PAYLOAD FLIGHT HAZARD REPORT				a. NO:	AMS-02-F04
b. PAYLOAD	Alpha Magnetic Spectrometer-02 (AMS-02)			c. PHASE:	II
d. SUBSYSTEM:	Pressure Systems	e. HAZARD GROUP:	Structural	f. DATE:	May 22, 2006
g. HAZARD TITLE:	Overpressurization of Orbiter Payload Bay			i. HAZARD CATEGORY:	CATASTROPHIC **X** CRITICAL
h. APPLICABLE SAFETY REQUIREMENTS:	NSTS 1700.7B, 200.1, 200.2, 200.3, 200.4a, 201.3, 202.6, 205, 206, 208.4, 208.4a, 208.4b, 208.4c, 208.4e				
j. DESCRIPTION OF HAZARD:	Nominal or fault venting/release of stored gases (Superfluid Helium, Warm Helium, TRD Gas Supply (CO_2, Xe) and the Thermal Control System (Ammonia, CO_2, Propylene) generates excessive volume/pressure within the Orbiter payload bay during ascent or entry (doors closed) damaging the payload bay doors or aft bulkhead. Damage of these critical structures can result in the loss of Orbiter safe entry capability.				

k. CAUSES

(list)

1. Nominal boil off of cryogenic helium
2. Loss of Vacuum Case thermal isolation
3. Leakage of Warm Helium Gas Supply
4. Leakage of TRD Gas Supply
5. Leakage of Thermal Control Systems
6. Blockage of Payload Bay Vents with MLI

o. APPROVAL	PAYLOAD ORGANIZATION	SSP/ISS
PHASE I		
PHASE II		
PHASE III		

PAYLOAD FLIGHT HAZARD REPORT		a. NO:	AMS-02-F04
b. PAYLOAD	Alpha Magnetic Spectrometer-02 (AMS-02)	c. PHASE:	II
l. HAZARD CONTROL (CONTROL), m. SAFETY VERIFICATION METHODS (SVM), n. STATUS OF VERIFICATIONS (STATUS)			OPS CONTROL
1. CAUSE: Nominal boil off of cryogenic helium			
1.1 CONTROL: By design the nominal vent rate of the superfluid helium will be well below values that could threaten to over pressurize the Orbiter Payload Bay. At launch, no venting will occur until a baroswitch or computer issued (timer) command is sent to open the vent valve. This will occur at approximately 5 mbar (0.04 psia, approximately 3 minutes into flight). The nominal venting rate of the super fluid helium system is approximately 3.2 liters/min @ STP. This has taken into account the thermal transfer capabilities of the Cryosystem Support Straps and the thermal isolation of the vacuum case. 1.1.1 SVM: Analysis/Test of AMS-02 nominal vent rate. 1.1.2 SVM: Approval of AMS-02 potential gas release by Shuttle Integration Office. 1.1.1 STATUS: Open. AMS-02 analysis of the worst-case nominal venting conditions for pressure has been completed. 1.1.2 STATUS: Open. Shuttle integration office has assessed the AMS-02 nominal vent rate of 3.2 liters/min @ STP (8.9mg/sec). This is at worst case, without cryocoolers.			
2. CAUSE: Loss of Vacuum Case thermal isolation			
2.1 CONTROL: The super fluid helium cryogenic system has been established to not have any credible failure modes that can result in an emergency venting that can over pressurize the Orbiter Payload Bay. The Loss of Vacuum failure mode has been controlled by the design of the vacuum case construction, a welded aluminum structure that includes four large sealing joints with two o-rings held between to flanges secured with minimum of 192 bolts (each large sealing joint has differing numbers) at a ~1 ¾ inch spacing. Considering this design, a very conservative worst-case leak was postulated and presented to the PSRP for consideration at a series of Technical Interchange Meetings (TIMs). This leak has been defined as a three-inch wide gap cause by pinching each of the o-rings, with a maximum gap space of 0.001 inch that equates to an effective hole size of 0.062 square inches. Details of this analysis are attached to this hazard report. Extensive testing and analysis support the loss of vacuum condition and monitoring of the vacuum case pressure and the Super Fluid Helium tank pressure and temperature will occur from approximately 12 months prior to flight to L-9 minutes. (Note this is an equivalent fault tolerance approach documented and approved in PSRP Minutes of the AMS-02 Special Discussion Meeting held October 11, 2001, TIM held October 16, 2001 and the AMS-02 TIM held January 17, 2003)			

2.1.1 SVM: Qualification Testing of Structural Test Article (STA) as defined in AMS-02 SVP (JSC-28792C):

- Vacuum Leak Test of STA Vacuum Case (VC)
- Proof Pressure Test of STA VC
- Full Assembly Static Test with STA VC
- Full Assembly Modal Test with STA VC
- Sine Sweep Test of STA VC
- Acoustic Test of STA VC

2.1.2 SVM: Acceptance Testing of Flight Vacuum Case as defined in AMS-02 SVP (JSC 28792C):

- Vacuum Leak Test of Flight VC
- Proof Pressure Test of Flight VC
- Vacuum Leak Test of Flight SFHe Tank
- Proof Pressure Test of Flight SFHe Tank

2.1.3 SVM: Small Scale Venting Tests to validate emergency flow rate.
2.1.4 SVM: Emergency Venting Analysis performed by AMS-02 organization and STS Integration for all mission events.
2.1.5 SVM: Review of design to verify redundant pressure and temperature sensors in SFHe Tank and the vacuum case.
2.1.6 SVM: Inspection of as built hardware to verify redundant pressure and temperature sensors in SFHe Tank and the vacuum case.
2.1.7 SVM: Functional Testing of pressure and temperature sensors in the SFHe Tank and the vacuum case.
2.1.8 SVM: Launch Commit Criteria for launch acceptability at L-9 minutes. Trend Data will be utilized to establish cryosystem health status prior to launch.
2.1.9 SVM: Approval of AMS-02 potential gas release.
2.1.1 STATUS: Open
2.1.2 STATUS: Open
2.1.3 STATUS: Closed. Ref "Loss of Vacuum and Venting from the AMS-02 Cryostat," dated 11 December 2002, S. M. Harrison.
2.1.4 STATUS: Open
2.1.5 STATUS: ~~Open~~Closed. Reference ESCG Memo ESCG-4390-06-SP-MEMO-0008, "Loss of Vacuum in the

PAYLOAD FLIGHT HAZARD REPORT	a. NO: AMS-02-F04
b. PAYLOAD Alpha Magnetic Spectrometer-02 (AMS-02)	c. PHASE: II

AMS-02 Cryostat", dated March 24, 2006.

2.1.6 STATUS: Open

2.1.7 STATUS: Open

2.1.8 STATUS: Closed. Boeing Memo No. TS-TM-02-064, dated December 19, 2002.

2.2 CONTROL: The SFHe Tank emergency vent has three burst disks in series. These relieve outside of the vacuum case. The vacuum case emergency vent has three burst disks in series. The burst disks have a reverse acting circumferentially scored design with cutting teeth as redundant burst method. These disks comply with the requirements of NSTS/ISS 18798, letter TA-88-074 (October 18, 1988) (reference AMS-02-F05)

2.2.1 SVM: Review of design for inclusion burst disks for the SFHe tank and for the VC.

2.2.2 SVM: Inspection of as built hardware burst disks for the SFHe tank and for the VC.

2.2.1 STATUS: Open

2.2.2 STATUS: Open

3. CAUSE: Leakage of Warm Helium Gas Supply

3.1 CONTROL: During ascent and descent the Warm Helium Gas Supply does not nominally have a vent path. Only the rupture of burst disks (320 bar high pressure and 10 bar low pressure) and a pressure relief device operating can release gas. The maximum flow rate out of the high pressure burst disk (worst case for system) is 0.24 kg/s and rapidly drops off. Other possible vent paths could vent at a substantially reduced rate and required additional component failures to occur. The total quantity of helium contained in the Warm Helium Gas Supply is 241 grams.

3.1.1 SVM: Venting Analysis

3.1.2 SVM: Filling Procedure on total quantity being less than or equal to 241 grams of helium.

3.1.3 SVM: Approval of AMS-02 potential gas release.

3.1.1 STATUS: Closed. Space Cryomagnetics Ltd Memo dated November 11, 2005, titled "AMS-02 Superconducting magnet - venting of warm helium vessel"

3.1.2 STATUS: Open

3.1.3 STATUS: Closed. Boeing Technical Memorandum TS-TM-05-037 dated December 9, 2005 From HB2-30/William R. Griebel.

PAYLOAD FLIGHT HAZARD REPORT		a. NO:	AMS-02-F04
b. PAYLOAD	Alpha Magnetic Spectrometer-02 (AMS-02)	c. PHASE:	II

4. CAUSE: Leakage of TRD Gas Supply

4.1 CONTROL: During ascent and landing phases, each of the TRD Xenon and Carbon Dioxide gas tanks are isolated by three valves and flow limiting orifices. Valves are normally closed and close when power is removed. If these valves are open, by three fault conditions in the valve mechanisms, and the gas pressure released through the vent line, protected by burst disk and pressure relief valves (will open under direct pressure of tanks), Xenon and Carbon Dioxide gas will be released into the payload bay. Xenon will have the highest mass flow rate potential with a value of 0.29 kg/sec (0.64 lb/sec, 1.12 ft^3/s). Carbon dioxide will have the highest volumetric flow rate at 0.06 m^3/sec (2.2 ft^3/s). Operation of valves would require powering of AMS control systems that are unpowered during ascent. Under nominal operations (installed on ISS) the worst case leakage through the sensor straws has been established by testing to be 4.3 x 10^{-6} l/sec. During operations on the ISS, a mixed gas purge may be used to assure a known mix of gases within Box C.

4.1.1 SVM: Review of design to confirm implementation of valves to isolate gas supply tanks.

4.1.2 SVM: Inspection of as built hardware to confirm implementation of valves to isolate gas supply tanks.

4.1.3 SVM: Functional testing of TRD confirms operation of valves to close with power removal.

4.1.4 SVM: Environmental/vibration testing to confirm valves remain closed during ascent/descent conditions.

4.1.5 SVM: Xenon and Carbon Dioxide Tanks will be filled with the appropriate gases per ground filling procedures.

4.1.1 STATUS: Open

4.1.2 STATUS: Open

4.1.3 STATUS: Open

4.1.4 STATUS: Open

4.1.5 STATUS: Open

4.2 CONTROL: The construction of the TRD high pressure gas supply utilizes stainless steel lines, (orbital) welded joints and fittings. Rupture of these DFMR lines would be required to release the pressure tank supply of gas. Reference DFMR compliance in AMS-02-F05.

4.2.1 SVM: Review of Design

4.2.2 SVM: Inspection of As Built Design.

4.2.1 STATUS: Open 4.2.2 STATUS: Open	
4.3 CONTROL: Fill and drain ports for the TRD tanks (Box S) and GSE interfaces (Box C) utilize check valves and dual sealed caps to preclude gas release. 4.3.1 SVM: Review of design 4.3.2 SVM: Inspection of as built hardware. 4.3.3 SVM: Post filling inspection of cap installation 4.3.1 STATUS: Open 4.3.2 STATUS: Open 4.3.3 STATUS: Open	
4.4 CONTROL: The amount of gas that can be released from the TRD Box C, including the mixing tank is limited by the volumes and pressure of mixed gases present and will not present a danger of over pressurization of the Orbiter Payload Bay during ascent and entry as the system is unpowered and the supply of gas is isolated though unpowered closed valves. The entire box operates at pressures lower than 20.4 psia and the total gas volume is 0.011m^3 (0.5 ft^3). The "straw" volume is divided into 41 segments, each is isolatable by redundant valves (provided for mission success reasons). A leak in any segment would release approximately 0.007 m^3 (0.25 ft^3) of mixed gas. If the volume of the entire straw system is released 0.3 m^3 (11 ft^3) of mixed gas could be released. Mixed gas is nominally a 4 to 1 ratio of xenon to carbon dioxide. The TRD sensor straws have been tested for leakage, which easily enveloped by the fault condition, with an established leak rate for an operational TRD of 4.3 x 10^{-6} l/sec. 4.4.1 SVM: Review of design 4.4.2 SVM: Inspection of as built hardware. 4.4.1 STATUS: Open 4.4.2 STATUS: Open	
5. CAUSE: Leakage of Thermal Control Systems	
5.1 CONTROL: The Tracker TCS (TTCS) utilizes two actively pumped carbon dioxide loops that contain approximately 874 grams of CO_2 per loop (approx 15.6 ft^3 (0.442 m^3) @ STP). Loops operate in a sealed mode qualified under DFMR	

without nominal or fault venting, reference AMS-02-F05. 5.1.1 SVM: Review of Design 5.1.1 STATUS: Open	
5.2 CONTROL: The Cryocooler Loop Heat Pipe utilizes 42 grams of propylene as a working fluid. Loop operates in a sealed mode qualified under DFMR without nominal or fault venting, reference AMS-02-F05. 5.2.1 SVM: Review of Design 5.2.1 STATUS: Open	
5.3 CONTROL: Radiator panels contain isolated heat pipe (and USS-02) elements with ammonia as a working fluid. Largest single heat pipe quantity of ammonia is less than 41 grams. Heat pipes operate as closed systems qualified under DFMR and have no nominal or fault venting conditions, reference AMS-02-F05. 5.3.1 SVM: Review of Design 5.3.1 STATUS: Open	
5.4 CONTROL: TTCS Oscillating Heat Pipe Experiment is a heat pipe that contains 2.56 grams of FC-87, a fully fluorinated liquid manufactured by 3M. The loop heat pipe is a closed system qualified under DFMR and has no nominal or fault venting conditions, reference AMS-02-F05. 5.4.1 SVM: Review of Design 5.4.1 STATUS: Open	
5.5 CONTROL: The CAB Loop Heat Pipe is an ammonia loop heat that contains 55 grams of ammonia. The CAB loop heat pipe is a closed system qualified under DFMR and has no nominal or fault venting conditions, reference AMS-02-F05. 5.5.1 SVM: Review of Design 5.5.1 STATUS: Open	
5.6 CONTROL: The Cryocooler is a Stirling Cycle heat pump that uses helium (275 cm^3 @ 16 bar, .72 grams) as a working fluid. The Cryocooler is a closed system qualified under DFMR and has no nominal or fault venting conditions, reference AMS-02-F05. 5.6.1 SVM: Review of Design	

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b. PAYLOAD Alpha Magnetic Spectrometer-02 (AMS-02)	c. PHASE: II

5.6.1 STATUS: Open

5.7 CONTROL: TTCE Accumulator Heat Pipe contains 3 grams of ammonia. The TTCS Accumulator Heat Pipe is a closed system qualified under DFMR and has no nominal or fault venting conditions, reference AMS-02-F05.

5.7.1 SVM: Review of the Design

5.7.1 STATUS: Open

6. CAUSE: Blockage of Payload Bay Vents with MLI

6.1 CONTROL: All MLI and thermal blankets used on the AMS-02 will be secured to AMS using positive mechanical means. "Soft": techniques such as hook and loop fasteners (Velcro ®) will not be used as a primary means of retaining the MLI and thermal blankets.

6.1.1 SVM: Review of design

6.1.2 SVM: Inspection of as built hardware.

6.1.1 STATUS: Open

6.1.2 STATUS: Open

Notes:

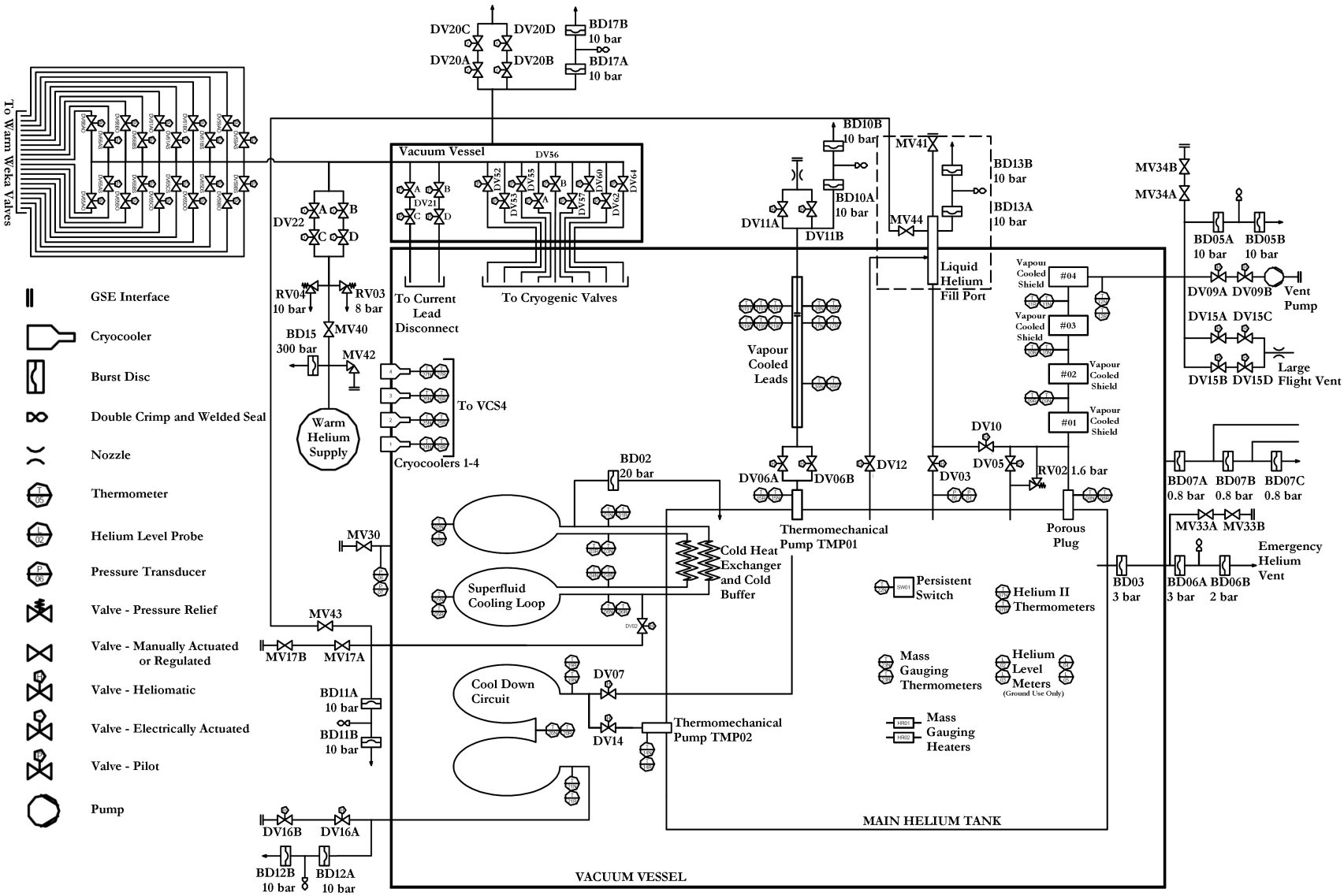
Fluid/Gas (at STP)	g/l	lb/ft^3
Ammonia	0.7710	0.11135
Carbon Dioxide	1.9769	0.12341
Helium	.1785	0.01114
Xenon	5.85	0.365
Propylene	1.783	0.1113
FC-87	1650	103.0
Superfluid Helium	145 g/l @ 1.8 K (-271.35 °C)	9.053 lbs/ft^3 @ -456.43 °F

ACRONYMS	
°C – Degrees Centigrade (Celsius)	MDP – Maximum Design Pressure
°F – Degrees Fahrenheit	mg/sec – milligrams per second
AMS-02 – Alpha Magnetic Spectrometer 02	min – Minutes
atm – atmospheres	MLI – Multilayer Insulation
C of C – Certificate of Compliance	MUA – Material Usage Agreements
CAB – Cryomagnet Avionics Box	Ops – Operations
CDC – Cool Down Circuit	PGSC – Payload General Support Computer
CHX – Cold Heat Exchanger	psia – pounds per square inch absolute
CO_2 – Carbon Dioxide	psid – pounds per square inch differential
COTS – Commercial Off the Shelf	PSRP – Payload Safety Review Panel
DDRS2 – Digital Data Recording System 2	QA – Quality Assurance
DFMR – Design for Minimum Risk	RTEF -
DLCM -	SCL – Space Cryomagnetics Limited
ft^3 – Cubit Feet	SCL – Superfluid Cooling Loop
ft^3/s – Cubit feet per second	SFHe – Superfluid Helium
g/l – Grams per liter	STA – Structural Test Article
He – Helium	STA – Structural Test Article
K – Kelvin	STP – Standard Temperature and Pressure
K – Kelvin	SVM – Safety Verification Method
kg/sec – kilograms per second	SVP – Safety Verification Plan

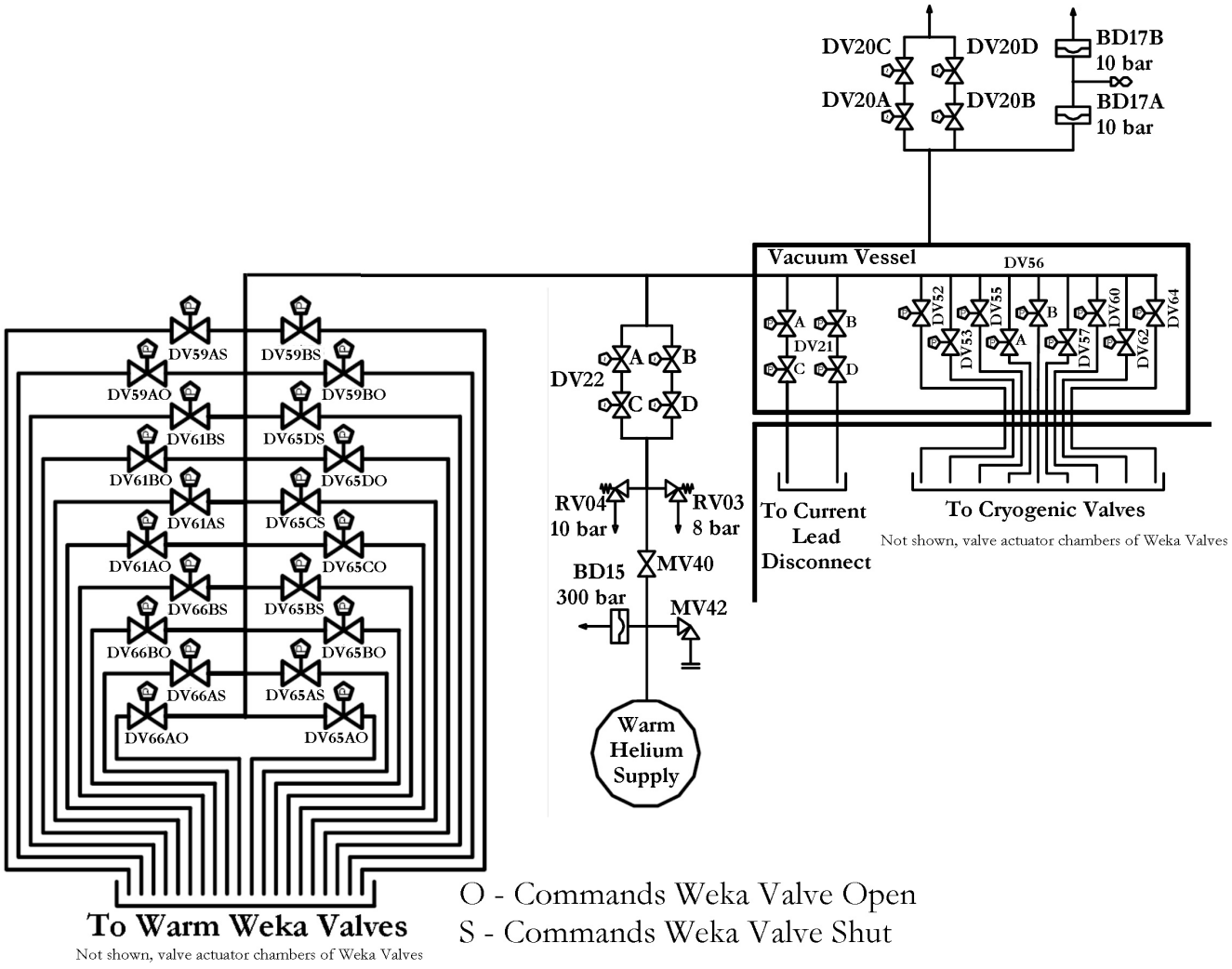
ACRONYMS	
ksi – kilo pounds per square inch	TCS – Thermal Control System
lb/ft^3 – Pound per cubic foot	TIM – Technical Interchange Meeting
lb/sec – Pounds (mass) per second	TRD – Transition Radiation Detector
lbf – pound force	TTCS – Tracker Thermal Control System
M/OD – Meteoroid/Orbital Debris	ult – Ultimate
m^3 – Cubic Meters	USS-02 – Unique Support Structure 02
m^3/sec – Cubic meters per second	VC – Vacuum Case
mbar – millibar	Xe – Xenon

Stored Gas Reservoirs				
System	Working Fluid	Quantity	Gas Volume (at STP)	Notes:
Superfluid Helium Tank	Superfluid Helium	800 lbs (362.8 kg) ~2500 liters@ 145 g/l @ 1.8 K	Thermal design limits release rate with worst case failure, heat must be introduced to phase change the superfluid helium.	
Superfluid Helium Tank	Superfluid Helium		Given worst case credible leak of VC, requires 23 minutes to warm up the cryogenic helium sufficiently to open burst disks and allow venting to begin. (Extremely conservative analysis, reference SCL Report on Loss of Vacuum.) This conditioned is monitored to L-9 minutes or less with a LCC in place if leak is detected.	
Superfluid Helium Tank	Helium		At baroswitch operation at external pressure of approximately 5 mbar, the nominal vent rate of 0.11 ft^3/min begins.	
Warm Helium Gas Supply	Helium	241 grams	47.68 ft^3 (1.35 m^3)	Worst case flow rate after failure of qualified burst disk (300 bar)
TRD Xenon Gas Supply	Xenon (Xe)	99 lbs (44.9 kg)	271.2 ft^3 (7.68 m^3)	Three failures to open valves during ascent/descent, worst case flow is 1.12 ft^3/s.
TRD Carbon Dioxide Gas Supply	Carbon dioxide (CO_2)	11 lbs (5 kg)	89.3 ft^3 (2.53 m^3)	Three failures to open valves during ascent/descent, worst case flow is 2.2 ft^3/s.
TRD Mixing Vessel/Box C	4:1 Xenon: CO_2 mix	Quantity supplied from TRD Box S ⇒	0.011 m^3	During ascent/descent this a non-operational system that requires the Box S to charge Box C with gas pressure and a failure of a relief valve.
TRD proportional counters "Straws", manifold &	4:1 Xenon: (CO_2) mix	Quantity supplied from TRD Box C ⇒	0.23 m^3 total with 0.007 m^3 per straw segment with interconnecting tubing and connection to Box C	Straw Modules are approximately 500 m in length with six straw per module (dia. of 6 mm). Interconnecting tubing and connection to the Box C account

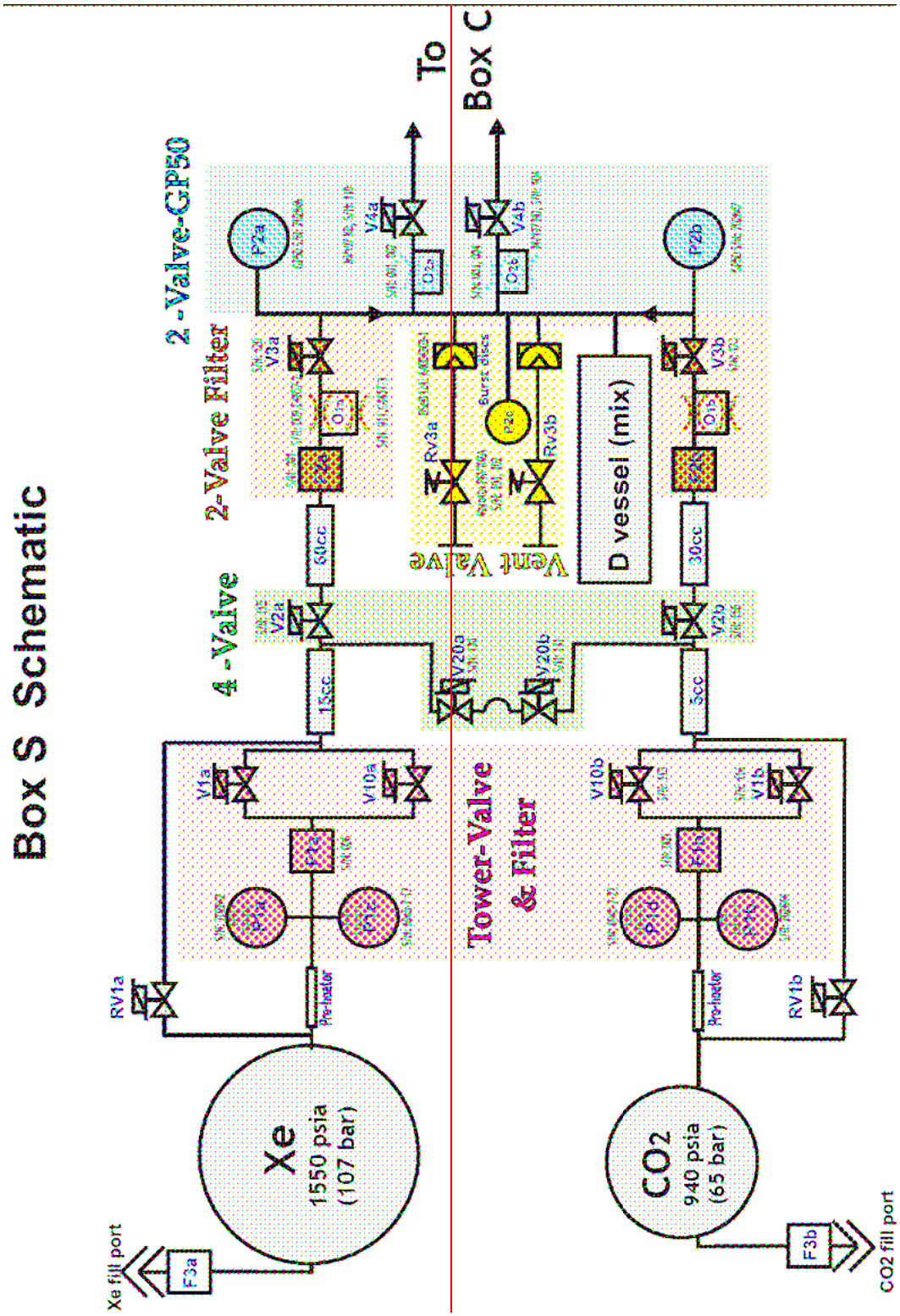
Stored Gas Reservoirs				
System	Working Fluid	Quantity	Gas Volume (at STP)	Notes:
delivery from Box C				for less than 0.001 m^3 each. This value is rounded up to 0.23 m^3.
Tracker TCS	Carbon dioxide	847 grams (Repeated in two loops)	15.1 ft^3 (0.428 m^3) @ STP per loop	Closed system design qualified under Design for Minimum Risk (DFMR) Criteria
Cryocooler Loop Heat Pipe (x8)	Propylene	42 grams each	0.83 ft^3 (0.024m^3)	Closed heat pipe qualified under DFMR Criteria
Heat Pipes (various)	Ammonia	Largest Quantity in single heat pipe is 41 grams	1.88 ft^3 (0.053 m^3)	Closed heat pipe systems qualified under DFMR criteria
CAB Loop Heat Pipe (x2)	Ammonia	55 grams each	2.52ft^3 (0.07 m^3)	CAB Loop Heat Pipe system qualified under DFMR Criteria
USS-02 Heat Pipes	Ammonia	3 pipes with 7 grams each	0.19ft^3 (0.005m^3)	Closed heat pipe qualified under DFMR criteria
TTCS Oscillating Heat Pipe Experiment	3M FC-87	2.56 grams	Liquid at STP	Closed heat pipe qualified under DFMR.
TTCS Accumulator Heat Pipe	Ammonia	3 grams	0.8ft^3 (0.0023m^3)	Closed heat pipe qualified under DFMR.
Cryocooler	Helium	0.72 grams	0.15ft^3 (0.004 m^3)	Closed Stirling Cycle Heat Pump under DFMR.
Note: Bypass valves used in the Cryocooler Loop Heat Pipe and the CAB Loop Heat Pipe have a small argon volume required for operations. The volume of argon has been calculated to be approximately 0.2 grams.				



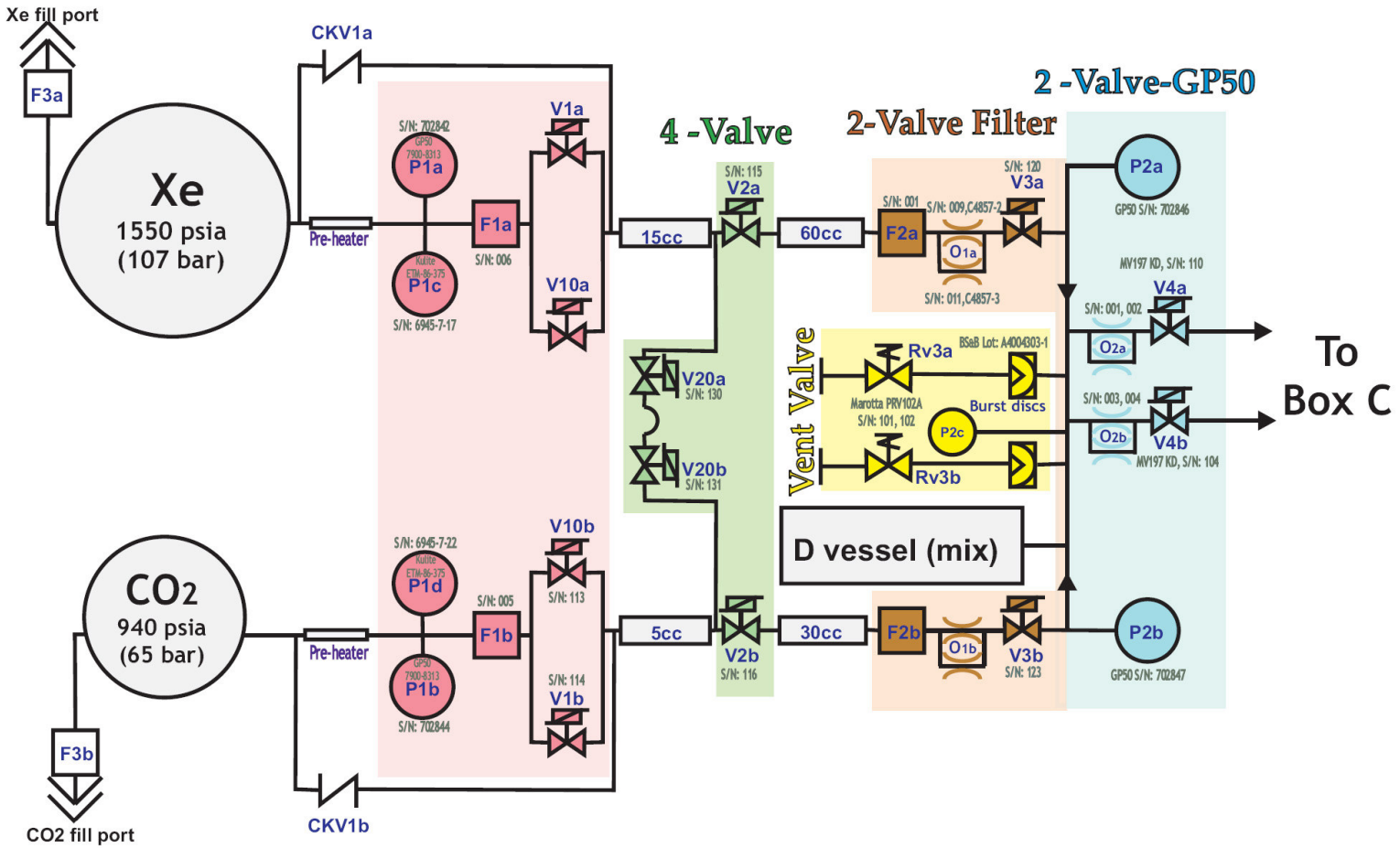
Cryogenic Superfluid Helium System (Note: Warm Helium Supply upper left corner, Cryosystem addressed in AMS-02-F03)



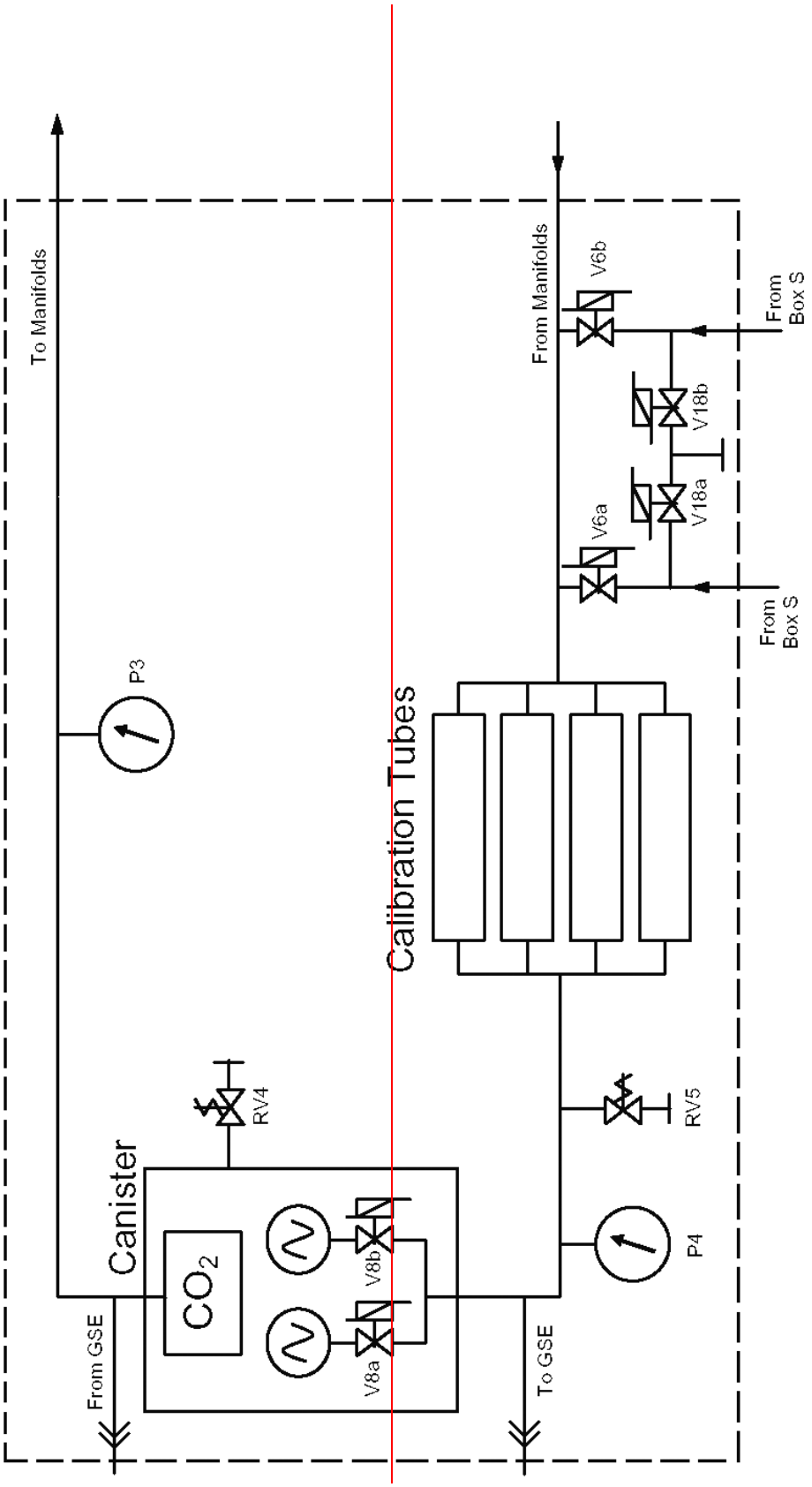
Cryosystem Warm Helium Gas Supply
(See Legend from Cryogenic Superfluid Helium System Diagram)

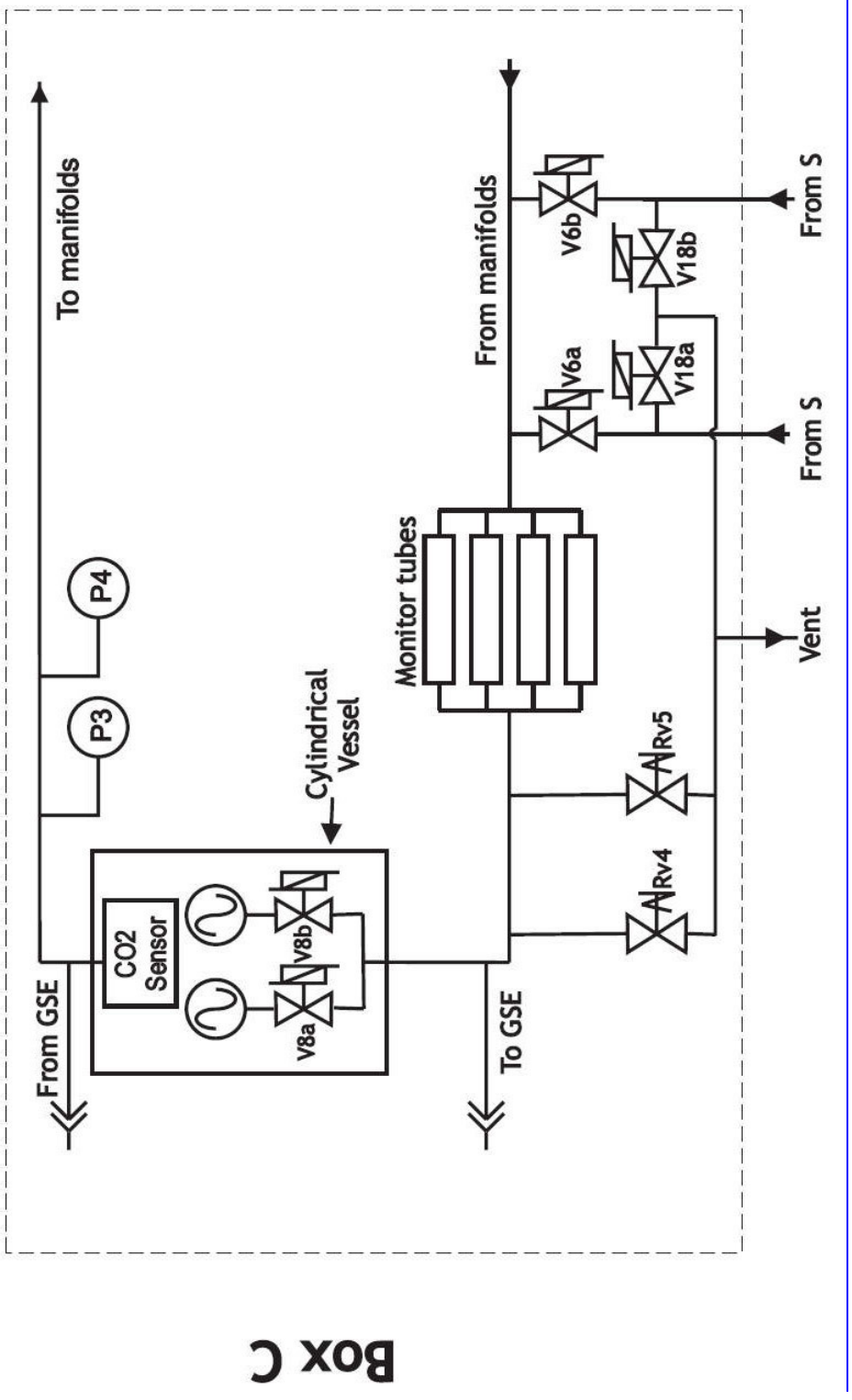

Box S Schematic
To Box C
2 -Valve-GP50
2-Valve Filter
4 -Valve
Vent Valve
D vessel (mix)
Tower-Valve & Filter
Xe
1550 psia
(107 bar)
CO2
940 psia
(65 bar)
Xe fill port
CO2 fill port
Pre-Heater
60cc
30cc
15cc
3cc

Box S Schematic

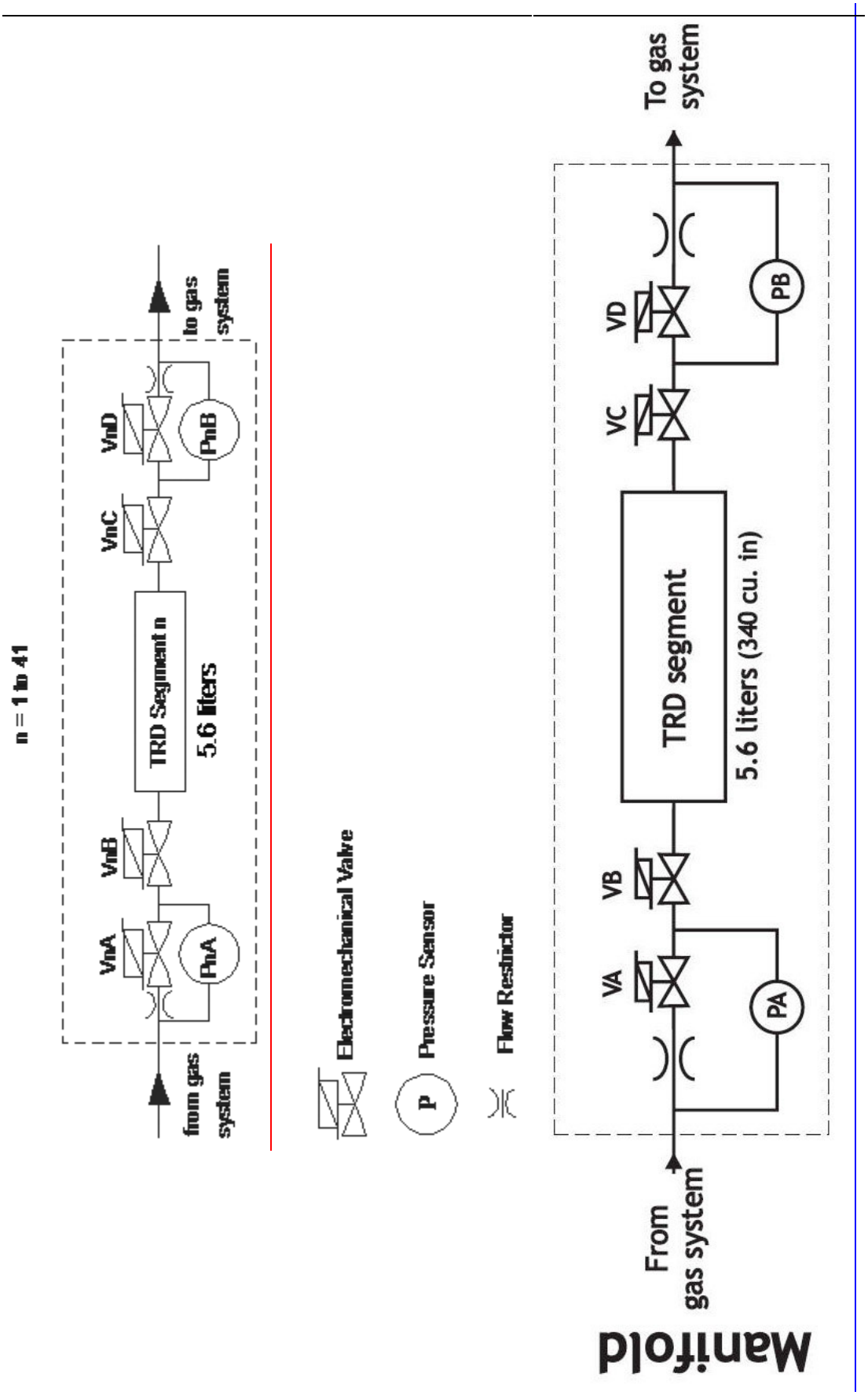


TRD Box S (Pressures are nominal operating pressure)

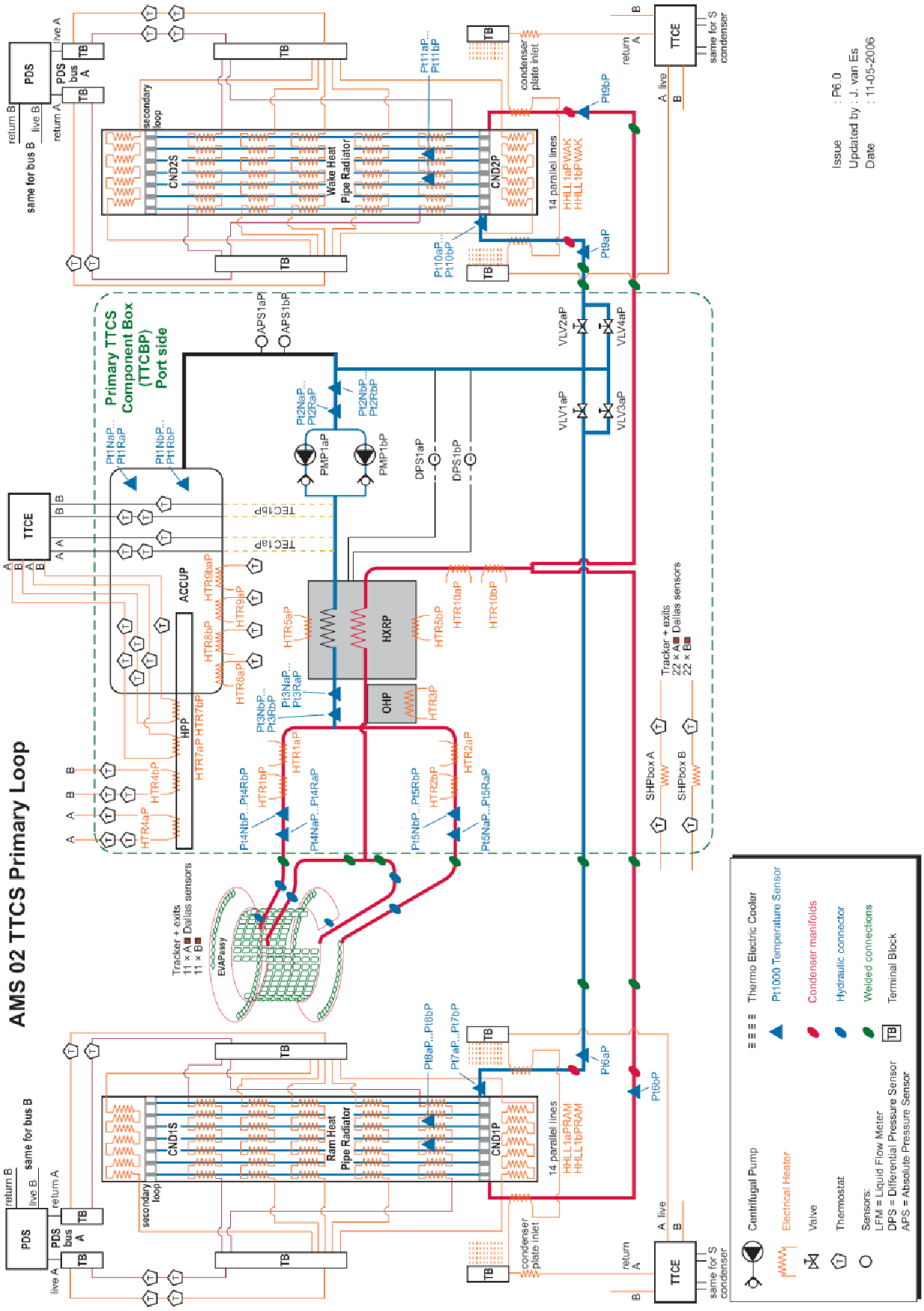

To Manifolds
From Manifolds
V6b
From Box S
V18b
V18a
V6a
From Box S
P3
Calibration Tubes
RV4
RV5
Canister
CO_2
V8b
V8a
P4
From GSE
To GSE

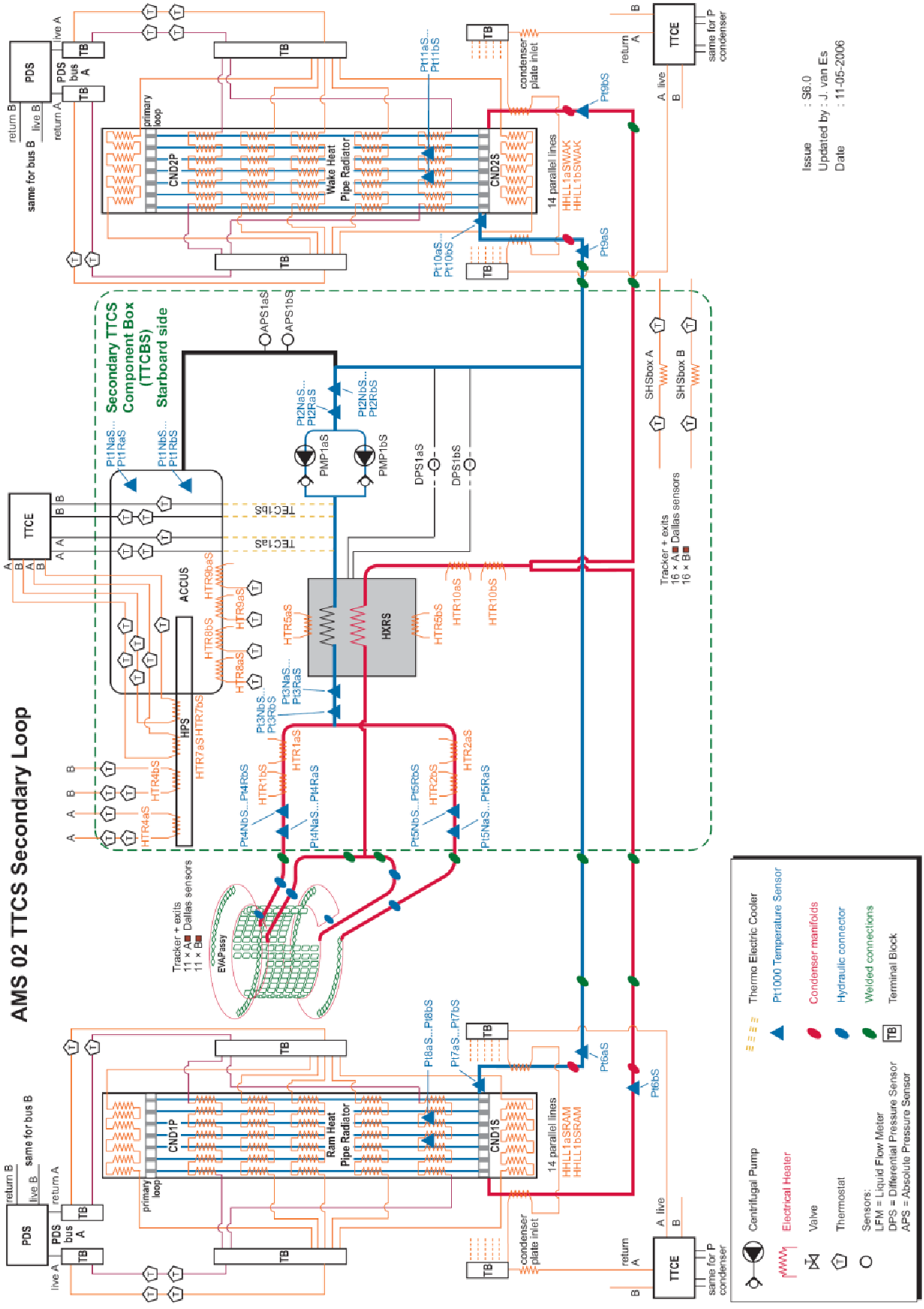

Box C
To manifolds
P4
P3
Cylindrical Vessel
CO2 Sensor
V8b
V8a
From GSE
To GSE
Monitor tubes
From manifolds
Rv5
Rv4
V6b
V18b
V6a
V18a
From S
From S
Vent

TRD Box C

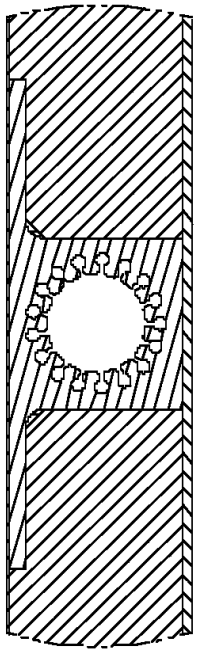

n = 1 to 41
from gas system
VnA
PnA
VnB
TRD Segment n
5.6 liters
VnC
VnD
PnB
to gas system
Electromechanical Valve
Pressure Sensor
Flow Restrictor
Manifold
From gas system
VA
PA
VB
TRD segment
5.6 liters (340 cu. in)
VC
VD
PB
To gas system

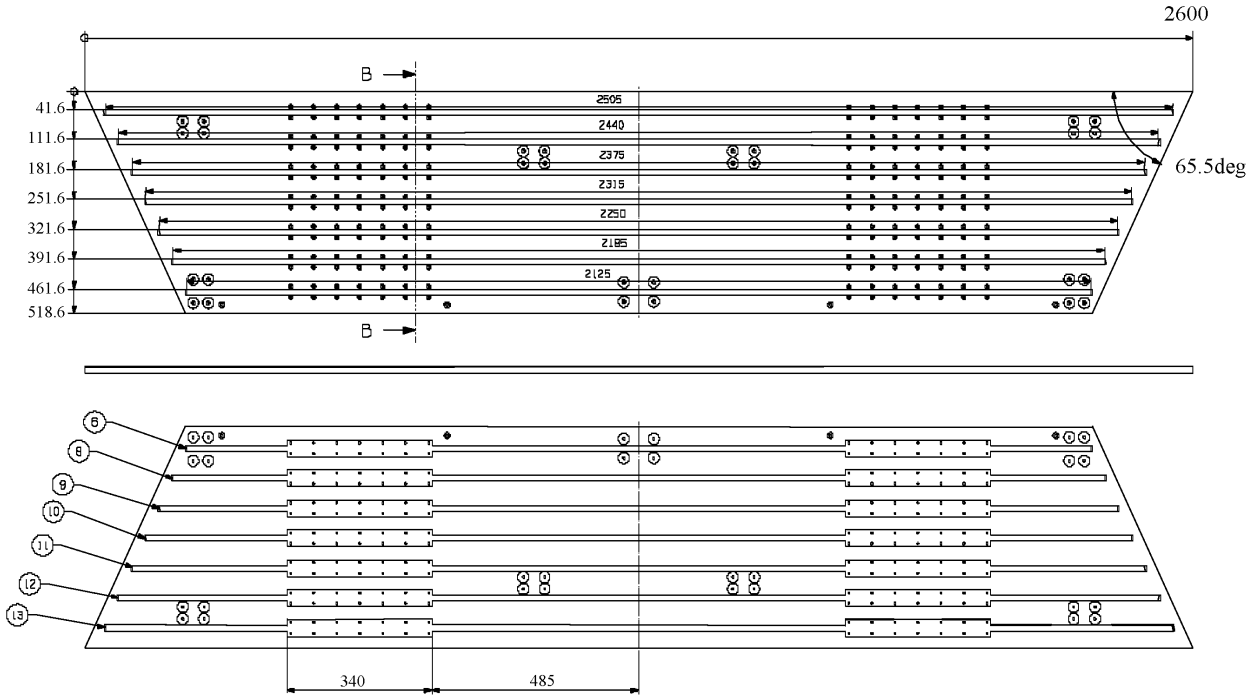
TRD Manifold-Straw Representation


AMS 02 TTCS Primary Loop
Primary TTCS Component Box (TTCBP) Port side
Issue : P6.0
Updated by : J. van Es
Date : 11-05-2006
PDS
TTCE
CND2S
CND2P
CND1S
CND1P
Wake Heat Pipe Radiator
Ram Heat Pipe Radiator
14 parallel lines
secondary loop
condenser plate inlet
same for bus B
same for S condenser
ACCUP
HPP
HXRP
OHP
PMP1aP
PMP1bP
DPS1aP
DPS1bP
APS1aP
APS1bP
VLV1aP
VLV2aP
VLV3aP
VLV4aP
SHPbox A
SHPbox B
Tracker + exits
22 × A■ Dallas sensors
22 × B■
11 × A■ Dallas sensors
11 × B■
EVAPassy
Centrifugal Pump
Electrical Heater
Valve
Thermostat
Sensors:
LFM = Liquid Flow Meter
DPS = Differential Pressure Sensor
APS = Absolute Pressure Sensor
Thermo Electric Cooler
Pt1000 Temperature Sensor
Condenser manifolds
Hydraulic connector
Welded connections
Terminal Block

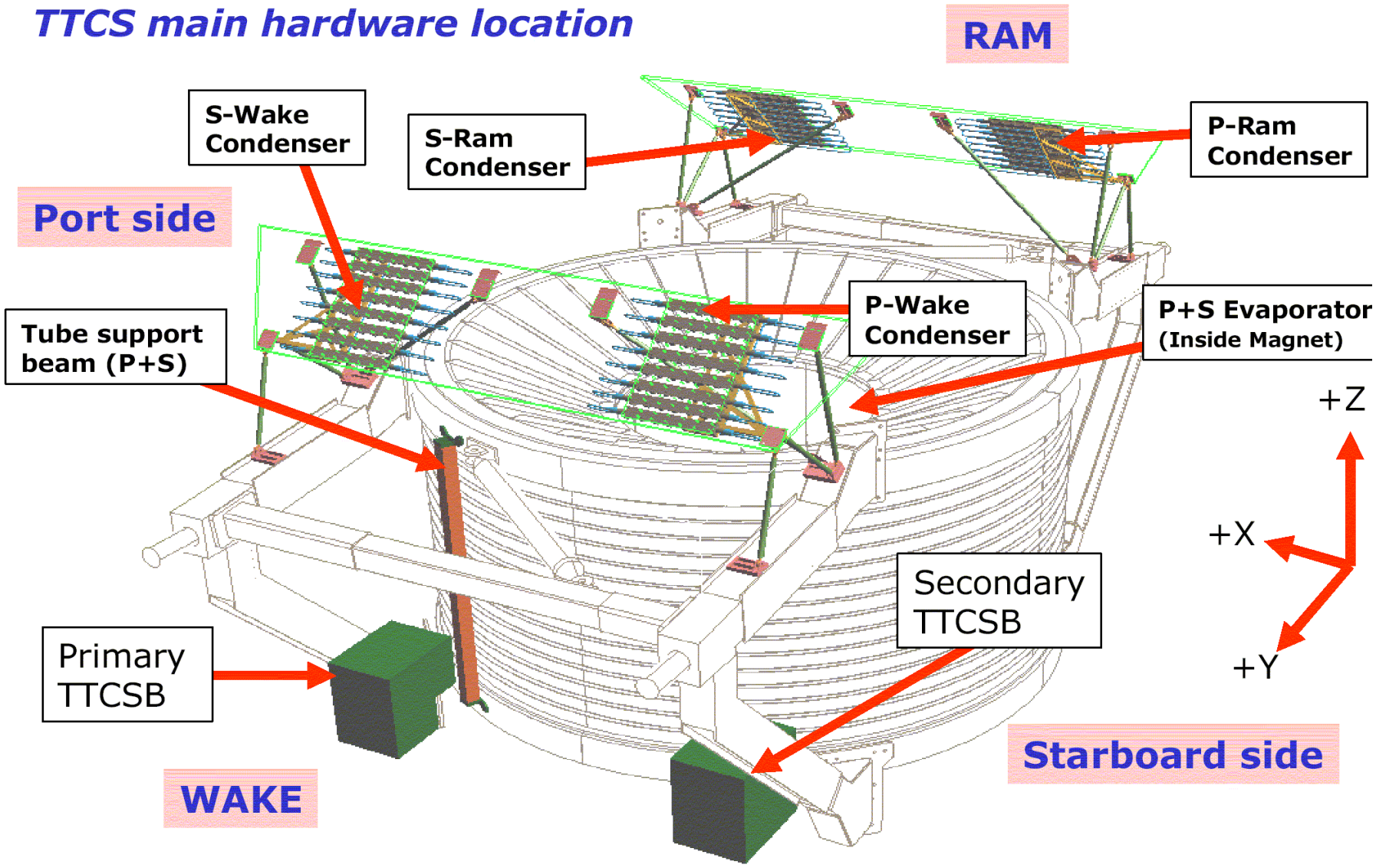

AMS 02 TTCS Secondary Loop
Secondary TTCS Component Box (TTCBS) Starboard side
Issue : S6.0
Updated by : J. van Es
Date : 11-05-2006
PDS
TTCE
CND2P
CND2S
CND1P
CND1S
Wake Heat Pipe Radiator
Ram Heat Pipe Radiator
primary loop
14 parallel lines
condenser plate inlet
ACCUS
HPS
HXRS
PMP1aS
PMP1bS
DPS1aS
DPS1bS
SHSbox A
SHSbox B
Tracker + exits
16 × A Dallas sensors
16 × B
11 × A Dallas sensors
11 × B
EVAPassy
Centrifugal Pump
Electrical Heater
Valve
Thermostat
Sensors:
LFM = Liquid Flow Meter
DPS = Differential Pressure Sensor
APS = Absolute Pressure Sensor
Thermo Electric Cooler
Pt1000 Temperature Sensor
Condenser manifolds
Hydraulic connector
Welded connections
Terminal Block

Tracker
Heat
Pipe

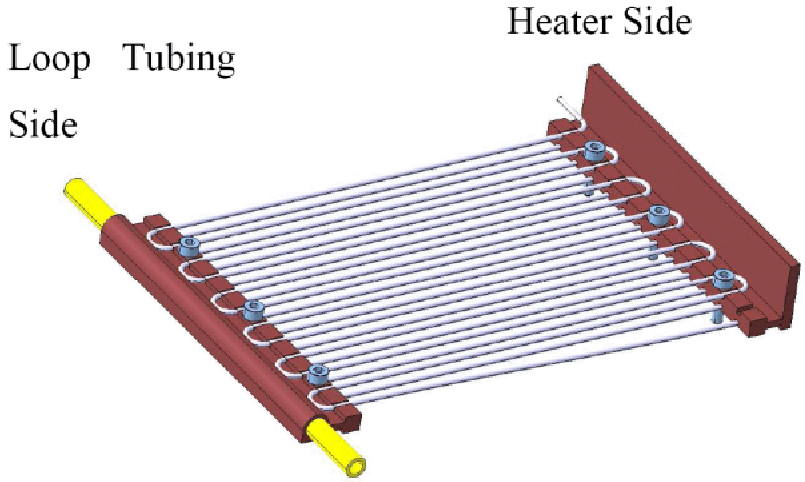




Tracker TCS Heat Pipe Layout

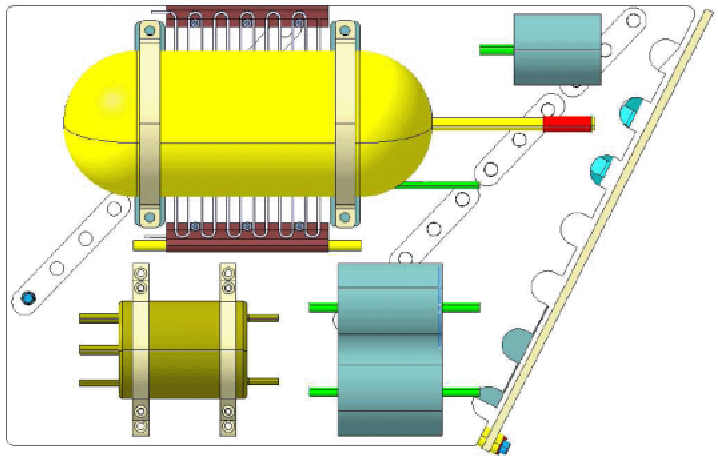


Components of the Tracker Thermal Control System



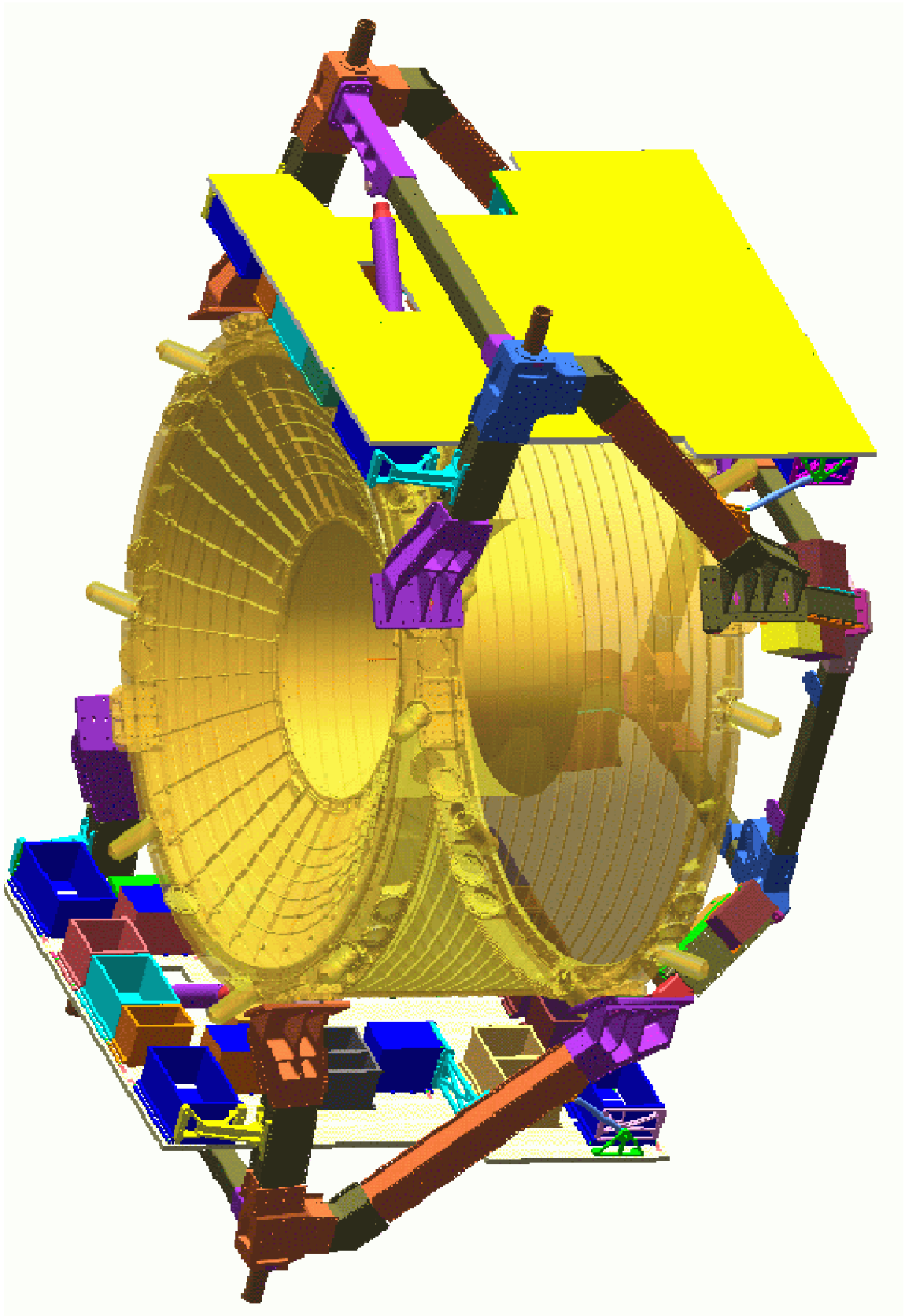
TTCS Oscillating Heat Pipe Layout

(Stainless Steel 316L 0.5 mm radius tube with 0.1 mm thickness)

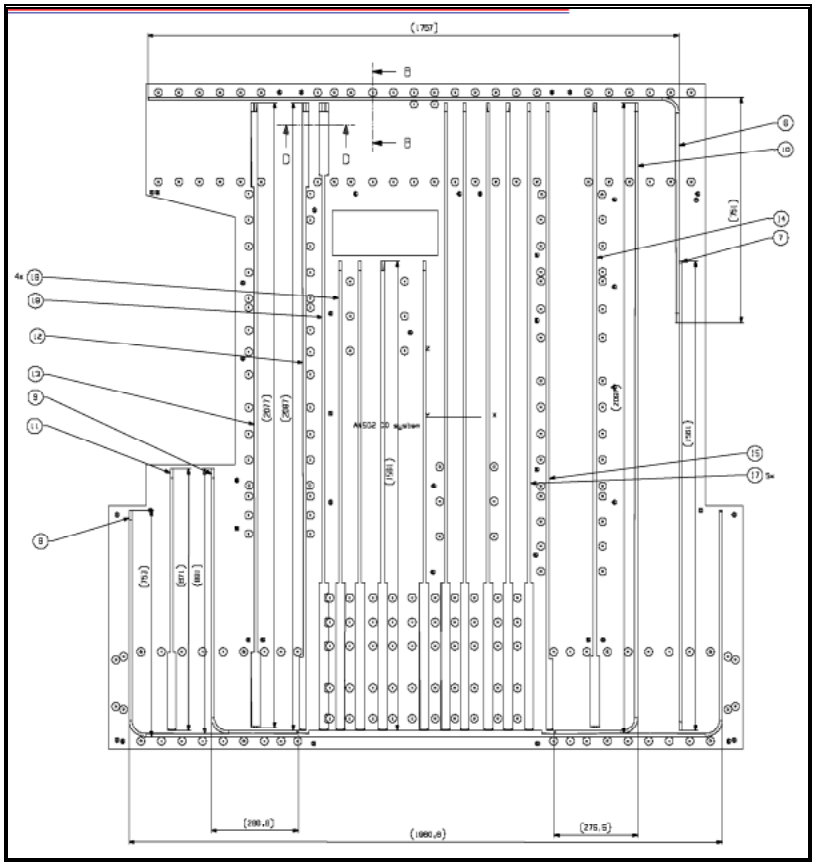


TTCS Oscillating Heat Pipe Experiment Located Behind TTCS Accumulator.

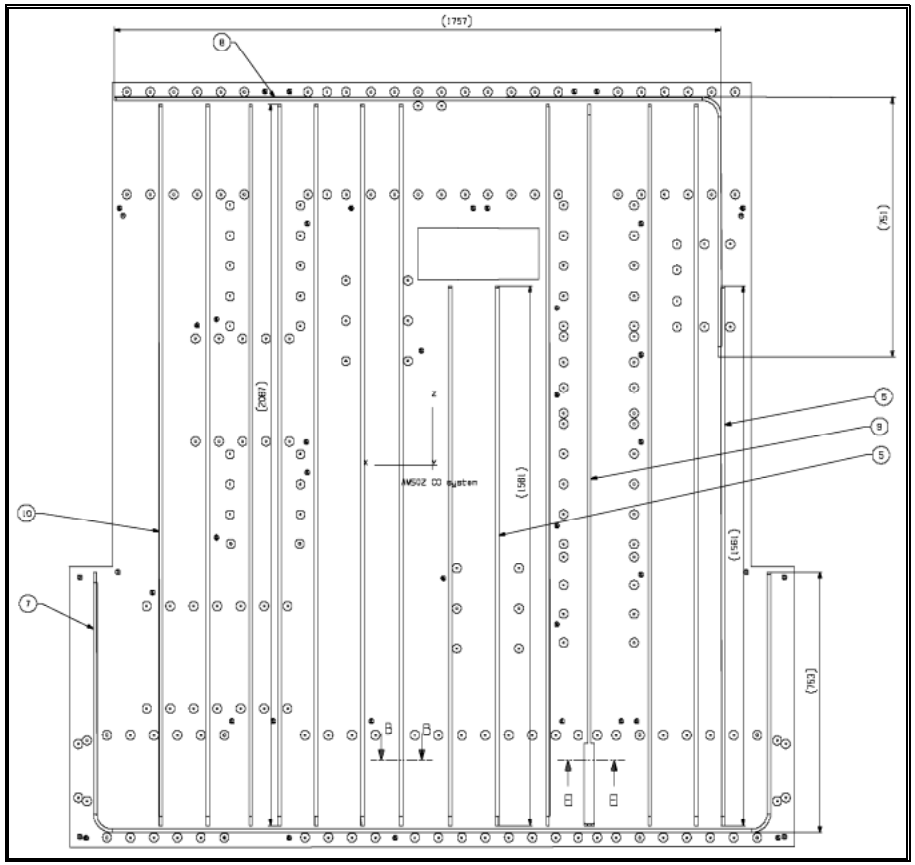
TTCS Accumulator Heat Pipe Projecting from Accumulator.



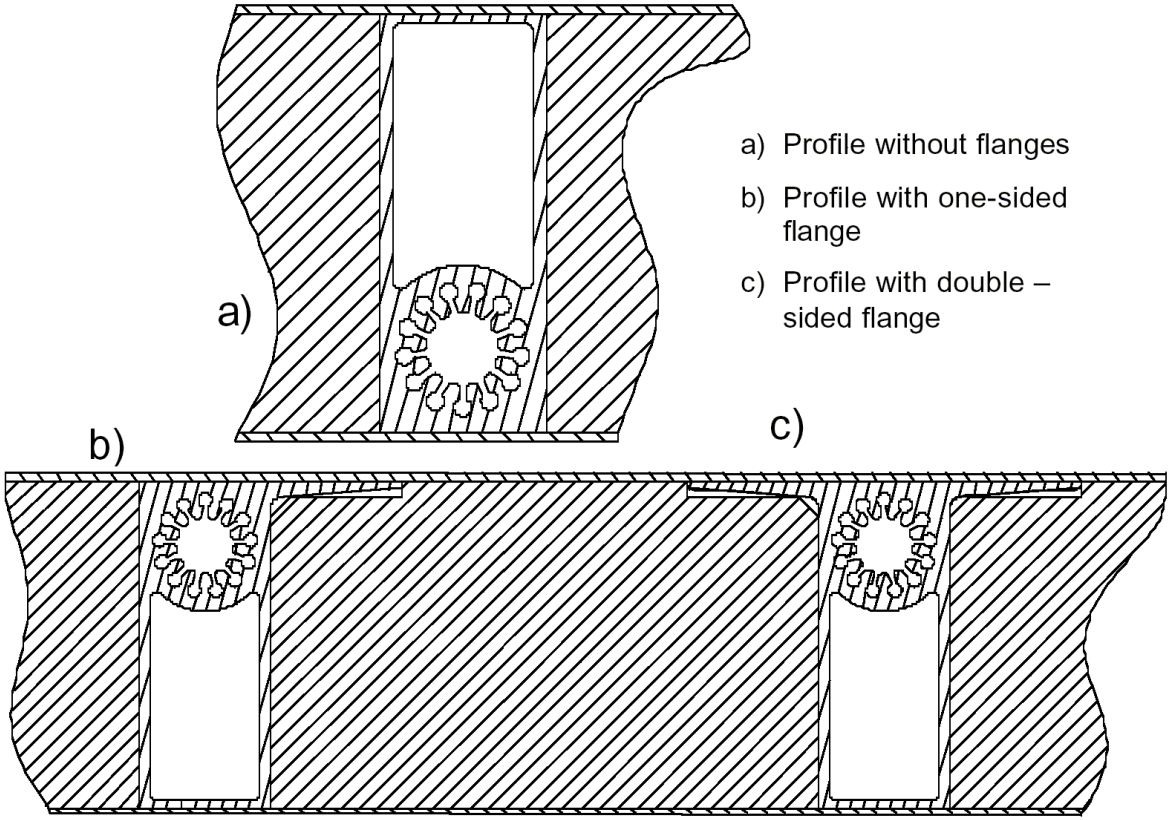
AMS-02 Wake and Ram Radiators



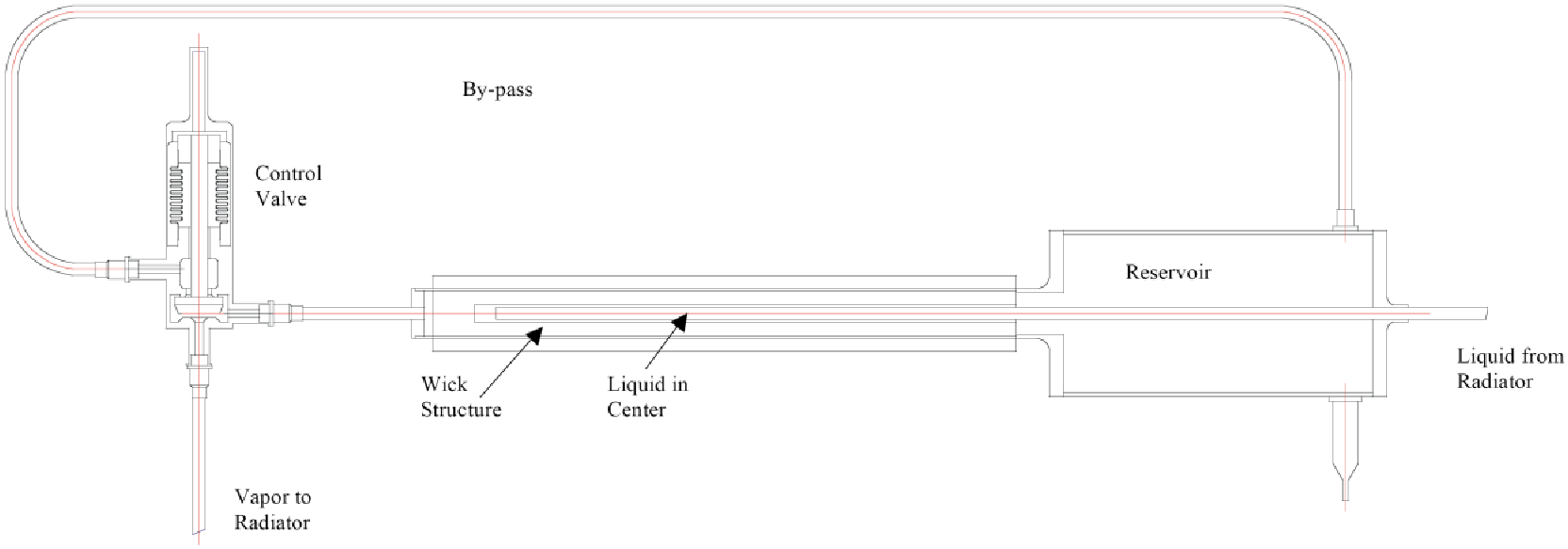
TCS – Wake Side Radiator for Avionics Crates



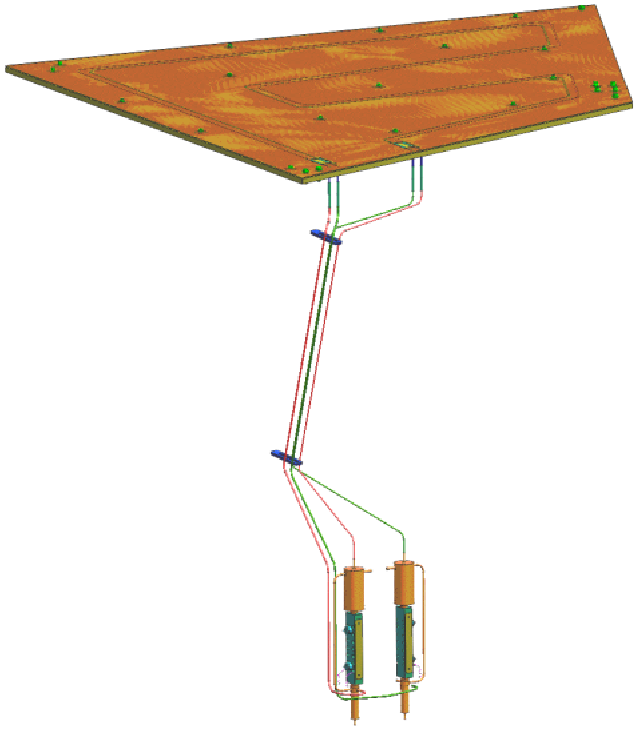
TCS – Ram Side Radiator for Avionics Crates



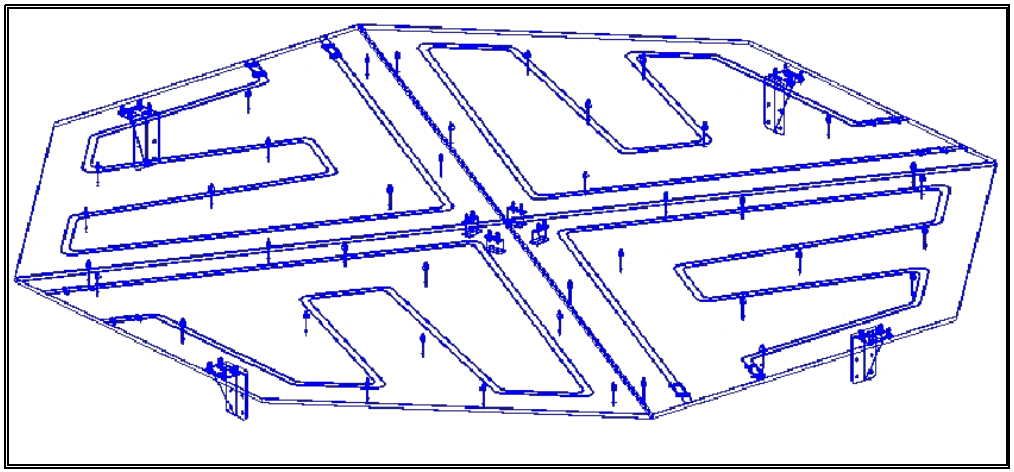
TCS Wake and Ram Radiators Heat Pipe Methods of Mounting



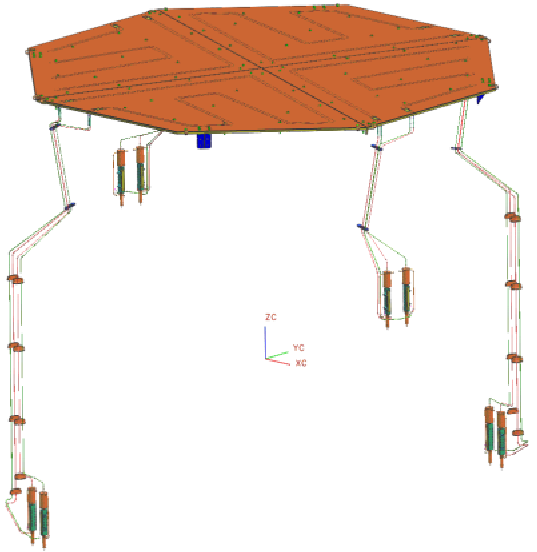
Cryocooler Loop Heat Pipe (to Zenith Radiators) Schematic



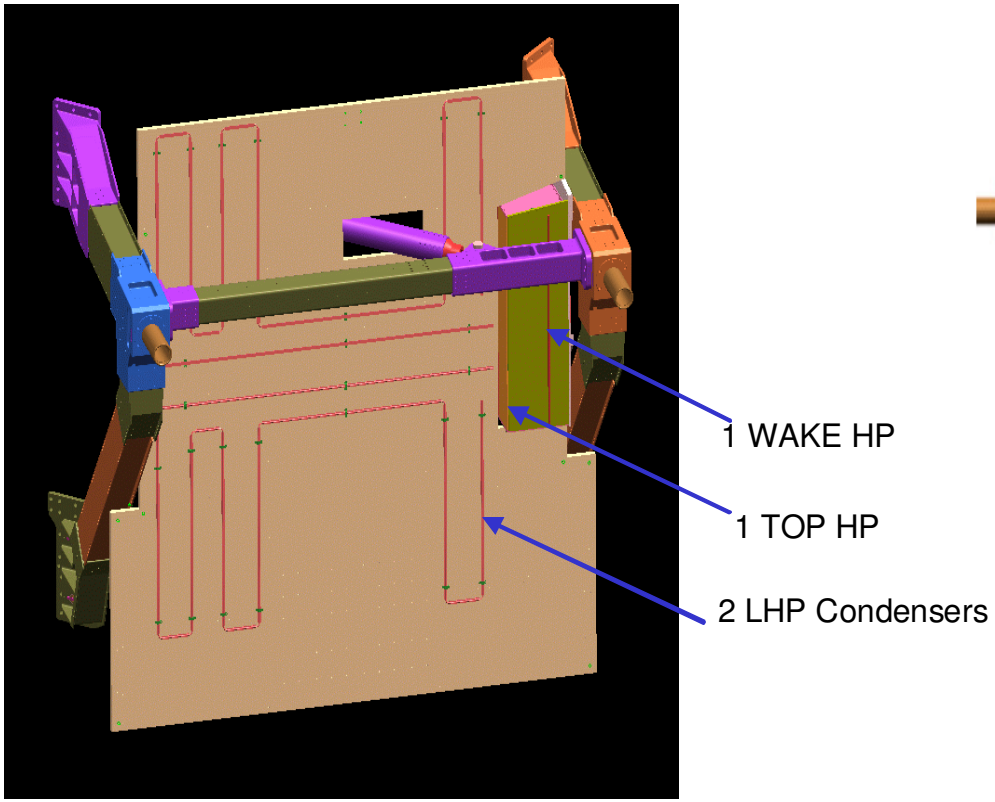
Cryocooler Zenith Radiator Sub Panel

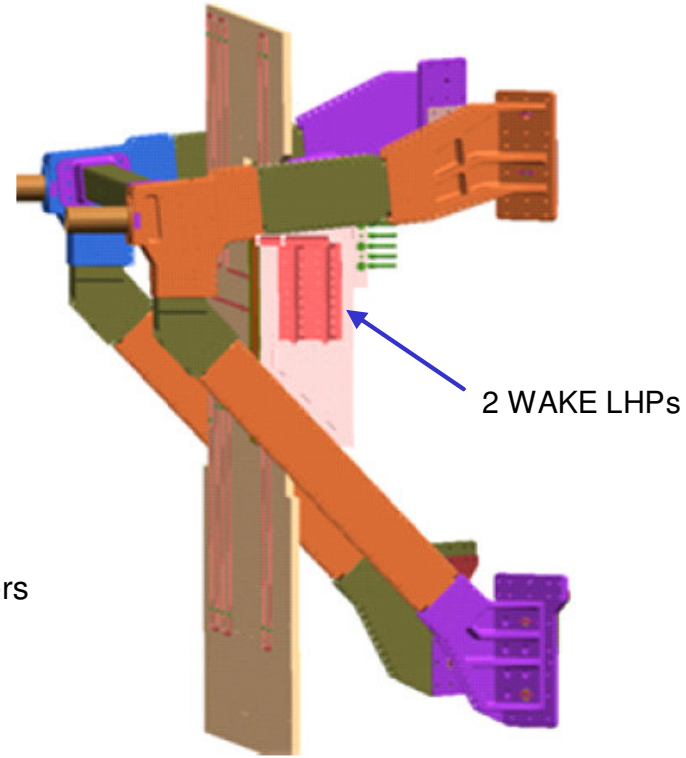


Cryocooler Zenith Radiator – Four Sub-Panel Layout



Four Cryocooler Loop Heat Pipes and Zenith Radiators





Cryomagnet Avionics Box
Layout and Configuration

CAB USS Heat Pipes – Enveloped in Heat Pipe Analyses

Space Cryomagnetics

Technical Report

Item:	Loss of Vacuum and Venting from the AMS-02 Cryostat	Author:	S M Harrison
Issue	01	Date:	11 December 2002
Dist.:	SCL, ETH, Lockheed Martin		

1 Introduction

The AMS-02 superconducting magnet cryostat contains a cryogenic vessel holding up to 2500 litres of superfluid liquid helium at a temperature of approximately 1.8 K (-271.35 C). If liquid helium at this temperature is converted to gas at room temperature and pressure (295 K, 1.01325 bar) the volume increases by a factor of 880, so the presence of such a large quantity of cryogenic liquid is considered potentially hazardous.

This report describes the development which has been undertaken to demonstrate that the AMS-02 cryogenic system is safe on the ground at the Kennedy Space Center – and in the Space Shuttle - under all conceivable modes of operation and fault conditions.

2 Basis of the Hazard

Superfluid helium has very high specific heat capacity so it takes a great deal of energy to increase its temperature. The power required for rapid warming can generally only be generated from two sources: either by quenching of a superconducting magnet immersed in the helium, or by a leak into the vacuum chamber which normally insulates the helium vessel. In the case of AMS-02, the superconducting magnet is entirely separate from the helium tank and is cooled by conduction, so a magnet quench cannot dissipate energy rapidly into the helium. (In addition, the magnet will never be energised inside the Shuttle.) However, there are some circumstances under which a rupture or leak of the vacuum case may be credible.

2.1 Insulation of Liquid Helium Vessels

Effective insulation of cryogenic tanks is always required to reduce the heat transfer from ambient temperature surroundings to the cold surfaces. This makes long-term storage of the cryogen feasible, and it prevents condensation or ice formation on components exposed to the atmosphere. Cryogenic insulation uses some combination of vacuum (to eliminate convection and conduction), radiation shields and multi-layer insulation (MLI) to reduce radiation.

2.2 Vacuum Leak

If a hole appears in the vacuum vessel, air begins to leak into the vacuum chamber. Because the pressure inside the vacuum case is so low, the air flow is choked in the hole and the rate of ingress is limited. What happens subsequently depends on the size of the hole and the cold surface area. If the hole is relatively small and the cold surface area is large, all the incoming air will freeze on the cold surface (this process is usually called "cryopumping"). The air gives up its latent heat and warms the cryogen, but the vacuum pressure remains very low because the cryopumping removes all the air from the vacuum space. However, if the hole is large enough (or the cold surface area is small) the air will enter the vacuum space faster than it can be removed by cryopumping. In this case the vacuum will be degraded, and convective heat transfer will be added to the heat load due to freezing and condensation of the air.

2.3 Catastrophic Loss of Vacuum

The worst conceivable fault scenario for any cryogenic system is a catastrophic loss of the insulating vacuum. This is what happens after a large hole (several inches in diameter) is suddenly punched in the vacuum vessel. Air rushes through the hole so quickly that any cryopumping is overwhelmed and the vacuum chamber quickly rises to atmospheric pressure.

3 Defining the Fault Scenarios

Two different fault scenarios have been defined for the AMS-02 magnet system, one for ground processing and the other for launch pad operations. (All possible landing scenarios were also considered, but none presented hazards as serious as launch.)

3.1 Loss of Vacuum During Ground Processing

During ground processing, the vacuum case could be punctured as a result of a major accident such as a collision with a vehicle or another unlikely mishap. For all ground operations, therefore, a catastrophic loss of vacuum - as defined in Section 2.3 above - has to be considered.

3.2 Vacuum Leak in the Shuttle Bay

Once the magnet is inside the Space Shuttle, a major incident such as a collision is no longer considered credible. The following text is from an e-mail sent by Ken Bollweg of Lockheed Martin on 20 September 2001, and it summarises the procedure agreed with NASA.

> *"A meeting was held on September 5, 2001 at JSC to discuss the status of the AMS-02 Helium Vent Tests at Space Cryomagnetics Ltd. (SCL) and to establish further test and analyses plans. Attendees included Rick Miller, Brad Harris, Mark Fields, Ray Serna, Jim Bates, Rick Sanchez, Daniel Newswander, Doug Cline, Trent Martin, Phil Mott, and myself . (Details on this meeting are included in Trent Martin's e-mail dated September 6th below.) Jim Bates and I then followed up with Dave O'Brien (PSRP Chair) on September 5th as well.*
>
> *It was agreed that there is no credible scenario that could lead to a sudden loss of vacuum in the AMS-02 Cryomagnet Dewar after the Orbiter payload bay doors were closed and prior to launch. The temperature of the Superfluid Helium (SFHe) Tank and pressure of the SFHe Tank as well as pressure of the Cryomagnet Vacuum Case (VC) will be monitored until Launch minus 9 minutes. At that time a go/no-go call on the status of the cryogenic systems will be made by AMS. The requirements for the frequency of measurements, number of sensors, etc. are still TBD.*

The following leak scenario was worked out with Dave O'Brien on September 5th and reviewed with Bill Manha on September 17th:

There are two large O-ring seals (~9 ft. diameter x ¼ inch diameter cross-section) at each of the four joints between the VC Outer Cylinder to Support Rings and Support Rings to the Conical Flanges; i.e. 8 large O-rings in all. There are several other dual O-rings throughout the hardware but they are much smaller (< 6 inches). We will consider two large O-rings to be pinched at assembly and that the pinches are right next to each other on the same joint. Both "pinches" will be ~3 inches long but will not be detected during initial leak tests on the individual O-rings using the test ports between the seals. We will then assume that it is determined (via the test ports) that one of them is leaking at the launch pad. It would be a monumental undertaking lasting SEVERAL months to disassemble the entire experiment, grind out the welds on the VC, open it up, repair the leaking O-ring(s), reassemble the Cryomagnet and re-weld the VC, reassemble the entire experiment, and recalibrate it. Obviously, we would argue against the need to do this.

So, we will then assume the second pinched O-ring starts leaking due to vibrations from SRB ignition at launch. Using the assumption that the leak path is ~3 inches long by the maximum gap we could possibly have gives us the maximum equivalent hole we should use in the next small dewar vent tests. This is still quite conservative since a very narrow, long, deep hole will never allow as much flow as a round, shallow hole of the same area.

Therefore, if the maximum gap is 0.001 inch, the area is 0.003 square inches, which is the equivalent area of a ~0.062 inch diameter hole. A 0.001" gap with 192 bolts at ~1¼ inch spacing is highly unlikely since the flanges will be in direct contact with each other and can be inspected. However, this will be assumed for the next small dewar vent test. For the last test, an even more unrealistic 0.003 inch gap will be assumed. This is the equivalent of a ~0.107 inch diameter hole. Both these hole sizes will be scaled down from the full-scale flight SFHe Tank (~2500 liters) geometry to the small dewar SFHe Tank (~15 liters) used in the vent tests. In these tests, there will be no insulation on the small dewar SFHe Tank. If successful, the flight SFHe Tank will be insulated with four vapor-cooled shields and ~200 layers of MLI. There would be no Cryocoat or other insulation on it.

Keep in mind, that the burst disks and ground vent plumbing still must be sized and designed to adequately protect the system against over-pressure and personnel exposure during all phases of ground processing at all sites."

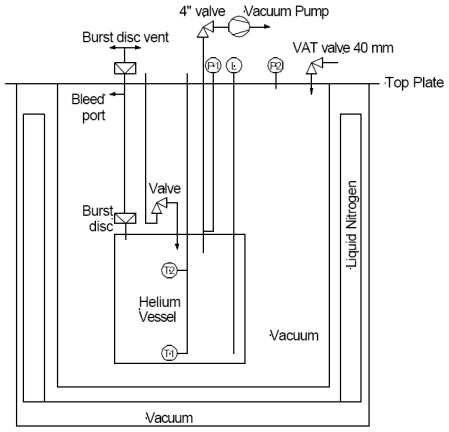


Figure 1

This procedure has been followed, with the single exception that Cryocoat insulation is now to be applied to the magnet superfluid helium vessel for reasons outlined below. Accordingly, the tests on the small dewar have been performed with this same insulation, prepared and applied in the same manner.

4 Venting Demonstration Test Rig

The venting demonstration test rig (VDTR) is shown schematically in Figure 1, and a picture of the test insert is given in Figure 2. The VDTR consists of a stainless steel vessel containing the superfluid helium. The vessel is suspended from a top plate by a neck tube, 40 mm in diameter, which allows the vapour pressure of the helium to be lowered so that the temperature can be reduced from 4.2 K (the boiling point at atmospheric pressure) to 1.8 K. The thin copper discs visible in Figure 2 are radiation baffles, which reduce the transfer of heat from the top plate - at room temperature - to the cold helium. The test insert is mounted inside a bucket test dewar. This is a cylindrical volume, 350 mm in diameter, which can be evacuated. It can be cooled with liquid nitrogen, which means that the test volume is normally under vacuum, with the walls at approximately 80 K. (The walls have to be cooled, otherwise the radiant heat load from room temperature would be so high that it would be impossible to collect liquid helium in the system. In the real AMS magnet, this function is achieved with MLI and radiation shields, but these would provide additional insulation following loss of vacuum, as well as extended surfaces for cryopumping, so the test arrangement is conservative.) The test volume can be opened to atmosphere through a 40 mm diameter, fast-acting valve. Different orifices can be positioned in series with the valve to control the rate of air ingress: with no orifice, the 40 mm hole is large enough to simulate a catastrophic rupture of the vacuum vessel.

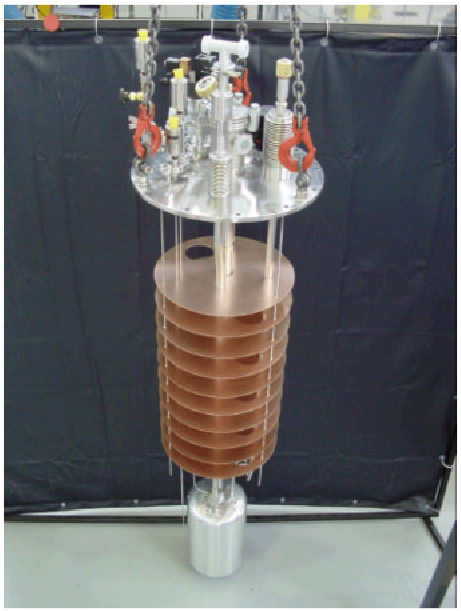


Figure 2

5 Vacuum Leak Tests

A set of three tests is required: one for each of the hole sizes required plus one with no hole at all to measure the background heating due to the test rig alone. This background heat load should be relatively much larger for the test rig owing to its small size and because it is not so thoroughly optimised for thermal performance as the AMS magnet system.

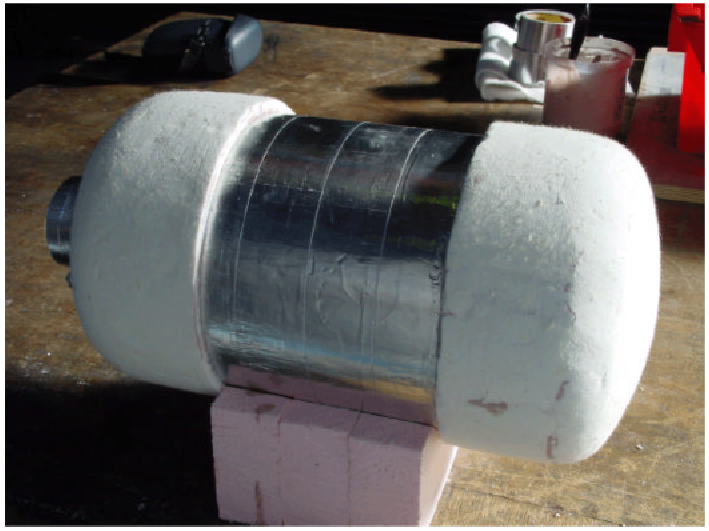


Figure 3

5.1 Insulation

The helium tank for the AMS magnet will be insulated using a proprietary system called "Cryocoat Ultralight", manufactured by Composite Technology Development (CTD) of Lafayette, Colorado. The insulation is produced in the form of 3 mm thick tiles with dimensions up to 300 mm x 300 mm. The tiles are conformable when first applied to the tank, but cure at room temperature after about 24 hours. Because the insulation may have an effect following a vacuum leak, identical tiles have been used to insulate the test vessel.

Another important feature of the insulation is that it should help to make the test vessel geometrically as similar as possible to the magnet system. Because the volume in the VDTR is about 200 times less than in the magnet helium vessel, the surface area to volume ratio of the VDTR is much bigger, even though the magnet helium vessel is toroidal rather than cylindrical. This could potentially distort the experimental results, since a large A/V ratio could make cryopumping in the VDTR more effective than in the magnet system. Additional insulation, to a thickness of 15 mm, has therefore been added to parts of the

VDTR vessel to control precisely the surface area over which cryopumping can take place (see Figure 3). The neck tube is also thickly insulated for the same reason. The thinly insulated area to volume ratio of the VDTR vessel is thus the same as the total A/V ratio of the magnet system helium vessel.

5.2 Hole Size Determination

Calculations show that the hole sizes under consideration are sufficiently small that virtually all the air entering the vacuum space will be cryopumped onto the cold surfaces. Under these circumstances, the heat given up to the helium will be directly proportional to the flow rate of air. Since the air ingress must be choked, the flow rate will be directly proportional to the cross-sectional area of the hole. It follows that if

$$\frac{A_{VDTR}}{V_{VDTR}} = \frac{A_{AMS}}{V_{AMS}}$$

where A is the area of the hole and V is the volume of superfluid helium then the rate of pressurisation of the helium should be identical in both cases. Given that the background heat load in the test vessel is relatively much higher than in the magnet vessel, and that the radiation shields and MLI in the magnet system provide considerable additional cryopumping compared with the VDTR, tests conducted using these ratios for the VDTR must actually be conservative. That is, the VDTR will pressurise more quickly than the AMS magnet system.

The surface area and volume of the AMS magnet helium vessel are 19 m^2 and 2460 litres respectively. The corresponding area and volume of the VDTR vessel are 0.106 m^2 and 13.8 litres, to give the same A/V ratio in each case.

5.3 Test Procedure

The procedure in each of the tests was the same. The vessel was filled with normal liquid helium boiling at 4.2 K. The temperature was reduced by pumping on the vapour above the liquid. By repeated filling and pumping cycles the vessel was filled with superfluid helium at around 1.6 K. The liquid level was monitored by a standard helium liquid level probe but, for better accuracy, the actual mass of helium inside the vessel was calculated from the change in mass (the whole VDTR is suspended from a load cell). Valves were then used to isolate the vessel, and the pressure and temperature inside were monitored. In the case of the two tests using orifices to simulate leaks, the vent valve was opened to admit air into the vacuum space. The purpose of the other test was simply to measure the background effect of the test rig itself, so the vent valve remained closed throughout. When the pressure in the tank reached about 4 bar, another valve was opened to vent the helium space.

MODEL HOLE DIAMETER	FULL SIZE HOLE DIAMETER	FULL SIZE O-RING GAP
0.12 mm 0.0047 inch	1.60 mm 0.063 inch	0.0264 mm x 76.2 mm 0.00104 inch x 3 inch
0.21 mm 0.0083 inch	2.79 mm 0.110 inch	0.0810 mm x 76.2 mm 0.00319 inch x 3 inch

The orifices were made by laser drilling stainless steel vacuum blanks then accurately measuring the hole diameters. The two holes used were 0.12 mm and 0.21 mm in

diameter. Using the analogy in Section 3.2 above, the equivalent gaps where the O-rings are pinched are 0.00104 and 0.00319 inches respectively, slightly exceeding the agreed maximum gap sizes in the full size vacuum case. The correlation between hole sizes in the test facility (model) and the full size vacuum case is summarised in Table 1.

5.4 Test Results

Figures 4 and 5 show the temperature and pressure in the helium tank for the three experiments. Zero time for the two experiments with orifices was taken as the instant when the vacuum vent valve was opened. Zero time for the calibration test was taken to give a start temperature close to the zero time temperatures of the other tests.

On the pressure plots, there is an abrupt change of slope at 1200 s, 2600 s and 4000 s for the 0.21 mm hole, 0.12 mm hole and no hole cases respectively. These correspond to points of inflexion on the temperature plots, and mark the transition of the helium from the superfluid to the normal state. The depressurisation can be seen on all the pressure plots when the pressure was between 3.5 and 4.5 bar: what is of interest is the time taken to reach 3 bar, as this is the set pressure for the burst discs on the AMS helium vessel. (Note that the actual maximum pressures reached in the three tests were different: this is because the pressure was released manually rather than waiting for a set of burst discs to be destroyed in each case.) The effect of the depressurisation can also be seen on the temperature plots as a sudden drop in temperature. In the case of the 0.21 mm hole, it can be seen that the temperature then recovers to 4.2 K and the helium continues to boil at atmospheric pressure.

- With no vacuum vent hole, the helium pressure reached 3.0 bar after 6440 s.
- With a 0.12 mm vent hole, equivalent to a double O-ring pinch 3 inches long and 0.00104 inches across, the helium pressure reached 3.0 bar after 4930 s.
- With a 0.21 mm vent hole, equivalent to a double O-ring pinch 3 inches long and 0.00319 inches across, the helium pressure reached 3.0 bar after 2590 s.

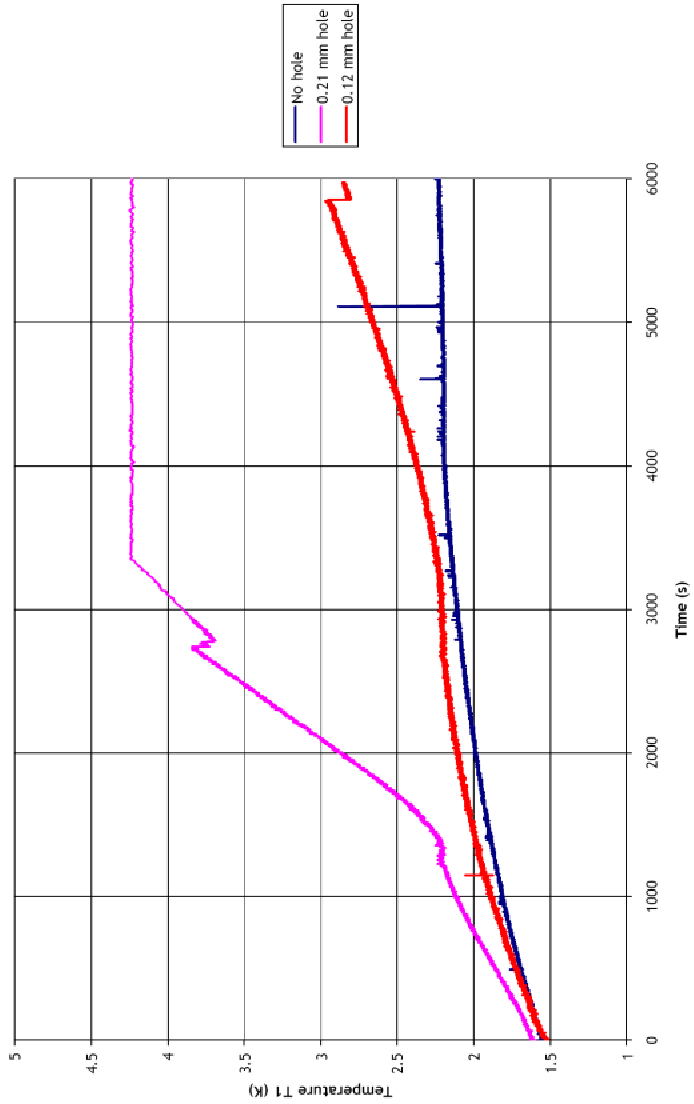


Figure 4

5.5 Discussion

The results above give an indication of the time taken for venting of the helium tank to begin after launch, following the severe damage to the O-rings postulated in Section 3.2 above. The analysis is conservative (times to vent are too short) because:

- The real AMS system has around 200 layers of MLI and four vapour-cooled radiation shields which would increase cryopumping and reduce any residual convection;
- The background losses in the real AMS should be two orders of magnitude lower (relative to helium volume) than in the VDTR, so all times to vent should be much longer.

Two remaining variables are the liquid level in the system at launch, and the exact temperature of the helium. If AMS was launched without the helium vessel being full the helium would warm up to the superfluid/normal liquid transition more quickly. Once through that transition, however, the rate of pressure rise would be lower because of the larger gas volume. The helium temperature in the tests was initially 1.6 K: it could be higher on the launch pad. Again the result would be that the helium reached the superfluid/normal liquid transition more quickly, but pressurisation above this point would proceed as in the tests.

Both these scenarios are very unlikely: the last operation carried out on AMS is a superfluid helium top-off on the launch pad, and the system is flown with a vent pump which pumps on the helium (keeping the temperature down) until 9 minutes before launch. Even if the worst case applied, and the magnet was launched at a temperature close to 2.2 K, the pressurisation curves indicate the times taken to reach 3.0 bar and vent the helium tank as follows.

- With no vacuum leak (VDTR baseline) 2440 s.
- With a 0.12 mm vent hole, equivalent to a double O-ring pinch 3 inches long and 0.00104 inches across, 2330 s.
- With a 0.21 mm vent hole, equivalent to a double O-ring pinch 3 inches long and 0.00319 inches across, 1390 s.

5.6 Conclusion

With all the following simultaneous faults

- Two of the vacuum case O-rings leak at the same position
- The gap between the vacuum case flanges is 0.003 inches
- The leak was not detected during the 12+ months between magnet integration and launch
- The second leak begins to admit air only at the instant of launch
- The MLI and vapour-cooled radiation shields on the magnet system have no effect
- The background heat load on the magnet system is more than 200 times worse than expected
- The system is launched partially full or at an elevated temperature

the helium tank will not pressurise sufficiently to vent the helium for 23 minutes after launch.

Figure 5

6 Catastrophic Loss of Vacuum (Ground Operations Only)

In addition to the vacuum leak tests carried out to determine the behaviour of the AMS system in the event of a leak in the vacuum case at launch, considerable development has been undertaken to determine what would happen in the event of a serious accident during ground operations which resulted in a major breach of the vacuum case. The results of the experiments and analysis were compiled in a paper "Loss of Vacuum Experiments on a Superfluid Helium Vessel" which was accepted for publication by the US Institute of Electrical and Electronics Engineers (IEEE) after peer review.

In brief, the research concluded that the heat flux to superfluid helium contained in an uninsulated tank increases to a level of approximately 31 kW/m^2 and then remains constant until the helium tank is vented through burst discs. Applying a 3 mm thickness of the Cryocoat Ultralight insulation reduced that heat flux by a factor of seven to 4.4 kW/m^2. Knowing the surface area and volume of the vessel, this heat flux was used to determine the calculate of pressure rise in the helium by isochoric heating until the burst disc ruptured. Once the relief path was open, classical compressible flow theory was used to calculate the venting rate of helium from the vessel to the environment. The thermodynamic energy equation was used, together with the venting rate, to calculate the pressure and temperature in the vessel as the helium continued to vent.

There was very close correlation between the results predicted from the calculations and those measured in the experiments (see the above referenced paper). The same technique has therefore been used to determine the required burst disc size on the magnet system. The calculation shows that the burst disc area required is 1520 mm^2, and this has been increased by 5% to 1590 mm^2 to give some additional margin.

The burst discs themselves are designed with intrinsic redundancy, that is there are two bursting mechanisms for each disc (a reverse buckling membrane with a peripheral score line and cutting teeth). This means that a single vent path is sufficient: there is no need for redundant burst discs. The design and arrangement of the burst discs have been provisionally approved by the PSRP, and will be subject to final approval at the Phase 2 safety review.

S M Harrison
11 December 2002

BOEING

Technical Memorandum

The Boeing Company
IDS – NASA Systems
13100 Space Center Blvd.
Houston, TX 77059

Date December 19, 2002 No. TS-TM-02-064

To: Darryl L. Archer
IDS – NASA Systems
D/J387, HS3-30

From: Mark E. Fields
IDS – NASA Systems
D/J351, HS3-30
281-226-5814

Subject: Alpha Magnetic Spectrometer II During Ascent and Descent Orbiter Operations

Contract:	NAS9-20000
Purchase Order:	1970483303
PDRD No.:	N/A
WBS No.:	1.7.1.1
Task No.:	70004
Artemis No:	N/A

References:

1. Request for Assessment, B. Harris, USA, Tracking # TH-GEN-010, December 16, 2002.
2. Fields, M. E., "Superfluid Helium Venting into the Payload Bay from the Alpha Magnetic Spectrometer II During Ascent and Descent Mission Phases", TM-TS-00-048, December 15, 2000.
3. Harrison, S. M., "Loss of Vacuum and Venting from the AMS-02 Cryostat", Lockheed Martin Technical Report, December 11, 2002

1.0 Summary

The Alpha Magnetic Spectrometer II (AMS-2) is an experiment proposed for flight to the International Space Station. The AMS-2 is comprised of a large superfluid helium dewar insulated by a vacuum jacket. The large volume of the superfluid helium if vented into the payload bay during ascent or descent phases would cause pressure increases on structures above Orbiter certification. Current failure venting scenarios of the AMS-2 specify that any release of helium into the payload bay would be after the critical portion of the ascent phase or would happen after landing of the descent phase (Ref 1).

2.0 Background

The AMS-2 contains 2460 liters (86.87 ft^3) of superfluid helium cooled to a temperature of 1.8°K (-456.4°F). The helium, if released, would vaporize to a volume of approximately 76000 ft^3. The payload bay and lower mid-fuselage volume is 18400 ft^3. Previous venting analysis of the AMS-2 (Ref 2) has demonstrated that the increase in the pressure due to the release of the helium would exceed Orbiter certification of existing structures. That study analyzed the helium leaking into the payload bay during the first 3 minutes of the ascent mission phase and during the open vent door portion of the descent mission phase. The leak rate was a blow-down curve that had a duration of 700+ seconds. The failure scenario involved a large hole in the vacuum jacket with an approximate area of 3.29 in^2 that allowed external air to compromise the AMS-2.

The current failure scenario of the AMS-2 involves the O-rings that seal the vacuum jacket. The equivalent hole size in the vacuum jacket is 0.0095 in^2 (Ref 3) due to the O-ring failure. This smaller hole along with factors associated with the size, allow for a longer time between vacuum jacket failure and the release of the helium. This extension prohibits the accumulation of external gasses due to the attainment of a near vacuum in the payload bay after 3 minutes of the ascent flight. During descent, the 23 minutes specified in Reference 2 would place the time of helium release after Orbiter landing.

3.0 Conclusion

The release of the superfluid helium from the AMS-2 cryostat into the payload bay would exceed the certification levels of many Orbiter structures if it occurred during the critical ascent and descent mission phases. The specified failure scenario of the protective O-rings sealing the vacuum jacket of the AMS-2 helium cryostat does not allow the release of helium during any of these critical mission phases.

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