COLUMBUS IFHX Isolation FDIR – Development and Implementation

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In 2015, Close Call investigation due to potential freezeing of Columbus Moderate Temperature Interface Heat Exchanger lead to the decision of the NASA VCB, held in Oct. 2015, which approved the pursuit related to the general concept to automatically close the Columbus IFHX WOOVs as part of the NASA APM IFHX Leak Response (Ref. NASA VCB presentation: "ITCS Isolation for IFHX Rupture Response"). This paper is describing the development, verification and integration of the European support to the implementation of such an integrated automatic reaction (FDIR). It has been developed via analytically defined sequence operation of the WOOV MkI and MkII at the Columbus IFHX interfaces to contain ammonia entering the Columbus ITCS water loop and to prevent the spread of ammonia and contamination of the Columbus cabin atmosphere in the event of an Interface Heat Exchanger (IFHX) rupture.

The following paper provides an overview of the analytical definition, the performed hardware recertification as well as the integration and implementation of the "new" Columbus IFHX Isolation FDIR into the ISS overall ammonia leak protection scenario.

Nomenclature

ADP = Acceptance Data Package
APM = Attached Pressurized Module (Columbus)
BPV = By Pass Valve
BSM = Berthed Survival Mode
CHX = Condensing Heat Exchanger
EATCS = External Active Thermal Control System
EM = Engineering Model
FDIR = Failure Detection, Isolation and Recovery
HX = Heat Exchanger
IATCS = Internal Active Thermal Control System
IFHX = Interface Heat Exchanger
IMV = Inter-Module Ventilation
ISS = International Space Station
IV = Isolation Valve

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LT = Low Temperature
LTL = Low Temperature Loop
MDM = Mission Data Management
MDP = Maximum Design Pressure
MkI & II = Mark I and II
MOP = Maximum Operating Pressure
MT = Moderate Temperature
MTL = Moderate Temperature Loop
MRB = Material Review Board
PDU = Power Distribution Unit (Columbus)
SPR = Software Problem Report
THMM = Thermal Hydraulic Mathematical Model
VCB = Vehicle Conntrol Board
WMV = Water Modulating Valve
WOOV = Water On Off Valve
WPA = Water Pump Assembly

I. Introduction

In the frame of the Columbus Moderate Temperature Loop Interface Heat Exchanger (MTL IFHX) Close-Call Investigation (NASA Mishap Report OB-2013-01)[1], the transient scenario related to a ruptured IFHX has been analyzed in detail and presented during a Technical Interchange Meeting in Houston *(March 25 – 28, 2014).*

Common understanding of the participating organizations and engineers in the meeting was that in case the impacted IFHX can not be unambiguously identified in case of an ammonia breach in one of the IFHXs the ISS External Active Thermal Control System (EATCS) will have to depressurize both ammonia loops which would lead to a complete loss of the ISS heat rejection capability.

Hence, outcome of the technical interchange meeting was to pursue a general concept to automatically close the Columbus IFHX Water On Off Valves (WOOVs) as part of the NASA Attached Pressurized Module (APM) IFHX Leak Response (Ref. NASA VCB presentation: "ITCS Isolation for IFHX Rupture Response").

Columbus Internal Active Thermal Control System (IATCS) is rejecting heat via two ISS Interface Heat Exchangers (IFHX) which are on their side connected to the External Active Thermal Control System (EATCS) ammonia loops.

While the maximum design pressure (MDP) of the Columbus IATCS water loop is limited to 8,3 bars the ammonia side of the IFHX is working with an MDP of up to 27 bars.

Figure 1 provides a rough description of the actual Columbus IATCS schematics highlighting the two Water Pump Assemblies (WPA), the Water Modulating Valves (WMV) for water flow mixture to guarantee the low inlet temperature for the Condensing Heat Exchanger (CHX) and medium temperature for the Plenum (cold plates and payloads). The two IFHXs (MT and LT) are at the Node2 interface on the right side of the schematics and represent the interface to the EATCS ammonia loop with the low temperature and high pressure ammonia system.

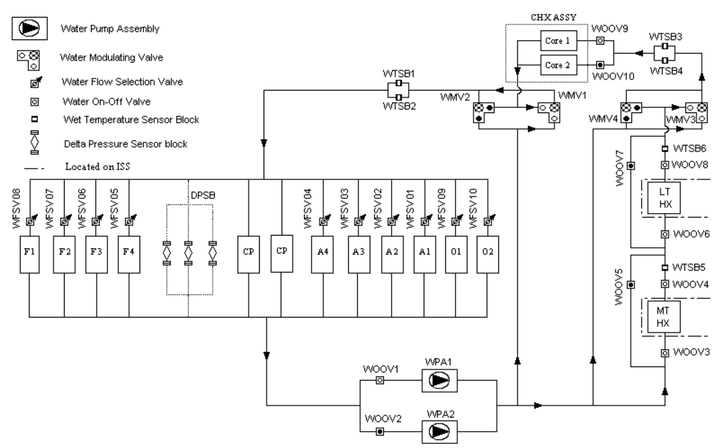

Figure 1. Actual Columbus IATCS lay-out

For the development of the automatic reaction to protect the ISS and Columbus from ammonia breach into the cabin as well as to pursue the capability to identify the leaking IFHX thermal-hydraulic simulations and analyses have been performed as described in S. De Palo, A. Tilloca and E.K.Ungar, Columbus IFHX Ammonia Leak Analysis, ICES-2018-94[2].

Based on the results of the thermal-hydraulic analyses parameters for the automatic reaction have been derived which have been used for the generation of the software implementation in the NASA Mission Data Management (MDM).

To ensure safe isolation of the failed IFHX the corresponding Water On-Off Valves will have to be operated. They are not qualified to the MDP of the ammonia breaching into the IATCS loop hence, needed a recertification effort to prove their capabilities to sustain and operate at pressures higher than the MDP of the IATCS water loop.

Finally, operational products like Flight Rules or procedures have to be updated resp. newly created to implement the appropriate FDIR reaction and follow on activities to protect Columbus and the ISS from the toxic high pressure ammonia.

II. IFHX Ammonia Leak Thermal-Hydraulic Analysis

In the frame of the analytical evaluation to identify the appropriate sequence of automatic reactions and to isolate the leaking IFHX as well as to determine ways to identify the leaking IFHX thermal-hydraulic analyses have been performed.

For the purpose of the analysis specific thermal-hydraulic mathematical models of the Columbus IATCS have been developed. This specific Thermal Hydraulic Mathematical Model (THMM) has been developed based on the former ESATAN FHTS model in SINDA FLUINT which has the capability to model two phase/two fluid modelling as well as to handle transients appropriately.

The extra modelling has been done in SINDA-FLUINT since this is not only able to simulate the physics of the ammonia leakage but due to the specific layout discretization it provides more accurate and specific inputs for the parameters of the automatic FDIR than in the previous version.

The following major assumptions have been used as inputs for the model:

- Bypass and isolate the ammonia valves on MTL IFHX when the WPA accumulator pressure reaches 210 kPa by opening WOOV5 and closing WOOV3 and WOOV4 (see Figure 1).
- Bypass and isolate the ammonia valves on LTL IFHX when the accumulator pressure reaches 250 kPa by opening WOOV7 and closing WOOV6 and WOOV8 (see Figure 1).

For the determination of the automatic FDIR parameters different analysis cases have been performed, mainly in order to identify the conditions which will allow to detect and isolate the leaking IFHX and to protect the crew as well as to be able to distinguish unambiguously the leaking heat exchanger.

After several iterations the following nominal initial conditions have been selected:

- Minimum active accumulator pressure 1.7 bar (instead of 1.65 bar)
- MTL IFHX isolation pressure trigger: 1.95 bar (instead of 2.1 bar)
- LTL IFHX isolation pressure trigger: 2.20 bar (instead of 2.5 bar)
- Ammonia pressure, Maximum Operating Pressure (MOP), 27 bar;
- Ammonia side of the IFHX is isolated however, bleed line will further provide ammonia (defined cross section);

The analysed reference cases have been selected in accordance to the known configuration of the “Close Call” where the IFHX has been isolated hence, there was no water flow through the interface HX core at the time of the potential freezing. Ammonia would have breached into the IATCS loop once thawing has started..

	Initial Water MFR (kg/h)	Initial accumulator volume (l)	Initial accumulator pressure (bar)	Initial WOOV Status
Case 5 **MTHX Failure through bleed line with stagnant water in the HX branch**	300 (worst operative value)	5.0 (maximum operational value)	1.7 (udated minimum set point pressure)	▪ WOOV 4: Closed ▪ WOOV 3 and 5: Open ▪ WOOV 7: Closed ▪ WOOV 6 and 8: Open
Case 6 **LTHX Failure through bleed line with stagnant water in the HX branch**	300 (worst operative value)	5.0 (maximum operational value)	1.7 (udated minimum set point pressure)	▪ WOOV 4 and 3: Open ▪ WOOV 5: Closed ▪ WOOV 7 and 6: Open ▪ WOOV 8: Closed

Table 2. Final reference analysis cases – initial parameters

Hydraulic analyses were then performed to finalize the FDIR in terms of IFHX WOOVs closure sequence, pressure profiles and wait times to contain the ammonia propagation to IATCS and properly identify the leaking IFHX. In addition, the analysis results provided reference pressure profiles to be used on console and by Engineering as support for the telemetry data processing in case of failure. Work performed investigated also pressure thresholds for the IFHX WOOV closure, with the goal of avoiding accumulator rupture while trying to identify the leaking heat exchanger resp EATCS branch.

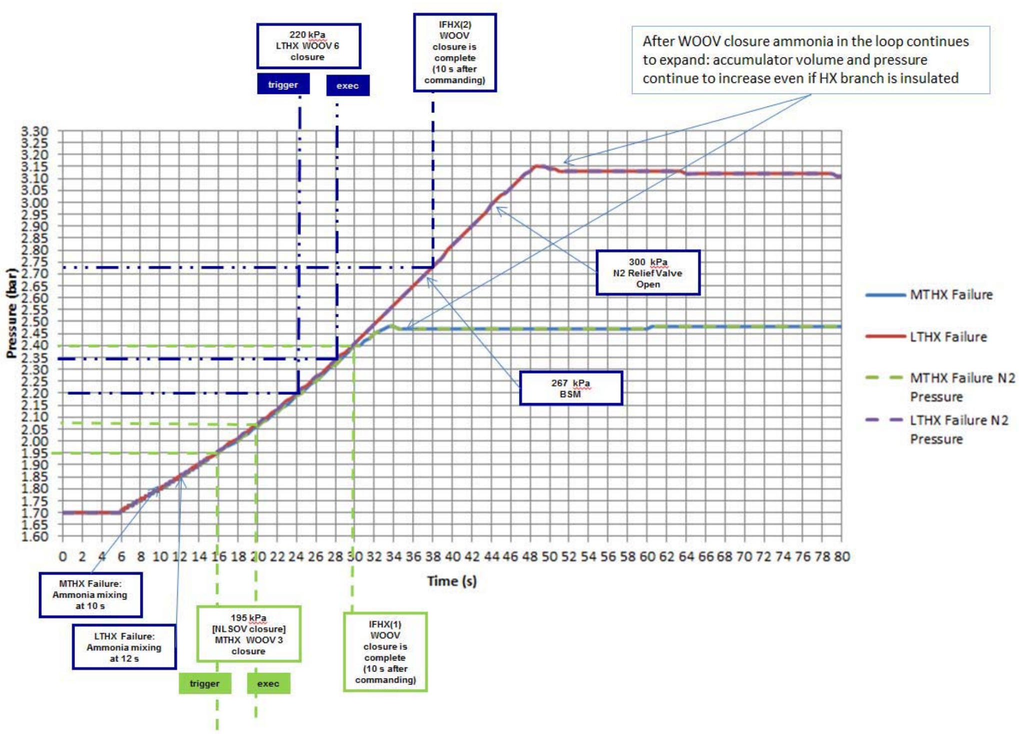

Figure 2. Accumulator pressure trend –Reference cases 5 and 6

Figure 2 reports the accumulator pressure trend for Cases 5 and 6 while Figure 3 reflects the corresponding accumulator water volume.

Ammonia starts flowing into the IATCS at time = 5 s.

For Case 5 (MTHX failure, stagnant water and a.m. assumptions)

- WOOV4 is closed while WOOV3 is open, water is flowing through the MTHX bypass branch (WOOV5 is open);
- After further 4 s, accumulator pressure reaches 1.95 bar (FDIR threshold No. 1), WOOV3 starts to close (full closing time: 10 s);
- After further 3 s, accumulator pressure reaches 2.20 bar (FDIR threshold No. 2), WOOV7 starts to open (full opening time: 10 s);
- Just 4 s after accumulator pressure has reached 2.20 bar WOOV8 and WOOV6 start to close (full closing time: 10 s);
- Maximum accumulator pressure reached: 2.5 bar
- Maximum accumulator volume reached: 9.6 l
- Ammonia enters into the IATCS loop before WOOV3 has been completely closed (3.8 g of ammonia breaches into the water loop);
- After WOOV3 closure ammonia, present in the loop, continues to expand; accumulatror volume and pressure continue to increase even if the MTHX has been isolated.

For Case 6 (LT IFHX failure, stagnant water and a.m. assumptions)

- WOOV8 is closed while WOOV6 is open, water is flowing through the LTHX bypass branch (WOOV7 is open);
- After further 3 s, accumulator pressure reaches 1.95 bar (FDIR threshold No. 1); WOOV5 starts to open (full opening time: 10 s);
- After further 4 s, accumulator pressure reaches 1.95 bar, WOOV4 and WOOV3 start to close (full closing time: 10 s);
- Maximum accumulator pressure reached: 3.15 bar
- Maximum accumulator volume reached: 12.0 l
- Ammonia enters into the IATCS loop before WOOV6 has been completely closed (8.3 g of ammonia breaches into the water loop);
- After WOOV6 closure ammonia, present in the loop, continues to expand; accumulatror volume and pressure continue to increase even if the LTHX has been isolated.

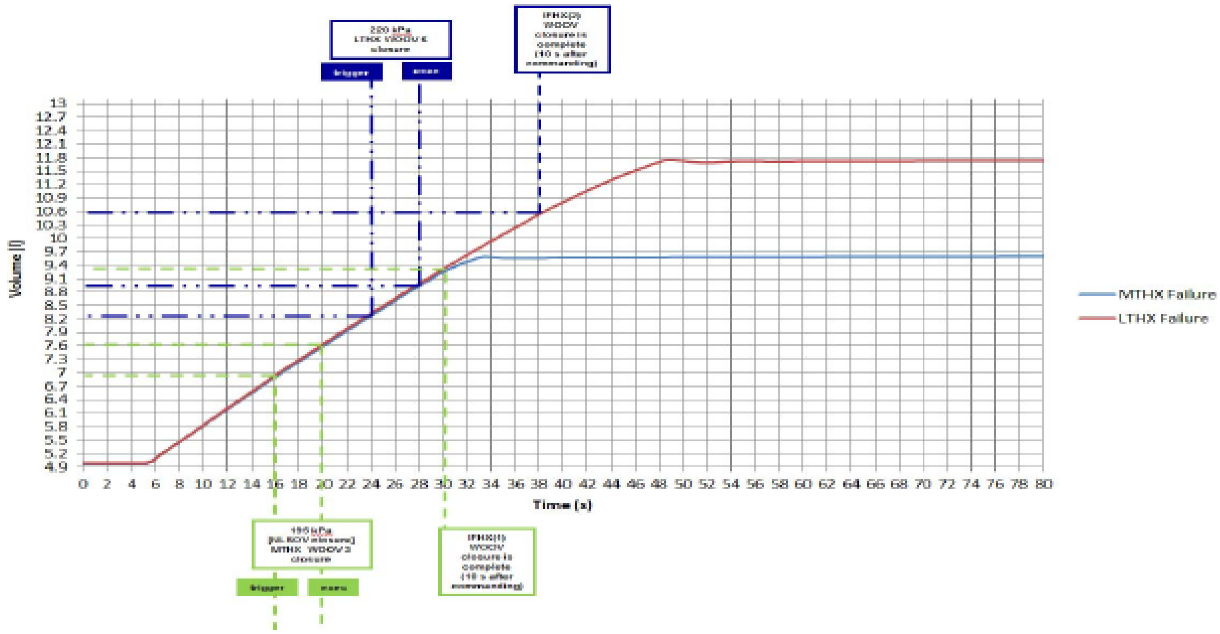

Figure 3. Accumulator water volume trend –Reference cases 5 and 6

Table 2 reflects the analysis results of Reference cases 5 and 6 in a summary highlighting the final accumulator pressure, volume reached as well as the amount of ammonia which entered the water loop despite the timely isolation of the MT (Case 5) and LT HX (Case 6).

This ammonia will later on also enter the cabin air due the permeability of the IATCS loop flex hoses. Reference 3 analysis performed an assessment about the to be expected ammonia concentration in the cabin air; this will then determine emergency reaction of the crew (as per the Emergency Crew Procedures).

	Accumulator Pressure (Bar)	Accumulator Volume (l)	Ammonia Mass in the COL Loop (g) (downstream WOOV)
Case 5: MTHX Failure: ▪ **Water MFR=300 kg/h** ▪ **Accumulator initial Volume=5 l** ▪ **Accumulator initial Pressure=1.7 bar** ▪ **WOOV 3 activation threshold = 1.95 bar**	2.5	9.7	3.8 (mixing after 5 s)
Case 6: LTHX Failure ▪ **Water MFR=300 kg/h** ▪ **Accumulator initial Volume=5 l** ▪ **Accumulator initial Pressure=1.7 bar** ▪ **WOOV 6 activation threshold = 2.2 bar**	3.15 (BSM)	12.0	8.3 (mixing after 7 s)

Table 2. Summary results of reference analysis cases 5 and 6

As per the above analyses reults the selected initial accumulator pressure and triggering threshold allows to unambiguously distinguish the failed IFHX hence, only this branch of the EATCS has to be depressurized and will not be available for further heat rejection of the ISS in case of an ammonia breach inside of the IFHX.

Additionally, with the present evaluated parameters for the automatic FDIR even in case of an LTHX failure, the WPA accumulator (as the weakest point of the Columbus IATCS) will not reach end of stroke hence, no accumulator rupture is subject of concern for the considered failure scenario.

III. Recertification of WOOV MkI & MkII

For a successful automatic FDIR isolation of a failed IFHX, in case of ammonia leakage into the IATCS water loop, the appertaining Water On-Off Valves (WOOV) are intended to be made use of (see Figure 1, WOOVs 3 through 8).

Due to the missing verification of the actual Columbus WOOV MkI and MkII valves to the pressure levels of the breaching ammonia in case of an IFHX rupture, a specific recertification test campaign had to be performed.

Reference 4 report is describing in detail the performed recertification Leak-Proof-Leak tests applied to the on-ground available 3 WOOV MkII units and to the only available WFSV EM MkI unit. Intention was to test the three WOOV MkII and the only one WFSV EM MkI valve and perform additional mechanical analyses (Mechanical Stress and Damage Tolerance Analyses) in order to conclude the results for all the already built WOOV MkII units. For the WFSV EM MkI, representing also the WOOV MkI, presently still present in the IATCS on positions WOOV3, 4 and 5, only the test result of the WFSV MkI could be made use of since no mechanical modelling were available any more hence, no finally concluding analyses could be performed.

The following describes the Leak-Proof-Leak tests performed with the WOOV MkII and the WFSV EM MkI units.

A. WOOV MkII Recertification Tests

The Units Under Test (UUT) were the on ground available WOOV MkII S/N 006, 007 and 008. The subject units have been specifically prepared and interface adapters built to be able to perform the required helium leak tests as well as pressurization to the required proof pressure.

The leak proof leak test has been performed in the pressure and vacuum chamber of Airbus Defence and Space in Bremen (within the Ariane test facility).

Figure 4 shows the WOOV MkII valve schematic and design description as applied for the subject test.

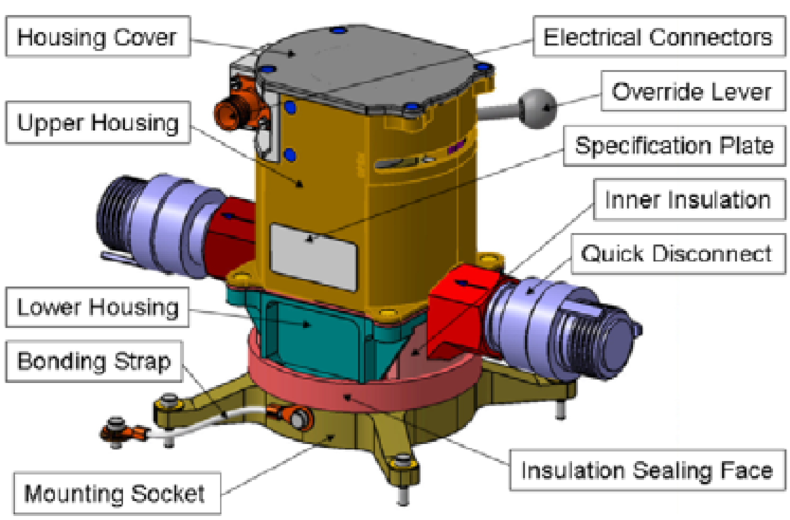

Figure 4. WOOV MkII Design Schematics – MkII test object

Figure 5. WOOV MkII and WFSV MkI UUTs – Test Preparation

Summary of the leak-proof-leak test results, which have been performed with all three units, are listed below.

1. FM WOOV MkII 3571785-01 SN 06

S/N 06 has passed all recertification leakage tests successfully being fully compliant with the equipment level leakage requirements.

Additionally, exposure to the 1,5 x "new" MDP of ca. 40 bar has shown no visible nor any functional deterioration of the subject valve. For the latter reference is made to the post Leak – Proof – Leak test functional and cycling test (Reference 5).

2. FM WOOV MkII 3571785-01 SN 07

S/N 07 has failed considerably the He leak test for the increased "new" MDP of ca. 27 bar and an SPR has been raised in order to decide on further proceeding with the subject valve.

The Material Review Board (MRB), held on May 3rd, concluded to complete the Leak – Proof – Leak test and provide conversion from He to water leakage in order to be able to judge on the acceptability of the actual leakage with respect to the intention of the recertification for ammonia leakage containment.

The calculated water leakage amounts to ca. 0,7 ccm/hr concluded that also with the actually "higher" than required leak rate the recertification purpose, namely to contain the ammonia in the isolated IFHX branch after breach of the IFHX, is fulfilled.

For the external leak rate the S/N 07 is fully compliant with the equipment level requirement.
Open point: Leakage verification at the “baseline MDP” resulted obviously still in a He leak rate which is ca. one order of magnitude higher than the requirement. Conversion of the actual He leak into water leakage resulted in a leak rate of ca. 0,59 ccm/hr water which had to be evaluated on Columbus system level to judge on acceptability of the “degraded” internal leakage performance. Conclusion was that the subject valve can be accepted with the amendment to the Acceptance Data Package (ADP) to make use of the subject valve at positions in the water loop where the partially higher leakage figure could be acceptable.

Project	Model	Inspected item	Item No.:	Serial No.:	Test date							
Columbus	FM	WOOV MkII	3571785-01	7	27.04 - 09.05.2017							
Type of test	Medium	Duration	Prime measurement device	Test pressure		Leakage limit				Leakage (max.)		Remark
				Upstream (p_1) [bar]	Downstream (p_2) [bar]		Helium [mbar l/s]		Water [cm³/hr]	Helium [mbar l/s]	Water [cm³/hr]	
Internal leakage	GHe	≥ 1 hr	Sniffer	2,70E+01	1,01E+00	≤	5,69E-03	≤		1,20E-01	7,00E-01	abort after 15 min.
External leakage	GHe	≥ 1 hr	Mass spectrometer	2,69E+01	3,80E-06	≤	3,41E-05	≤		2,60E-05	1,58E-04	
Proof pressure	GHe	≥ 5 s	Pressure transducer	4,07E+01	1,02E+00							no visible damage
External leakage	GHe	≥ 15 min	Mass spectrometer	8,34E+00	7,60E-07	≤	3,41E-05	≤		6,50E-07	1,27E-05	
Internal leakage	GHe	≥ 15 min	Sniffer	8,96E+00	1,02E+00	≤	5,69E-03	≤		3,60E-02	5,90E-01	extension 69 min.

Table 3. Summary results of Leak-Proof-Leak Test for S/N 07

3. FM WOOV MkII 3571785-01 SN 08

S/N 08 did not comply to the equipment level leak requirements during the first internal He leak measurement for the increased “new” MDP of ca. 27 bar being one order magnitude higher than the requirement. A second leak test has been performed with extended duration which showed that the internal leakage requirement is nearly met (7.1E-03 instead of the required 5.69E-03 mbarl/s). For the baseline leak test and for the external leakage tests WOOV MkII SN 08 was in line with the equipment level leakage requirement.
As well as for the other valves, exposure to the proof pressure of ca. 40 bar did not show any deterioration and the post Leak-Proof-Leak test Cycling test was performed successful (see Reference 5).

B. WFSV MkI Recertification Test

The Unit Under Test (UUT) was the only one on ground available WFSV MkI EM. The subject units has been specifically prepared and interface adapters built to be able to perform the required helium leak tests as well as pressurization to the required proof pressure.

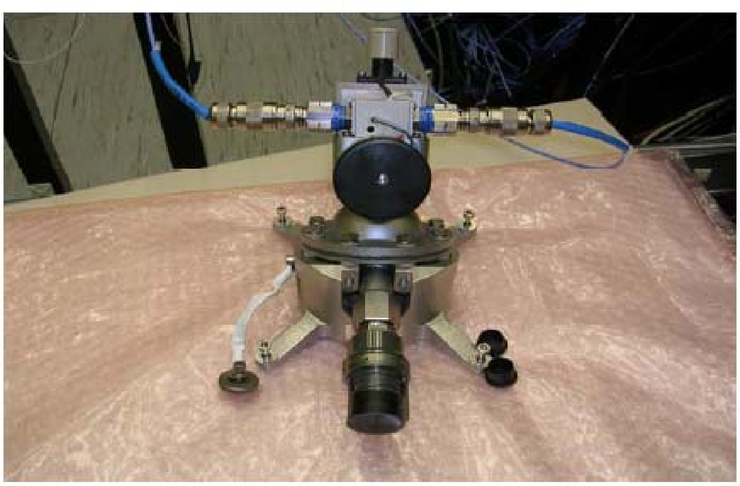

Figure 6. WFSV EM MkI - Test object

1. EM WFSV MkI 1279118 S/N 98-019

The only WOOV MkI similar WFSV EM tested in the frame of the recertification activity has passed all recertification leakage tests successfully being fully compliant with the equipment level leakage requirements.

Also the specifically agreed "reverse internal leak test" as agreed to in the test readiness review could be successfully performed and leak rates are full in line with the somewhat different equipment level leakage requirements.

Additionally, exposure to the 1,5 x "new" MDP of ca. 40 bar has shown no visible nor any functional deterioration of the subject valve. For the latter reference is made to the post Leak – Proof – Leak test functional and cycling test (Reference 5).

C. Final verification –Mechanical Analyses

Extension of the recertification via test to all" other WOOV MkII required an update of the Mechanical Analysis as well as of the Damage Tolerance Analysis applying the increased MDP of 27 bars.

An analysis update for the pressure increase up to MDP = 27 bar is documented in the ANNEX 5 of the Mechanical Analyses.

The analytical assessment, performed for the Columbus WOOV MkII valves, facing an increased internal pressure load of 27 bar, lead to positive margins of the functional calculations. It has also been shown that parts directly affected by the pressure increase (i.e. housing flange and the associated bolts) have positive margins of safety when MDP inside the valve is increased to 27 bar.

IV. FDIR Implementation

For implementation of the automatic FDIR, developed for a potential rupture of the Columbus IFHX (triggered by the WPA accumulator pressure thresholds), an algorithm has been developed by NASA and Boeing software engineering which will be implemented in the ISS MDM within the software cycle X2R17, planned for installation on-board the ISS end of 2018.

The subject algorithm is based on the definition prepared for the NASA Software change ISS SCR 43355 and has been submitted for verification testing within May 2018.

A. MDM software implementation

The APM IFHX Leak Response bypasses and isolates the ammonia valves on both of the exchangers when accumulator pressure on the active WPA exceeds a commandable threshold. The valves on both IFHXs are repositioned because APM has only one ITCS loop that flows through both exchangers: the detection algorithm has no way to determine which of the two has the leak, so the conservative response is to bypass and isolate the ammonia valves on both.

Although the detection algorithm has no insight, in most cases flight controllers can surmise which APM IFHX has the leak based on EATCS activities at the time (e.g., one EATCS loop was being repressed from saturation or was being restarted from very cold ammonia temperatures while the other loop was operating nominally).

If they cannot determine empirically which IFHX encountered the leak however, flight rule B2-359 (IFHX Rupture Ground Response) ultimately results in the flight controllers depressing or venting both EATCS loops, which mitigates risk of crew ammonia exposure at the cost of subsequently losing all of USOS.

For cases where no external clues are available to flight controllers, the only way to determine which APM IFHX has a leak is by hydraulically isolating the exchangers and the leak from the ITCS loop.

Automatically hydraulically isolating the APM IFHXs internally as quickly as possible after a leak is detected can determine which IFHX has the leak and, if the first HX that is isolated has the leak, can delay or prevent APM from transitioning to Berthed Survival Mode.

Even if the leaking HX is not identified, automatic internal isolation of the leak removes the immediate need for flight controllers to depress or vent both EATCS loops (and thereby lose USOS) because it impedes ammonia into the ITCS loop and subsequently into the cabin, which provides more time for crew egress.
Inhibiting heaters on internally-isolated exchangers mitigates the risk of over-pressurization for a non-leaking IFHX.
Providing separate functional inhibits for the internal response for each exchanger individually (over and above the main inhibit for APM IFHX Leak Response) provides flight controllers with flexibility for contingency configurations or philosophical changes to operational strategy in the future.
When APM is not in BSM, the response will preferentially isolate the MT HX first because it has shorter ITCS lines (takes less time for ammonia to enter the rest of the ITCS loop through an MT leak than an equally-sized LT leak); in Berthed Survival Mode (BSM), however, the algorithm isolates whichever HX it can first because power to one of the PDUs must be cross-strapped before the WOOVs for the other exchanger can be controlled.

B. Operational Products - Procedures

Operational products, e.g. procedures, flight rules, presently available, will have to be updated to reflect the implemented automatic FDIR and corresponding flight control team support activities (e.g. safings, set point changes, etc.).

One of the most important procedures to be updated to be able to cope with the ammonia leakage scenario is required for crew protection (EMER 9.13 – COL IFHX Leak Response). Update of the subject procedure is presently in coordinated work between NASA & ESA flight controllers and engineers.

C. Flight Rules

To reflect detection and response requirements for a ruptured IFHX the corresponding Columbus relevant IFHX Rupture Detection and Response flight rules are also part of the final implementation activities and will have to be worked in time before the automatic FDIR will be implemented into the ISS MDM via software cycle X2R17.

V. Conclusion

In consequence of the Columbus MTL IFHX Close Call investigation decision has been made by the agencies (NASA & ESA) to pursue an automatic FDIR protection and safing mechanism to protect the ISS and Columbus from a breached IFHX (e.g. due to freezing, etc.) and the follow on ammonia leakage into the IATCS and finally into the cabin. The developed automatic reaction will provide (depending on the failure scenario) a reliable means to distinguish and isolate the failed EATCS branch hence, not to loose heat rejection capability for the ISS completely.

The subject paper highlights the analytical effort done to evaluate the automatic FDIR reaction trigger parameters, provides proof of successful recertification of the WOOV MkII as well as the verification be test only for the WOOV/WFSV MkI valves.

Implementation of the automatic FDIR is mainly done in the NASA MDM as well as via the updated operational products like the Crew Emergency and other related procedures and flight rules.

Further work can be proposed for similar investigation of the "Moderate Ammonia Leakage" handling on the ISS to detect and appropriately react on a potential ammonia leakage with more time for reaction available.

Acknowledgments

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References

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