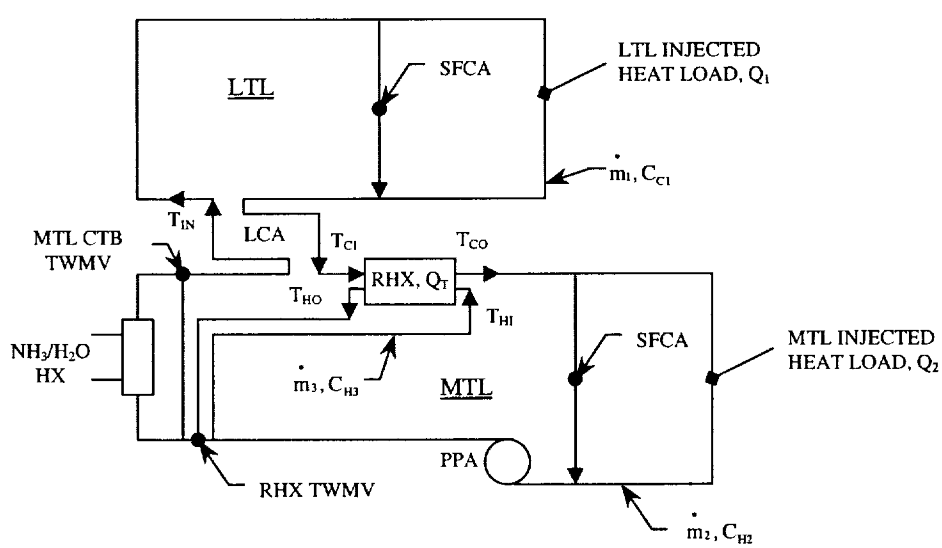

Figure 2. Closed Form Solution Schematic

The Pump Package Assembly (PPA) total flowrate considered in the calculation was 2300 lbm/hr due to single loop mode pump performance degradation from the nominal 3000 lbm/hr. The MTL TWMV temperature setpoint (T_{IN}) was changed from 63.0 °F (MTL nominal) to 50.0 °F, and the RHX TWMV outlet temperature (T_{CO}) was set to 65.0 °F to avoid condensation. The known variables, LTL (Q_1) and MTL (Q_2) injected heat loads and RHX hotside flowrate ($mdot_3$) were varied in the analysis to ascertain the useful working envelope for the system. T_{CO} and T_{IN} were also specified in the analysis. Assumptions made included the following: constant specific heat for the coolant (water), c_p = 1.0 Btu/lbm °F, $C_{MIN} = C_{H3} = mdot_3 c_p$ and $C_{H2} = C_{C1}$ = 2300 Btu/hr °F.

The hotside effectiveness for the Payload/Regenerative Heat Exchanger (P/N 2351340) [2] at a coldside flowrate of 2300 lbm/hr has been expressed linearly as:

(1) $$\mathring{a} \approx \left(\frac{-0.28}{1500}\right)\left(\dot{m}_3 - 1500\right) + 0.93$$

The following relationships [3] are appropriate for the effectiveness - NTU method of heat exchanger analysis:

(2) $$Q_{MAX} = Q_T / \mathring{a}$$

(3) $$T_{CI} = T_{IN} + Q_1 / C_{CI}$$

(4) $$T_{CI} = -Q_{MAX} / C_{MIN} + T_{HI}$$

(5) $$T_{HI} = T_{CO} + Q_2 / C_{H2}$$

(6) $$T_{CO} = T_{CI} + Q_T / C_{CI}$$

(7) $$Q_T = \mathring{a}\,(C_{MIN})(T_{HI} - T_{CI})$$

Combining equations 1 through 7 and solving for $mdot_3$ in terms of Q_1, Q_2, T_{CO} and T_{IN} with assumptions 1 through 3 yields:

$$\dot{m}_3 = \frac{-1347.92\left\{\left[-\left(Q_1 + 5.78\left(Q_2 - 397.81\left(T_{CO} - T_{IN}\right)\right)\right)\right]^{(1/2)} - 2.41\left[\left(Q_1 - Q_2 - 2300\left(T_{CO} - T_{IN}\right)\right)\right]^{(1/2)}\right\}}{\left[\left(Q_1 - Q_2 - 2300\left(T_{CO} - T_{IN}\right)\right)\right]^{(1/2)}}$$

With the aforementioned relationships, a Microsoft Excel spreadsheet was developed to perform trade studies for the system. With the "solver" function, it was possible to determine either flow rates or heat loads necessary for the system to operate successfully. Figure 3 illustrates the graphical interface to the spreadsheet.

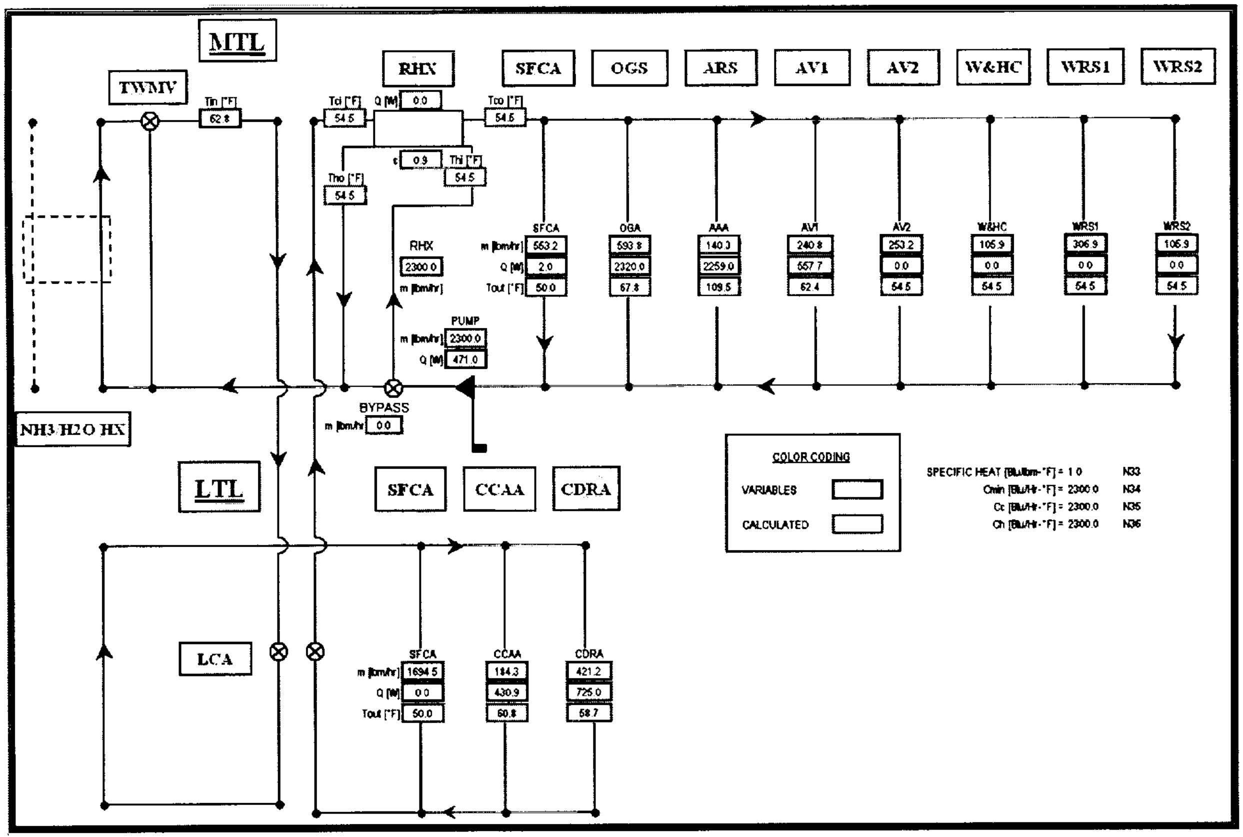

Figure 3. Microsoft Excel Graphical Interface

The flow distribution in the parallel branches of the LTL was determined by the SINDA/FLUINT model. Details of this model are noted in the next section. Results of the closed form analysis illustrate the RHX hotside flowrates corresponding to MTL and LTL injected heat loads required to maintain the RHX coldside exit temperature above the dew point temperature (60.0 °F). The boundary of acceptable performance is also shown, based on a total flowrate of 2300 lbm/hr. Figure 4 shows the closed form solution.

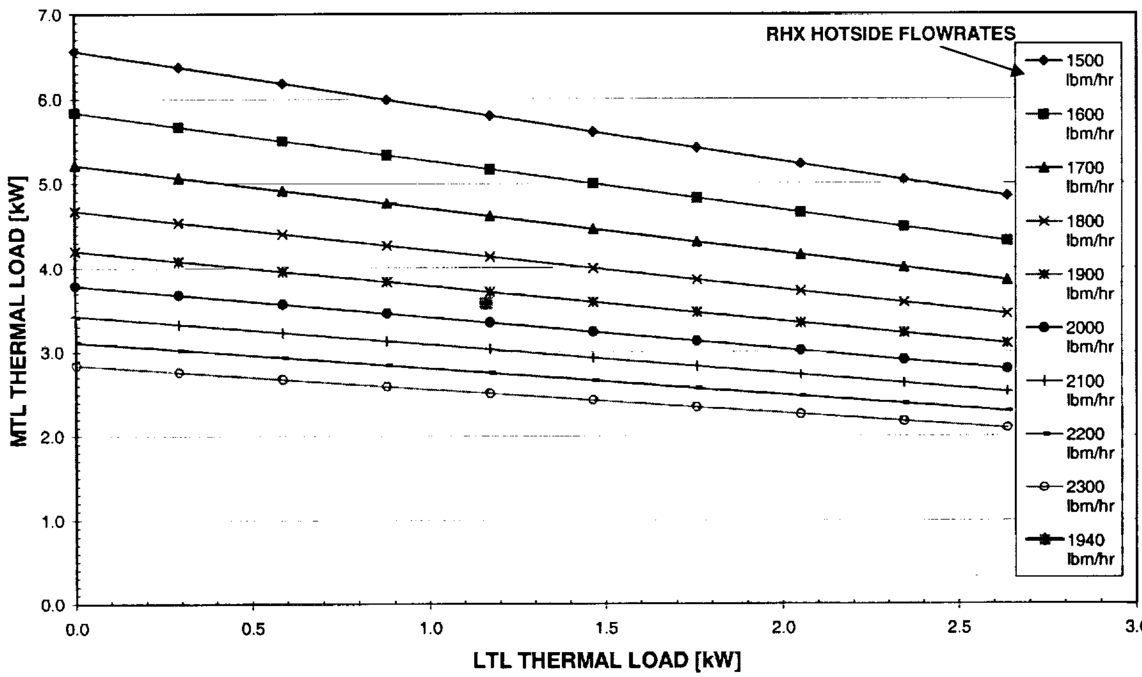

Figure 4. Closed Form Results

SINDA/FLUINT

A simplified SINDA/FLUINT mathematical model, representing the Node 3 single loop configuration (Node 3 core only; no resources provided to Node 1/Airlock or HAB), was developed to determine the RHX performance independent of the closed form solution. Figure 5 schematically illustrates the SINDA/FLUINT model.

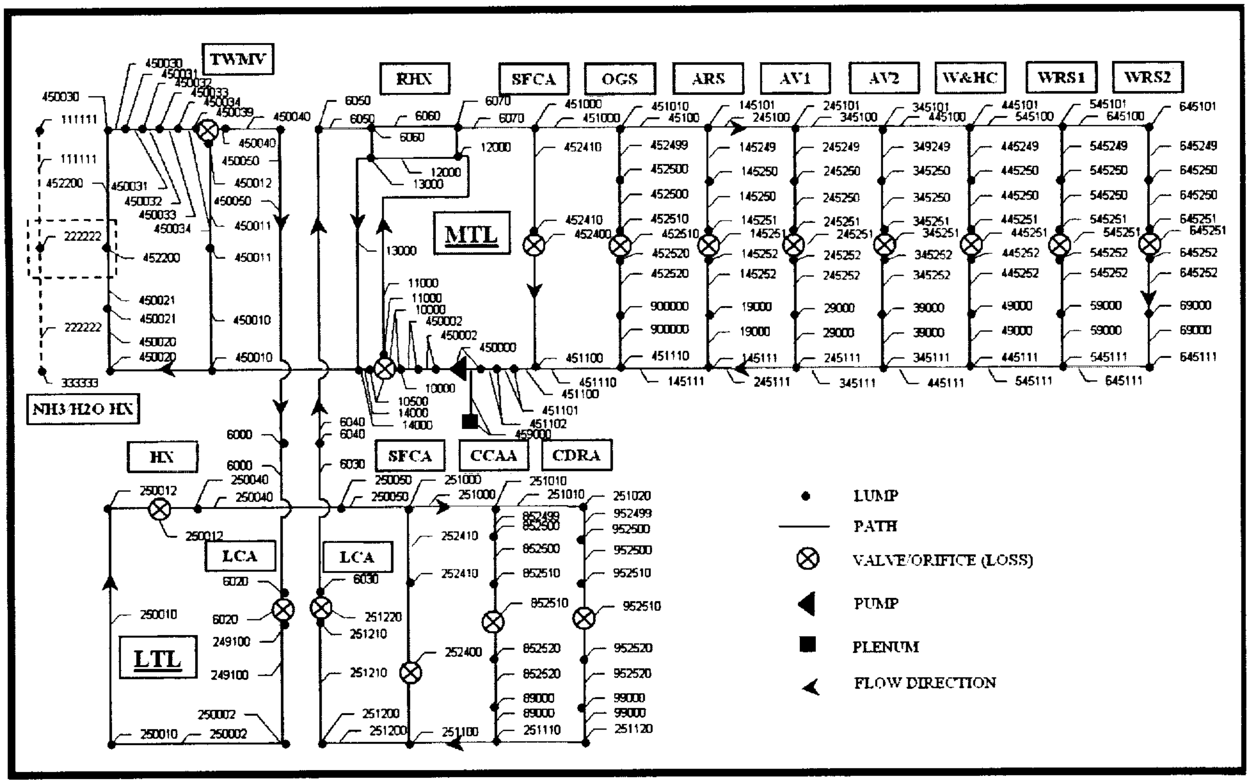

Figure 5. Node 3 IATCS SINDA/FLUINT Schematic

The rack MFCVs will not be manipulated during a failure, and thus, all rack simulated "LOSS" values remained constant based on nominal design flowrates. A failure of EATCS loop B or EPS power domain 2/3 would result in the SFCA remaining in the last commanded position, which was assumed to be nominal. Therefore, the LTL SFCA valve coefficient was set to a constant based on the calculated value for a nominal LTL flowrate and setpoint of 13 psid. The LTL TWMV loss coefficient was set to a constant corresponding to a full bypass condition. It was assumed that in case of the aforementioned failure, the TWMV would be manually set to this position. The MTL PPA was set to a constant flowrate of 2300 lbm/hr based on performance degradation from the nominal 3000 lbm/hr. Setpoints used in the analysis for the MTL TWMV and RHX TWMV were 48 °F and 63 °F respectively. The loop A ammonia inlet temperature was set as 40.0 °F.

When compared, the trends of the SINDA/FLUINT and closed form solution differed only slightly due to the control algorithm software error band, and the differences in TWMV setpoints.

CONCLUSION

These analyses were performed to determine if the condensation preclusion requirement could be satisfied with the IATCS in single loop mode under a "low load" scenario. Currently, the heat loads are not guaranteed accurate or final in the Node 3 design. This ambiguity makes it somewhat difficult to modify the more complex SINDA/FLUINT model. The closed form solution allows for a "quick look" assessment and trade study capability without sacrificing accuracy.

REFERENCES

1. Node 3 DR1, Torino, Italy, July 1999

2. Allied Signal Aerospace Equipment Systems, Doc. No. 97-69186 pg. 3.3.2-4

3. Frank P. Incropera and David P. DeWitt, "Heat and Mass Transfer," Chapter 11, John Wiley & Sons, New York, 1996