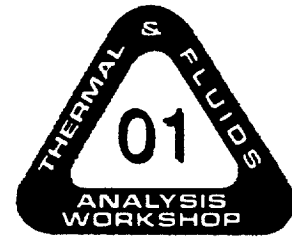


AN ANALYSIS OF AN AUTOMATIC COOLANT BYPASS IN THE INTERNATIONAL SPACE STATION NODE 2 INTERNAL ACTIVE THERMAL CONTROL SYSTEM



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ABSTRACT

A challenging part of International Space Station (ISS) thermal control design is the ability to incorporate design changes into an integrated system without negatively impacting performance. The challenge presents itself in that the typical ISS Internal Active Thermal Control System (IATCS) consists of an integrated hardware/software system that provides active coolant resources to a variety of users. Software algorithms control the IATCS to specific temperatures, flowrates and pressure differentials in order to meet the user-defined requirements. What may seem to be small design changes imposed on the system may in fact result in system instability or the temporary inability to meet user requirements. The purpose of this paper is to provide a brief description of the solution process and analyses used to implement one such design change that required the incorporation of an automatic coolant bypass in the ISS Node 2 element.

INTRODUCTION

The Internal Active Thermal Control System (IATCS) is a critical system that ensures a safe, habitable environment within the pressurized elements of the International Space Station (ISS). The IATCS is an integrated system designed with the purpose to provide heat rejection for subsystem avionics equipment, for the environmental control system and for subsystems and payloads within elements attached to Node 2. A challenging aspect of integrated design, such as the IATCS, is the ability to incorporate design changes into the system without negatively impacting performance. This paper describes an example of one such change and details the decision process which incorporated hardware identification, performance analyses and failure propagation analyses to determine a viable design with minimal cost and minimal system performance impacts.

Prior to the final Node 2 design review, a new requirement was levied on the IATCS to provide the capability to “dry out” the Common Cabin Air Assembly (CCAA) to prevent microbial growth and fouling of the condensing heat exchanger. The “dry out” operation could only be

performed by the interruption of coolant flow through the CCAA. However, the IATCS architecture, at that time, did not allow for interruption of flow through the CCAA due to the need to provide active cooling to critical avionics located downstream of the heat exchanger. Therefore a coolant bypass had to be incorporated into the IATCS in order to provide continuous cooling for the avionics equipment and to perform CCAA “dry-out” operation simultaneously. The technical challenge associated with this design change was that the bypass would have to hydraulically mirror the CCAA in order to minimize potential adverse effects on system flowrate that is actively controlled by the System Flow Control Assembly (SFCA).

NODE 2 IATCS ARCHITECTURE

The Node 2 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 2. 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 2 IATCS is schematically shown in Figure 1.

Each loop is designed in an integrated manner such that software algorithms are used to command and modulate various components to control the IATCS to specific temperatures, flowrates and pressure to meet specified requirements. Items that provide pressure control include a Pump Package Assembly (PPA) capable of providing a mass flowrate of 3000 lbm/hr and a System Flow Control Assembly (SFCA) that maintains a constant differential pressure across the system. Thermal control components include an ammonia/water heat exchanger, a Three-Way Mix Valve (TWMV) that controls the coolant supply temperature to subsystems and attached elements, a regenerative heat exchanger (LTL only) and a CCAA. The CCAA includes a condensing heat exchanger (CHX) for cabin air temperature and humidity control (LTL only). The Node 2 IATCS also provides cooling resources to attached ISS pressurized payload/experiment modules. The Multi-Purpose Logistics Module (MPLM) requires a maximum LTL flowrate of 500 lbm/hr while the Centrifuge Accommodations Module (CAM) requires a maximum LTL coolant flow of 1421 lbm/hr and an MTL coolant flow of 1789 lbm/hr.

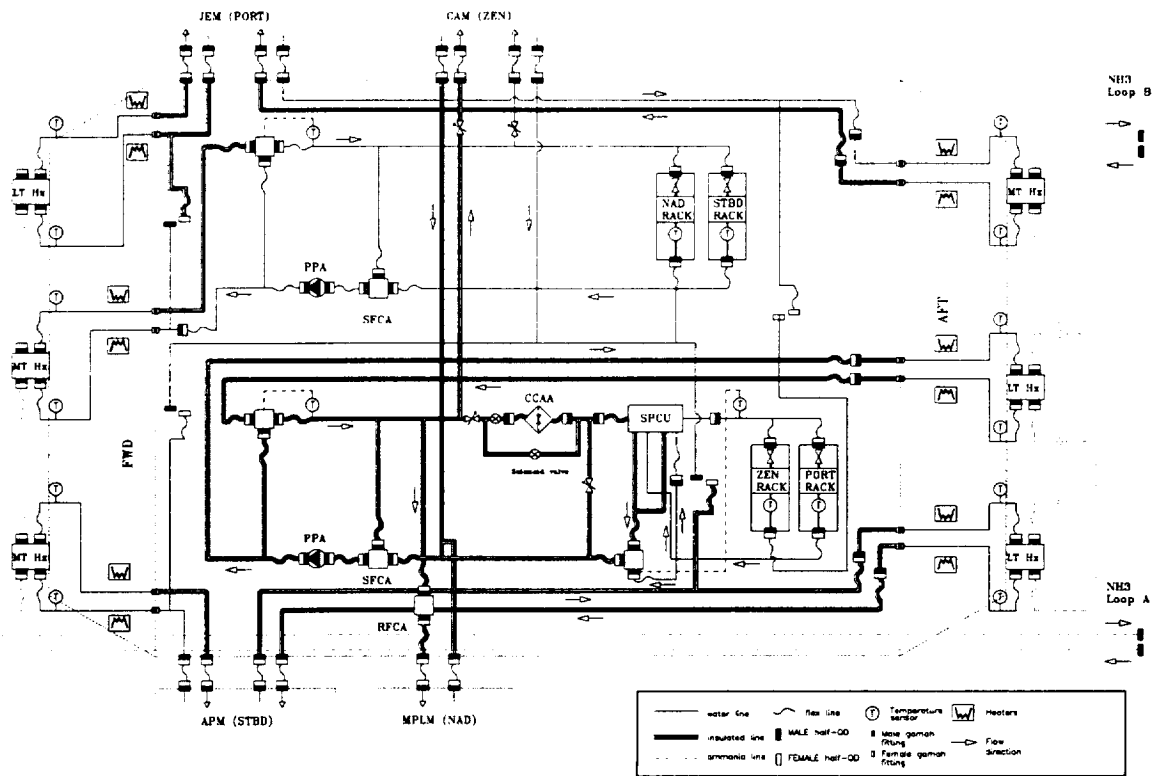


Figure 1. Node 2 IATCS

NODE 2 CCAA BYPASS DESIGN OPTIONS

Three design options were identified as potential viable candidates to implement the CCAA/CHX bypass. These options included either the use of two Manual Flow Control Valves (MFCV), a single TWMV, or two electro-magnetic solenoid valves in which to effectively divert LTL coolant around the CCAA/CHX and through the bypass. All options were considered without bias until the evaluation regarding technical feasibility, cost and human factors could be completed. A similar feature to all options was the inclusion of an orifice located in the bypass, adequately sized to simulate the pressure drop of the CCAA/CHX. This was required to maintain system pressures and flowrates identical to the nominal IATCS operation that was based on the CCAA/CHX hydraulic characteristics.

OPTION 1 BYPASS WITH MANUAL FLOW CONTROL VALVE (MFCV)

Option 1 incorporated a MFCV to be used in conjunction with the existing MFCV located at the CCAA inlet. The existing valve is pre-set based on the SPCA pressure differential set point in order to maintain the CCAA/CHX design flowrate of 600 lbm/hr. Option 1 is schematically shown in Figure 2 and the physical layout is depicted in Figure 3. This option required crew

intervention in manually tilting the port avionics rack in such a manner to allow accessibility to the CCAA. The operational sequence was to manually open the bypass MFCV and then close the CCAA MFCV. The crew would have to perform the reverse procedure including re-stowing the rack after completion of the dry-out procedure. The inlet MFCV would have to be re-set to the previous position in order to have the proper flowrate through the CCAA/CHX. The advantages of implementing Option 1 were:

- no software impact
- no additional manufacturing or integration of electrical cabling/harnesses required
- minimal hardware costs

The disadvantages associated with this option were:

- rack tilting operation
- crew intensive
- concern with repeatability of MFCV settings after return to CCAA flow

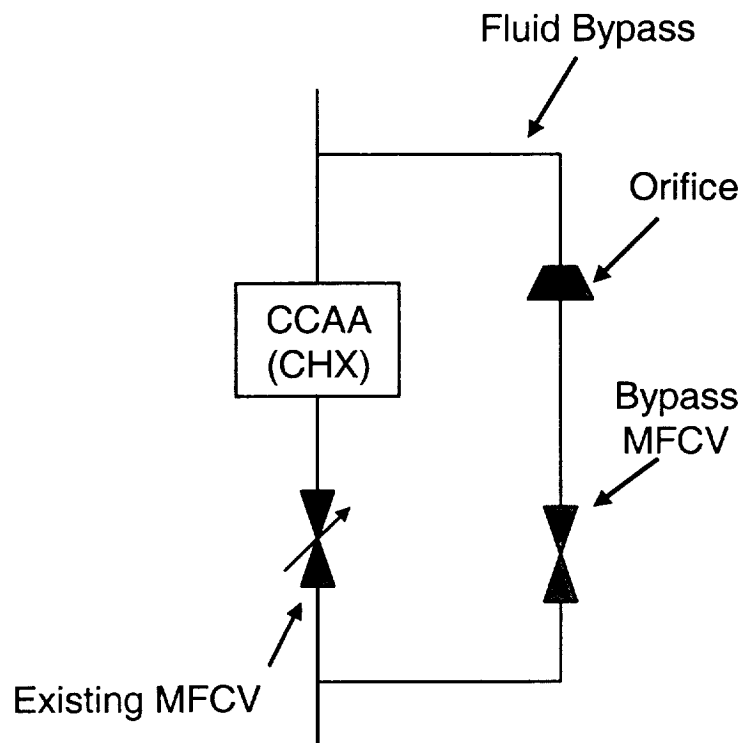


Figure 2. Option 1 Manual Flow Control Valve Bypass - Schematic

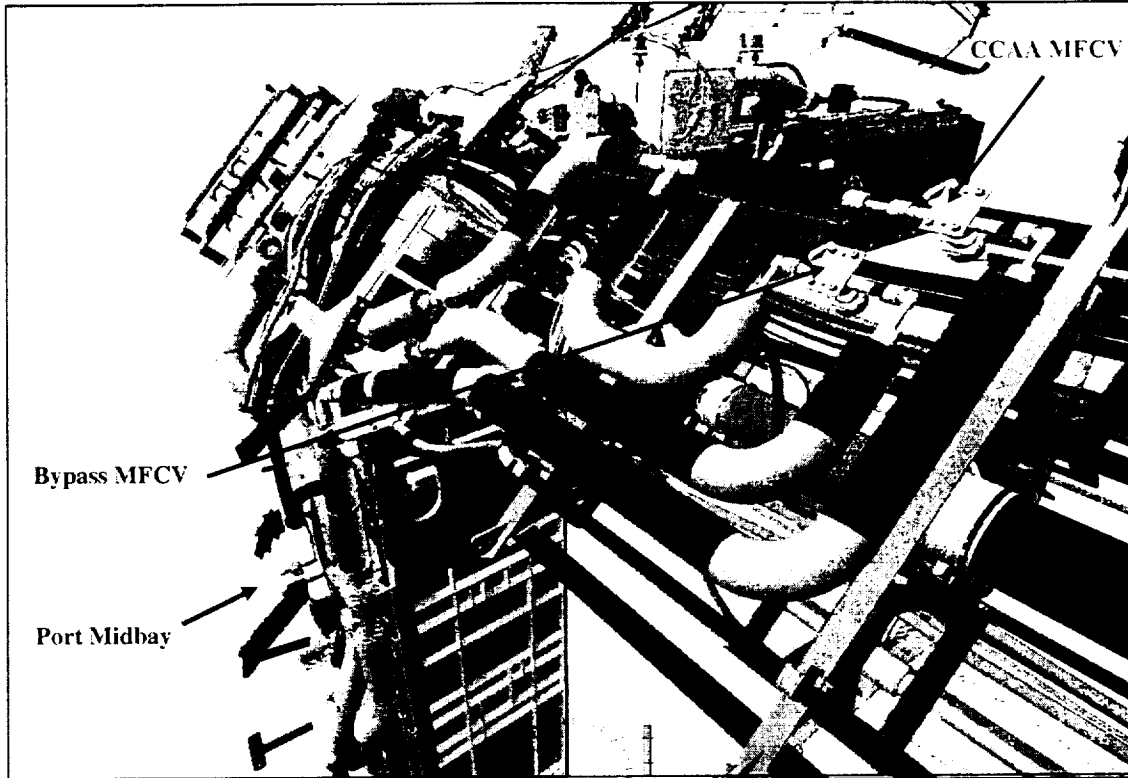


Figure 3. Option 1 Manual Flow Control Valve Bypass – Physical Layout

OPTION 2 BYPASS WITH THREE-WAY MIX VALVE (TWMV)

Option 2 implemented the use of a TWMV to divert the flow through the bypass. This option is schematically shown in Figure 4 and the physical layout is depicted in Figure 5. The typical use of a TWMV is to provide a controlled outlet temperature from two inlet streams via control of a modulating valve with temperature sensor feedback. The TWMV is powered from a 120 VDC power channel and valve modulation is commanded over a voltage of ± 5 VDC. The 120 VDC power channel is consistent with channelization from the Node 2 Remote Power Control Module (RPCM) and the command voltage requires power from the Multiplexer Demultiplexer Module (MDM), which must have appropriate software to provide voltage commanding. The TWMV has a manual override in case of power failure.

Option 2 would require the TWMV to be integrated in the reverse configuration allowing for one inlet port and two outlet ports. This option became known as the “Cadillac” option since the TWMV is a dynamically controlled modulating valve but for use as a bypass valve, would simply be commanded from one port to the other via a constant voltage. The proposed operational sequence was simply to divert flow through the bypass via ground commanding of the TWMV.

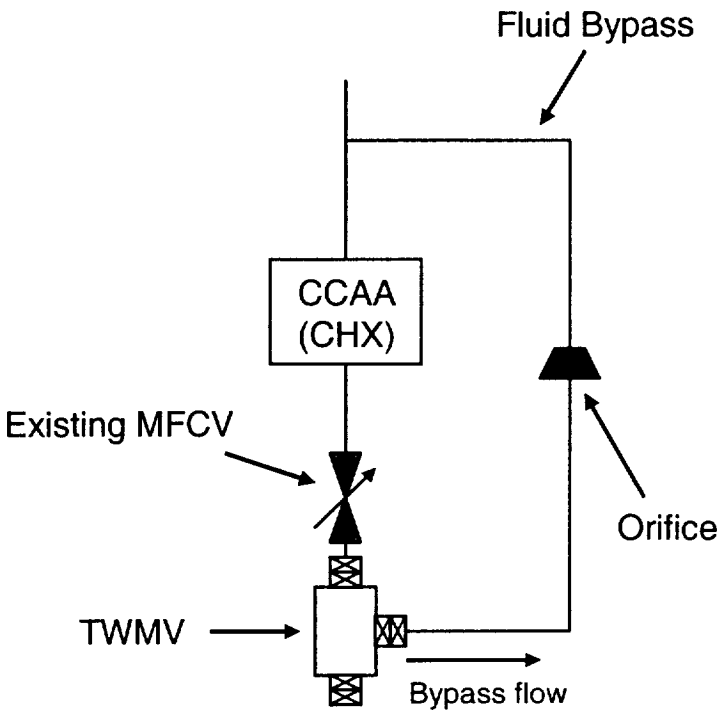


Figure 4. Option 2 Three Way Mix Valve Bypass - Schematic

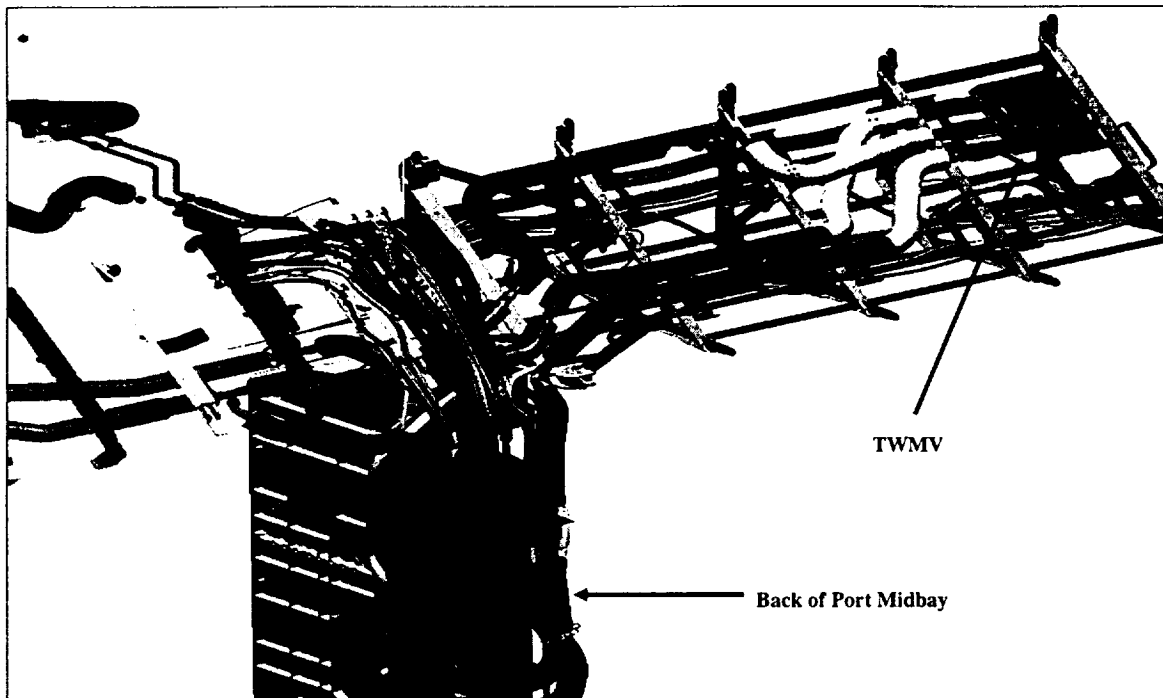


Figure 5. Option 2 Three Way Mix Valve Bypass – Physical Layout

The advantages of implementing Option 2 were:

- minimal impact to ITCS performance during bypass operations
- minimal crew activity required - bypass could be commanded from the ground

The disadvantages associated with this option were:

- software modification required (associated cost)
- additional manufacturing and integration of electrical cabling/harnesses required
- potential hardware cost for procurement of the TWMV (spares dependent)

OPTION 3 BYPASS WITH SOLENOID VALVE

Option 3 is similar to the MFCV option (Option 1), however considers the use of two solenoid valves. This option is schematically shown in Figure 6. The advantages gained here as opposed to Option 1 is the ability to command the solenoid valves remotely, eliminating the need for crew intervention. One major obstacle encountered during the initial search for commercial flight qualified solenoid valves was the fact that most were rated for operation with a voltage less than 120 VDC. This limitation would require a power channel routed from the MDM resulting in a software modification. The search ultimately yielded available flight qualified solenoid valves that were in inventory from a previously cancelled microgravity experiment facility. Two

advantages associated with these valves were that they were rated for 120 VDC, thus allowing for a direct power feed from the RPCM (lessening any software modification impacts), and that there were no procurement costs. However, the valves did not have a manual override, but did have an electronic position indicator which would require channelization to the MDM. The position indicator could be used in lieu of a manual override to detect a failure and alert the crew to take appropriate corrective action. The advantages associated with this option were:

- minor software impact
- no hardware costs
- minimal crew activity required - bypass could be commanded from ground

The disadvantages associated with this option were:

- additional manufacturing and integration of electrical cabling/harnesses required
- concern with lack of a manual override - crew intensive operation would be required to correct failure

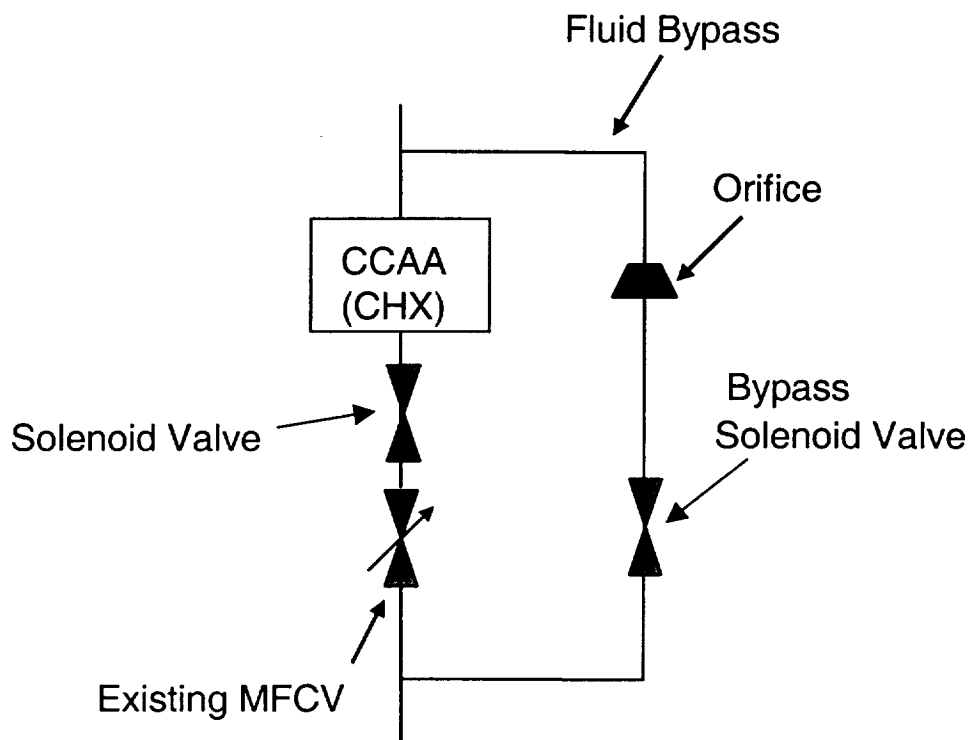


Figure 6. Option 3 Solenoid Valve Bypass - Schematic

NODE 2 CCAA BYPASS ANALYTICAL ASSESSMENT

Analytical assessments were performed for the proposed bypass design options to ascertain which of the proposed design options provided greater technical and performance benefits. The MFCV design option was not included in this paper, but investigations showed similar performance to the solenoid valves, assuming perfect repeatability of the MCFV valve. System performance impacts were not considered for the attached MPLM to Node 2 configuration since the MPLM is a transport/logistics module and nominally will not be attached to the ISS.

The hydraulic performance analyses of the Node 2 LTL were based on the Node 2 Design Review 1 (DR1) SINDA85/FLUINT IATCS Thermal Hydraulic Mathematical Model (THMM) originally developed by Alenia Aerospazio. The mathematical fluid network was constructed by "lumps" and "paths" to solve mass storage and mass transport equations.

Major losses, those losses associated with skin friction over the length of a tube, were determined by solving the equation:

$$\Delta P = f * (L/D) * [(FR/AF)**2 / (2.0 * g_c * \rho)]$$

where,

ΔP pressure difference
f..... friction factor
L..... tube length
D..... tube hydraulic diameter
FR.... mass flowrate
 g_cgravitational constant
 ρfluid density

Minor losses, those losses associated with fittings, valves, etc. were determined by solving the equation:

$$\Delta P = FK * (FR/AF)**2 / (2.0 * g_c * \rho)$$

where,

ΔP pressure difference
FK.... loss coefficient
FR.... mass flowrate
 g_cgravitational constant
 ρfluid density

Resistances of the TWMV and SFCA were simulated through the use of user-developed subroutines that vary FK to meet desired temperature and pressure drop setpoints. FK values for

the MFCV were predetermined to equate to the SFCA pressure drop setpoint for the given design flowrate.

The head rise across the centrifugal pump was modeled using the "VPUMP" option. The pressure rise across the pump is determined from the equation:

$$\Delta P = (\text{SPD}/\text{RSPD})^2 * c * \rho * (1.0 - \text{DEG}(\alpha)) * H(G * \text{SPD}/\text{RSPD})$$

where,

ΔP pressure difference

SPD.... current shaft speed

RSPD.. reference shaft speed

c conversion constant (internal to SINDA/FLIUNT)

ρ fluid density

DEG ... two-phase degradation factor as a function of void fraction α

H(G) ... head as a function of volumetric flowrate (user supplied data)

Additional parameters and logic were added to the THMM in order to model the CCAA bypass transition and hydraulic effects. The additional bypass network also contained "lumps" and "paths" with estimated volumes to simulate transient flow effects. The system, while in nominal configuration (flow through the CCAA), was allowed to achieve a steady state condition prior to the bypass transition being initiated.

The hydraulic characteristics of the TWMV were modeled using a linear valve position function based on a port-to-port travel time of 15 seconds. The two TWMV ports are configured such that the valve positions equate to 90 degrees. Therefore, a 90 degree valve position is full open for one port with the corresponding port fully closed at a 0 degree valve position. The angular position as a function of valve travel time as used in the model is shown in Figure 7. For the solenoid valve, the actual loss coefficient for the solenoid valve was not known and a minimal loss was assumed due to the fact that a low resistance in the bypass would provide a "worst case" scenario for the system flow disturbance. An actuation time of 10 seconds was assumed for the solenoid valve bypass configuration.

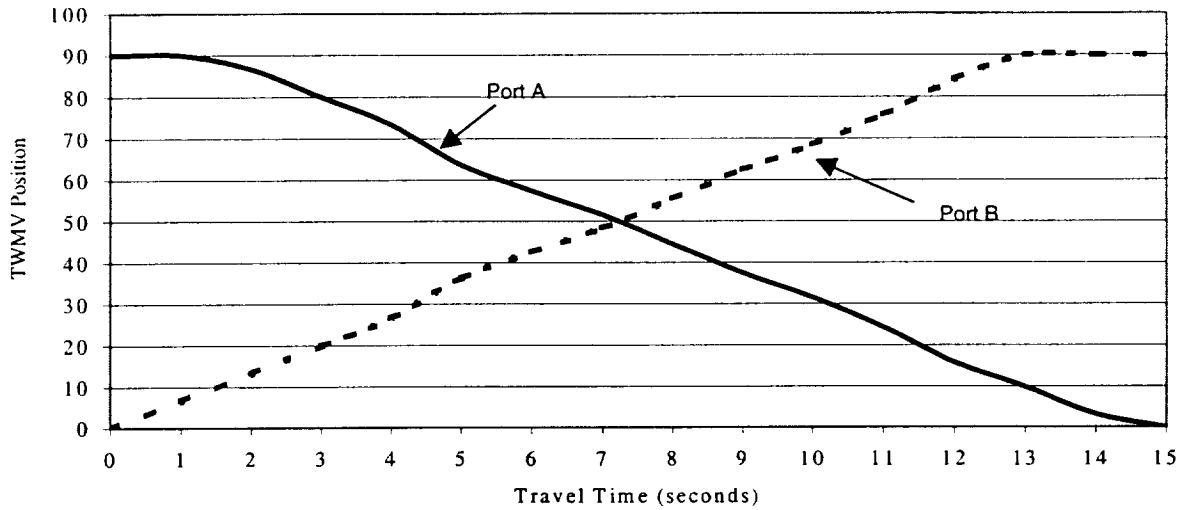


Figure 7. TWMV Port Position

Critical performance parameters were assessed for scenarios considering SFCA with closed-loop software control enabled and inhibited. Parameters considered in the assessment are as follows:

- SFCA Differential Pressure
- SFCA Minimum Flowrate
- CCAA Flowrate
- CAM Flowrate

Analytical results were assessed based on design requirements listed in Table 1.

Table 1. Design Requirements

Item	Requirement
SFCA Differential Pressure	13.0 psid \pm 0.375 psid
SFCA Minimum Flowrate	100 lbm/hr
CCAA Flowrate	600 lbm/hr
CAM Flowrate	1421 lbm/hr

CCAA Bypass Hydraulic Analysis with SFCA Closed Loop Control Enabled

Bypass operations considering the TWMV and solenoid valves were analyzed in conjunction with closed loop control of the SFCA enabled. Results are presented in Figures 8 – 11. As expected, the TWMV option provided a smoother transition from nominal to bypass flow. This transition is directly related to the linear “port-to-port” actuation. During the transition process, the TWMV operation showed stable pressure effects for the SFCA as well as meeting the minimum flowrate requirement. Similarly, the TWMV bypass configuration showed CCAA and CAM supply flowrate transients closer to design set points. The solenoid valve option showed greater SFCA pressure fluctuations and predicted a flowrate lower than the minimum constraint. Either of these two parameters could result in SFCA control instability during actual operations. Results for both the TWMV and solenoid valve bypass operations showed agreement for all parameters after establishing full bypass flow.

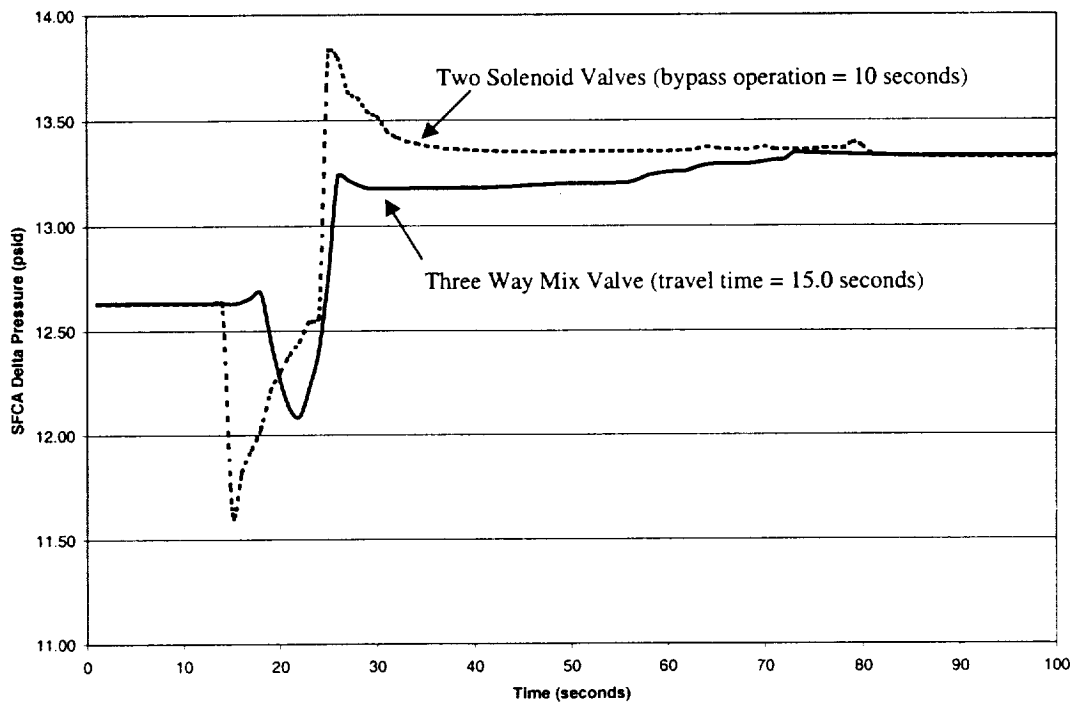


Figure 8. CCAA Bypass Operation (SFCA Enabled): SFCA Pressure Differential

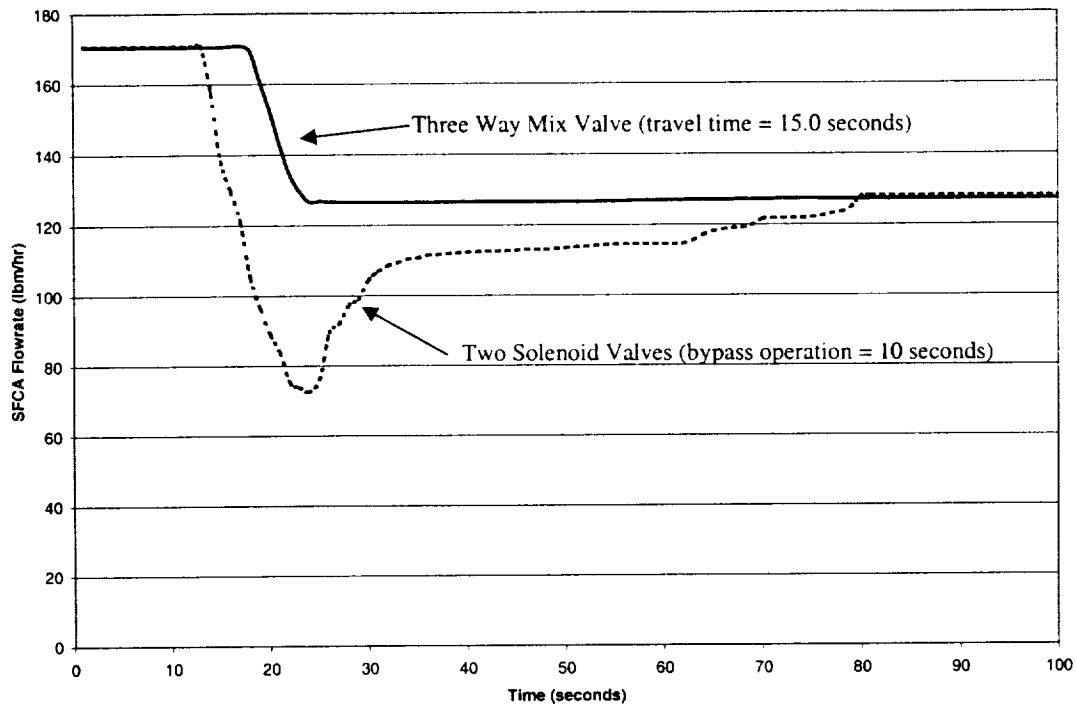


Figure 9. CCAA Bypass Operation (SFCA Enabled): SFCA Flowrate

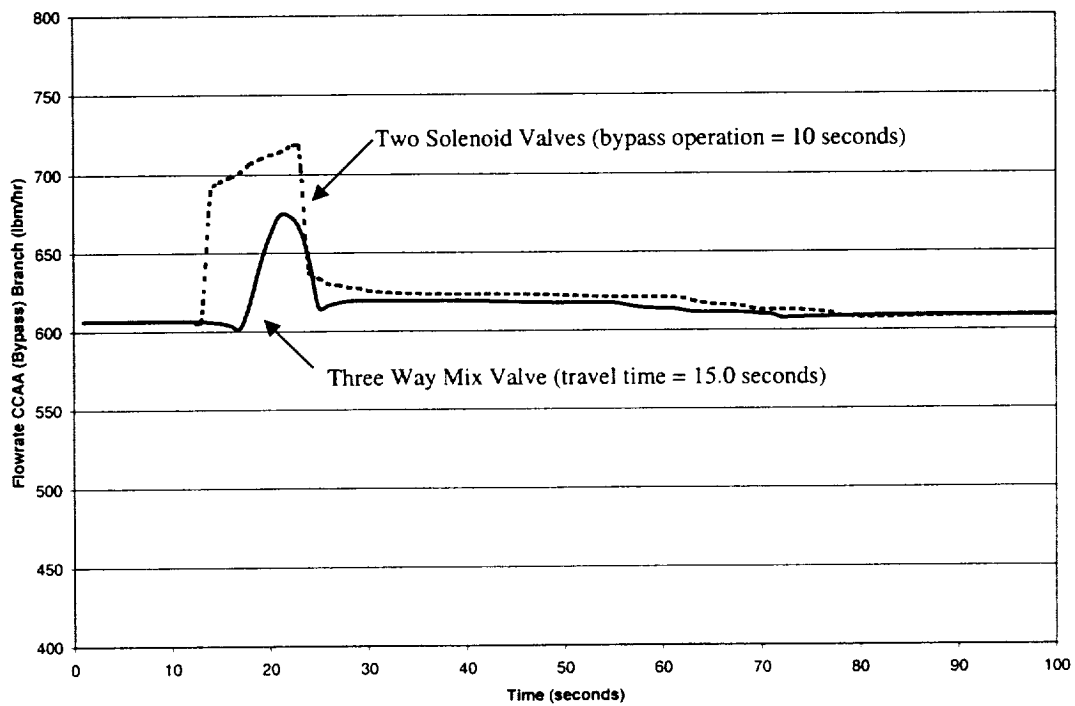


Figure 10. CCAA Bypass Operation (SFCA Enabled): CCAA Flowrate

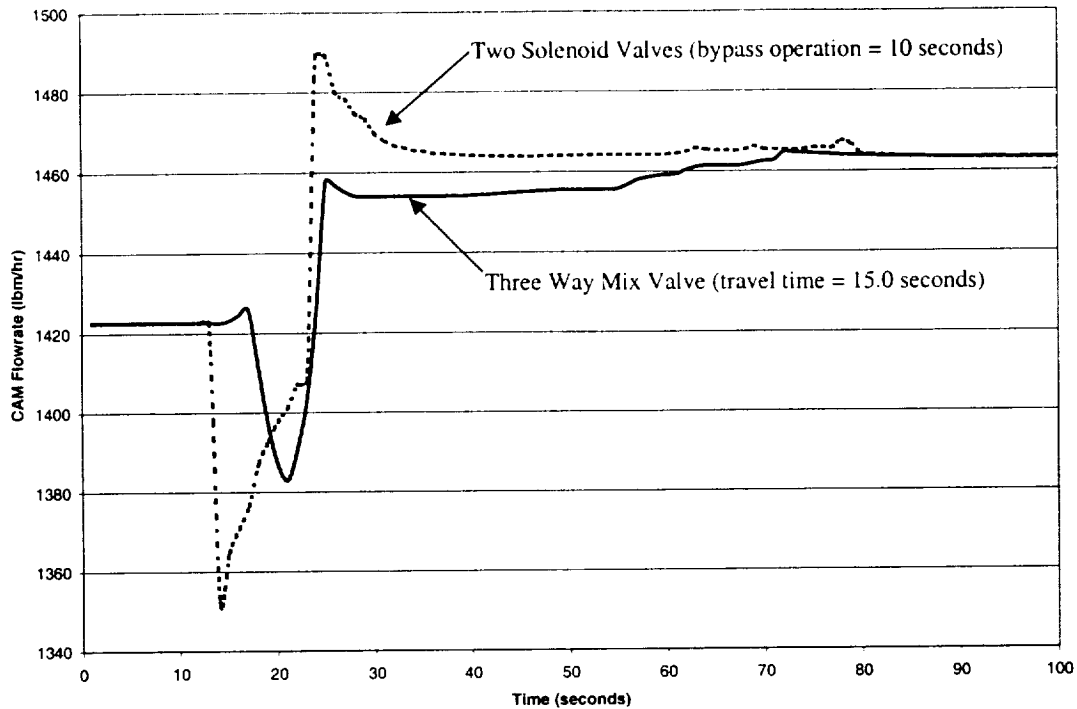


Figure 11. CCAA Bypass Operation (SFCA Enabled): CAM Flowrate

CCAA Bypass Hydraulic Analysis with SFCA Closed Loop Control Inhibited

Bypass operations considering the TWMV and solenoid valves were analyzed in conjunction with closed loop control of the SFCA inhibited. The SFCA closed loop control is enabled once the transition is complete. Results are presented in Figures 12 – 15. The analysis showed similar agreement between the TWMV and solenoid bypass options. The primary difference was the predicted trends during the flow transition. The TWMV exhibited the linear trend, as seen for the previous analysis with closed loop control of the SFCA enabled, while the solenoid valve indicated a step function behavior. Results for both options during the transition phase are considered within appropriate design limits. The system shows hydraulic stability once the bypass operation is complete and closed loop control of the SFCA is enabled.

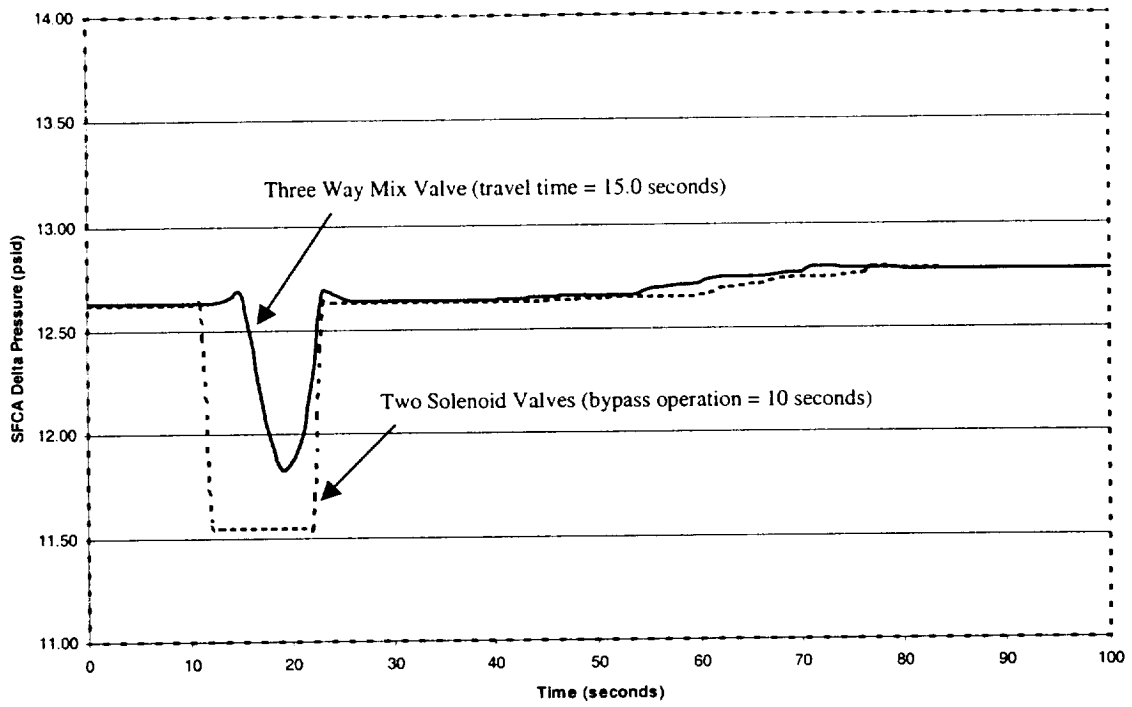


Figure 12. CCAA Bypass Operation (SFCA Inhibited): SFCA Pressure Differential

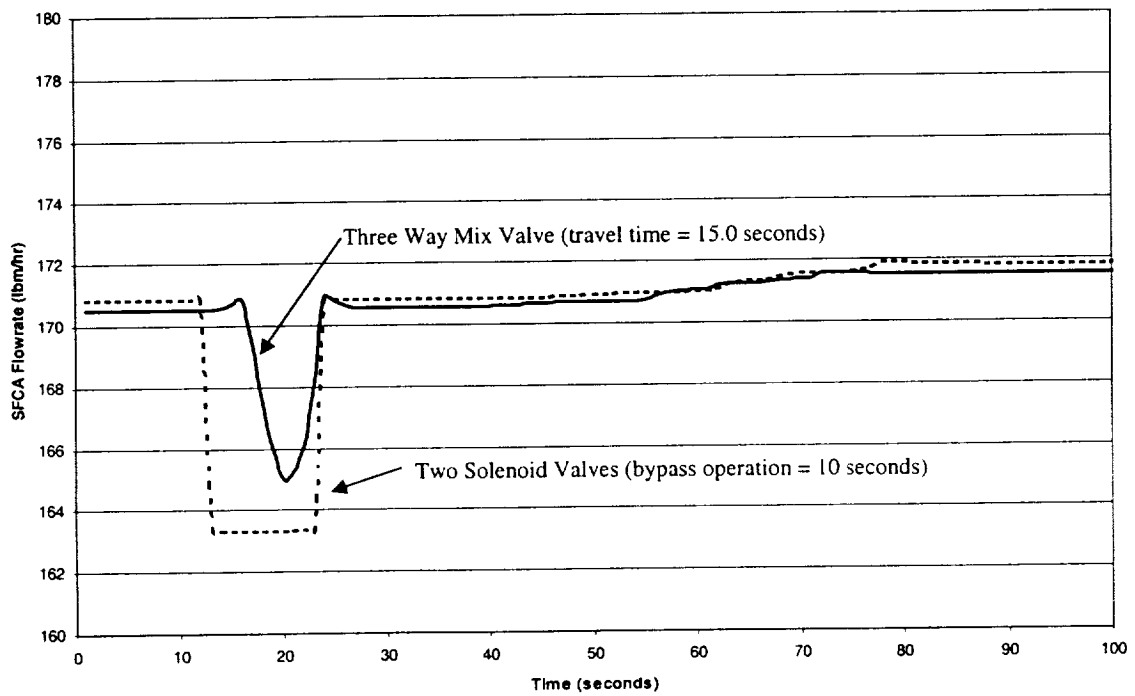


Figure 13. CCAA Bypass Operation (SFCA Inhibited): SFCA Flowrate

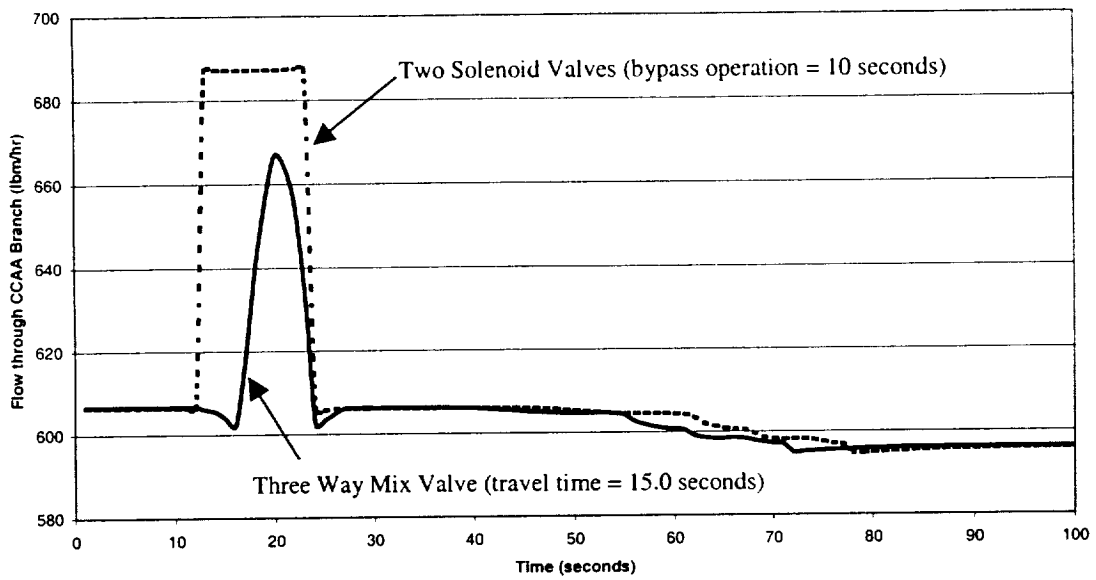


Figure 14. CCAA Bypass Operation (SFCA Inhibited): CCAA Flowrate

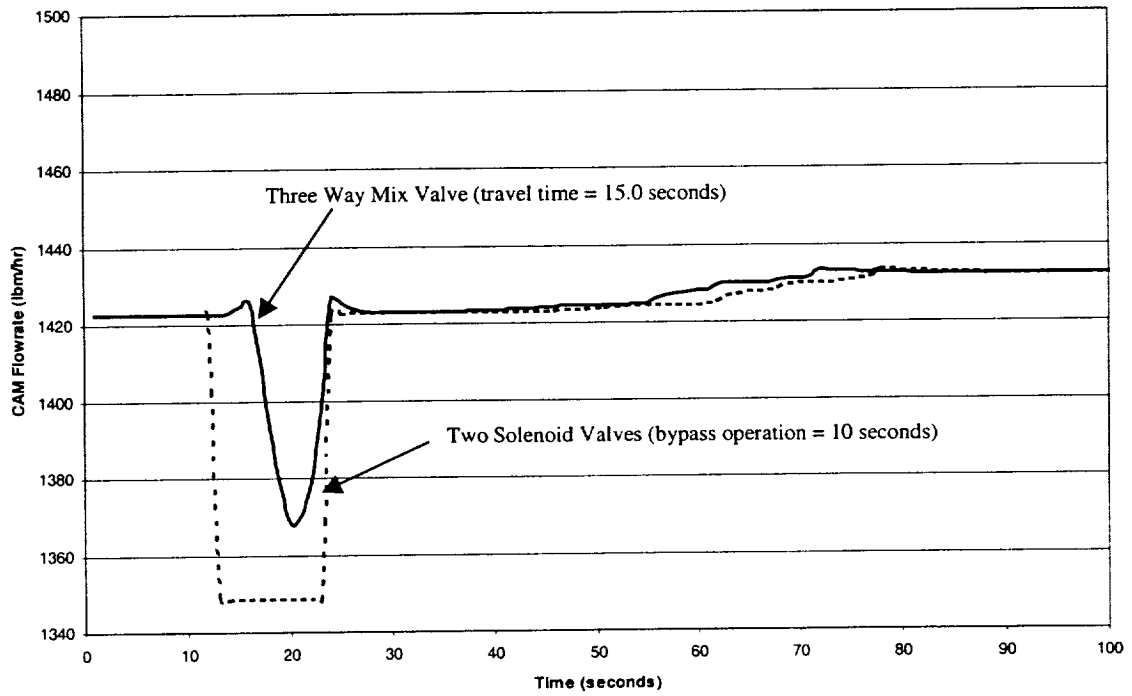


Figure 15. CCAA Bypass Operation (SFCA Inhibited): CAM Flowrate

Waterhammer Effects Due to Solenoid Valve Actuation

Waterhammer effects were analyzed using the SINDA85/FLUINT THMM. The FLUINT subroutine "COMPLQ" was used to set the compliance of all liquid filled "tanks" in the model to the compressibility of the working fluid. Additional compliance due to flex hoses was not considered for this analysis. The liquid compliance factor was modeled based on the compressibility:

$$\text{COMP} = \frac{1}{F\rho a^2}$$

where,

F ...unit conversion factor: 1.0 SI units, 1.665E-11 for standard English units

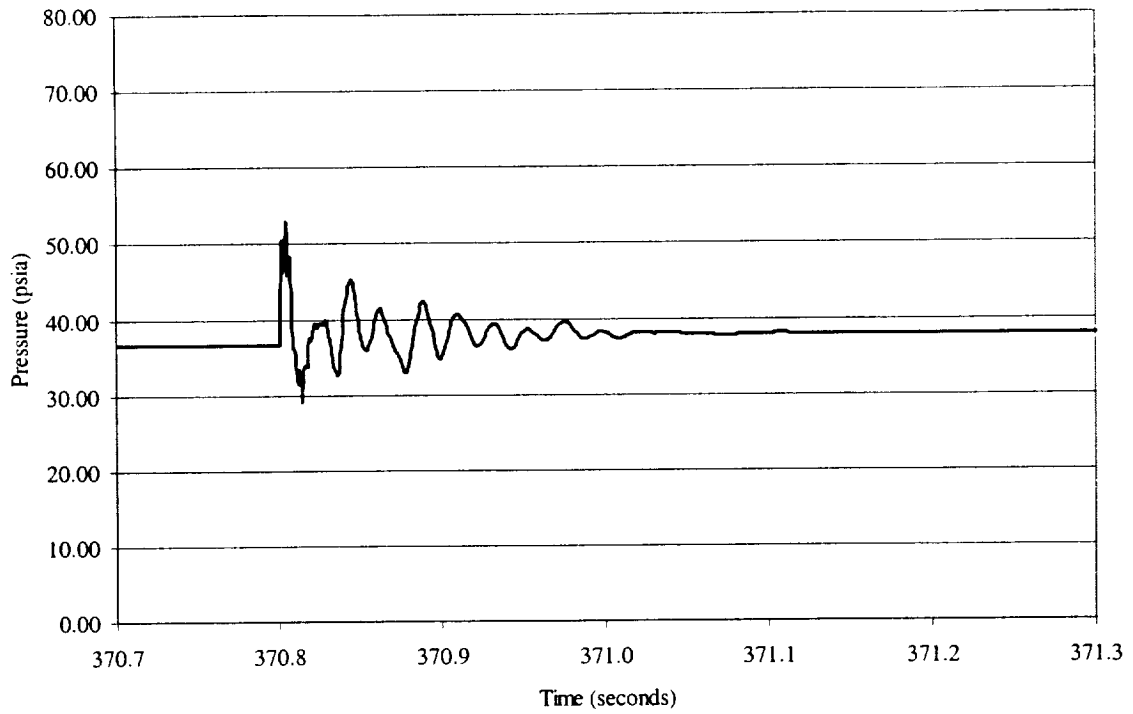
ρ ... liquid density

a ... speed of sound in liquid

The speed of sound in liquid was calculated by the use of the FLUINT property routine "VSOSF" based on the absolute pressure and temperature at the point of interest.

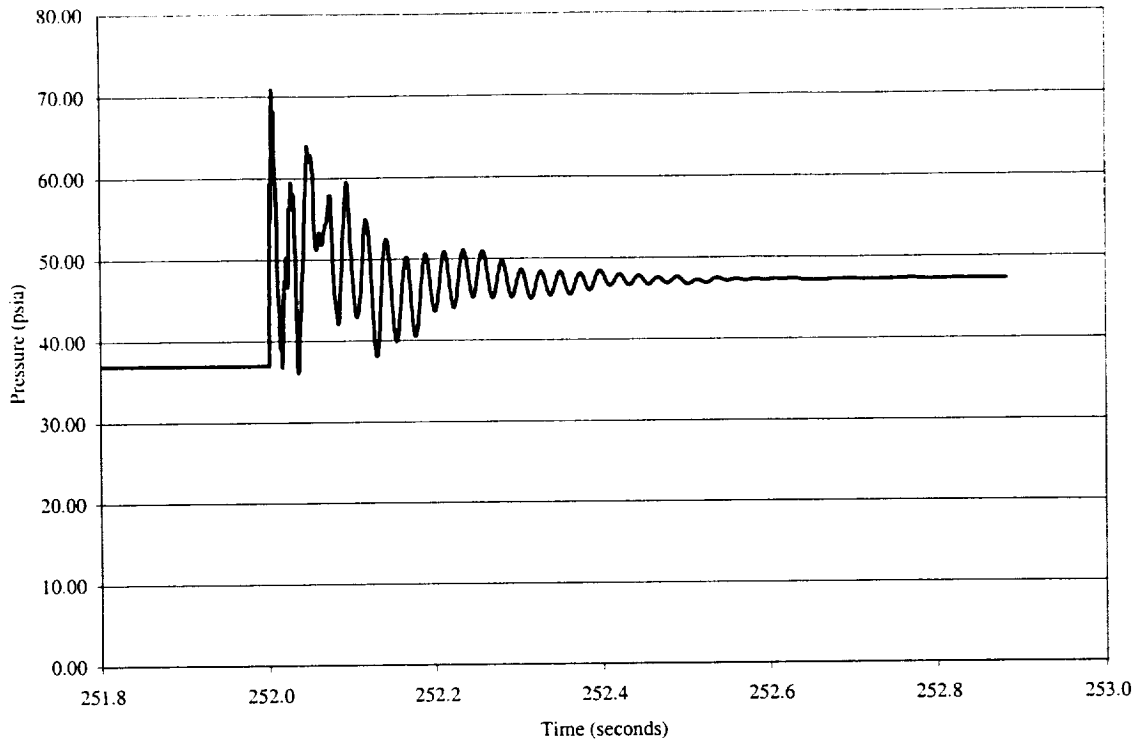
Two analyses were performed to examine waterhammer effects and pressure transients for the solenoid valve bypass option. The first analysis was performed to determine pressure effects due to the solenoid actuation speed under nominal conditions. The scenario involved the normal planned operation in which the bypass valve would be opened prior to closure of the CCAA inlet solenoid valve. The second analysis considered an operation failure in which the CCAA solenoid was commanded closed while the bypass solenoid valve also remained in the closed position. The solenoid actuation time in both analyses was conservatively assumed to be instantaneous at the simulated time of event. Pressure results were compared to the Node 2 IATCS system maximum design pressure of 100 psia. The TWMV was not included in the waterhammer analyses because previous testing had shown that the valve travel time of 15 seconds was sufficient to preclude waterhammer effects. Results for nominal operation is shown in Figure 16 and results for dual closure is shown in Figure 17.

Results show that that waterhammer effects are negligible for the nominal solenoid closure operation (CCAA solenoid closed while bypass solenoid valve open). The maximum pressure transient caused by the actuation of the CCAA solenoid is 53 psia. The pressure fluctuations quickly dampen to a steady state condition. Likewise, results that consider an operation failure in which both valves are closed are also considered acceptable. Pressure transients are greater in magnitude (maximum of 71 psia) when compared to the latter case, but well below the maximum design pressure.



[note: time axis indicates total simulation time with event start at 370.8 seconds]

Figure 16. CCAA Bypass Operation: Waterhammer Due to Solenoid Valve Nominal Operations



[note: time axis indicates total simulation time with event start at 252.0 seconds]

Figure 17. CCAA Bypass Operation: Waterhammer Due to Solenoid Valve Failure

CONCLUSION

In order to determine the optimum bypass option, a weighting factor between 1 and 5 was subjectively assigned to key factors based on the study results. The value of 1 denotes a poor rating, 3 is moderate and 5 represents an excellent rating. The results of this assessment are presented in Tables 2 and 3.

Table 3. Bypass Option Summary – SFCA Closed Loop Control Enabled

CCAA Bypass Option	System Performance	Crew Intervention	Cost	Avg.
Option 1: MFCV	1	1	4	2.0
Option 2: TWMV	5	5	1	3.7
Option 3: Solenoid	2	5	5	4.0

Table 4. Bypass Option Summary – SFCA Closed Loop Control Inhibited

CCAA Bypass Option	System Performance	Crew Intervention	Cost	Avg.
Option 1: MFCV	3	1	4	2.7
Option 2: TWMV	5	5	1	3.7
Option 3: Solenoid	4	5	5	4.7

Based on these results, the bypass option with solenoid valves is shown to be the most viable candidate, and in fact, was the choice for implementation into the Node 2 IATCS LTL architecture. The choice of the solenoid valves as opposed to the TWMV had an estimated cost delta considering hardware procurement and software modifications in the range of \$500,000 to \$1,000,000 and minimal performance impacts.

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NOMENCLATURE, ACRONYMS, ABBREVIATIONS

ΔP pressure differential
f..... friction factor
L..... tube length
D..... tube hydraulic diameter
FR..... mass flowrate
 g_cgravitational constant
 ρfluid density
FK..... loss coefficient
SPD.... current shaft speed
RSPD... reference shaft speed
c conversion constant (internal to SINDA/FLUINT)
DEG ... two-phase degradation factor as a function of void fraction α
H(G) ... head as a function of volumetric flowrate (user supplied data)
Funit conversion factor: 1.0 SI units, 1.665E-11 for standard English units
a speed of sound in liquid

ATCS	Active Thermal Control System
CAM	Centrifuge Accommodations Module
CCAA	Common Cabin Air Assembly
CHX	Condensing Heat Exchanger
DR1	Design Review 1
FLUINT	Fluid Integrator
IATCS	Internal Active Thermal Control System
ISS	International Space Station
LTL	Low Temperature Loop
MDM	Multiplexer Demultiplexer
MFCV	Manual Flow Control Valve
MPLM	Multi-Purpose Logistics Module
MTL	Moderate Temperature Loop
PPA	Pump Package Assembly
RPCM	Rack Power Control Module
SFCA	System Flow Control Assembly
SINDA	Systems Improved Numerical Differencing Analyzer
TCS	Thermal Control System
THMM	Thermal Hydraulic Mathematical Model
TWMV	Three-Way Mix Valve