SAFETY MANUAL

FRS II TARGET

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SUMMARY

1 - OVERVIEW OF THE SYSTEM:

This document describes 3 cryogenic targets to be used in G.S.I at S2 and S4 positions of the FRS spectrometer, and the experimental room Cave B.

- First target used at S4 is a copy of the existing target at the entrance of the FRS: 1 cm long and 3 cm in diameter delimited by titanium foils (15 µm thickness).
- Second target used at S2, 20 cm long and 6 cm in diameter is made of mylar (125 µm thickness).
- Third target used in cave B, 10 cm long and 3 cm in diameter is made of mylar (100 µm thickness) glued on a sandblasted vespel piece.

Hydrogen is cooled and liquefied by contact with the second stage of the displex 208 closed-cycle refrigeration system AIR PRODUCTS. This configuration limits liquid volume to 20 cm³ for S4 target, 740 cm³ for S2 target and 125 cm³ for cave B target.

The target and the refrigeration system are in a residual 54 liters vacuum chamber for S4 (respectively 85 for S2 and 52 for cave B) which provides a secondary containment volume in case of a target flask rupture.

The target is connected to a 40 liters storage tank for S4 (respectively 1000 for S2 and 175 for cave B) through two separate check valves. The final pressure in the storage tank will be 1.05 bar. This eliminates any risk of explosion fueled by oxygen leaking into the system. This pressure will be the vapor pressure of the liquid, corresponding to a temperature of 20.5 K for hydrogen.

Filling the target with hydrogen requires about 17.5 liters of gas at NTP for S4 (respectively 640 for S2 and 110 for cave B). As a result, the storage tank is at a pressure of 1.5 bars for S4 (respectively 1.7 for S2 and 1.65 for cave B) before the hydrogen liquefaction. The total amount of hydrogen in use in the entire system is 60 liters at NTP for S4 (respectively 1700 for S2 and 290 for cave B).

According to the Fermilab regulations, *Storage and use of flammable gases at physics experiments*, our system is classified as risk class 0 (hydrogen volum $\leq 7.4\ m^3$). This still does present some explosion potential, so the system has been designed to be fail-safe and constitutes a totally closed loop with two levels of containment.

The basic idea behind safe handling of any flammable or explosive gas is to eliminate oxygen and to prevent exposure to any energy source that could cause ignition. The most likely source of oxygen is of course the atmosphere and the most likely ignition sources are from electrical equipment.

The following general guidelines are used for the design of the gas handling system :

- no valves which could open the system to air
- each pressure monitor is sparkproof
- the pumps RP02 used in the storage tank circuitry is leakproof (hermetic).
- the only other electrical equipment in direct contact with hydrogen are liquid level sensors.

2 - MECHANICAL SYSTEMS :

2.1. - TARGET CELLS:

2.1.1 TARGET CELL S4 :

The target, shown in figure I APPENDIX D, consists of an inox body where the filling and return gas tubes are connected to the cryostat by the means of KENOL connectors (CEFILAC Industry/CARBONE-LORRAINE).

The KENOL system consists of a single seal cup clamped between the flat contact face of one connector, and the machined annular surface on the mating connector. Two nuts rotating freely on the pipe permit tightening of the seal cup.

The target is closed by two titanium foils (15 µm thickness and 3 cm in diameter : see structural calculation in APPENDIX A2). When the two foils are assembled, the cell is secured by Helicoflex elastic metal seals, coated with aluminium. Helicoflex is a patented system LCL-CEFILAC/CEA (French Atomic Energy Commission)/ CEA license. Helicoflex seals feature high sealing capacity and exceptional elastic recovery over a large range of temperatures.

Two level sensors (470 carbon resistor) which allow detection of the thermal exchange difference between gas and liquid are used to determine the two states of empty and full target. The controller RN12 SI of TBT Industry/AIR LIQUIDE, is approved for hydrogen use.

The transfer operation is stopped when a level pressure of 1 bar is reached on the PTS pressure transducer of the storage tank. For safety, this operation can also be stopped when the upper level sensor is activated.

2.1.2 TARGET CELL S2:

The target, shown in figure II APPENDIX D, is divided into two parts. The first part consists of an inox body with filling and return gas tubes which are connected to the cryostat by the means of Kenol connectors.

The second part is the mylar cell. The cap was thermoformed at 160°C by mechanical stamping, and glued to the cylindrical part which itself is glued to an inox tube (see structural calculation in APPENDIX A.1.3) .

When the two part are assembled, the cell is secured by an Helicoflex elastic metal seal.

Two level carbon sensors are used like S4 target.

2.1.3 TARGET CELL CAVE B:

The target, shown in figure III APPENDIX D, is divided into two parts. The first part consits of an inox body with filling and return gas tubes and the mylar entrance window (50 µm thick and 3 cm in diameter: see structural calculation in APPENDIX A2).

The second part is the mylar cell (100µm thickness) bonded on a sandblasted Vespel piece (polyimid resin, density 1.4) which is also glued on inox tube (see structural calculation in APPENDIX A.1.3 and the results of finite element calculations on Vespel in figure IX APPENDIX D).

The two parts are gathered with an Helicoflex seal.

2.2. – CONDENSER:

The condenser is a copper cylinder 8.7 cm long and 14.1 cm in diameter (see APPENDIX A.1.3 for structural calculations). It is cooled by contact with the second stage of the expander module, and thermally isolated from the exterior by a copper shield cooled by contact with the first stage of the cold head.

The temperature of the condenser is monitored and regulated by PC, which reads the temperature from a calibrated carbon resistance (560 ohms) and drives a 47 ohms heater in a PID control loop. For additional safety, this instrumentation is duplicated.

2.3. - VACUUM CHAMBER:

The target cell is located inside a sealed vacuum chamber which provides a secondary containment volume in case of target rupture. The volume of the insulting vacuum space available for the release of hydrogen shall be at least 52 times the volume of hydrogen liquid contained in the target flask (Safety Manuel of Fermilab : II.D.1.a). Hydrogen expands 52 times as liquid is vaporized to cold gas at atmospheric pressure .Sizing the vacuum space in this manner limits the maximum vapor evolution rate to be vented in a target flask failure.

When the target is operational, the pump is closed and vacuum is preserved by cryopumping using Actitex fabric which is more efficient than activated carbon.

2.3.1- VACUUM CHAMBER S4 (figure I APPENDIX D):

The entrance and outlet windows, 3 cm in diameter, are made of titanium foil. The thickness is 15 µm (see APPENDIX A2 for structural calculation and tests).

2.3.2- VACUMM CHAMBER S2 (figure II APPENDIX D):

The vacuum chamber is a cylinder, 26 cm long, 10.5 cm in diameter and 1.25 cm thickness made in ROHACELL.(rigid foam plactic PMI, density 0.07): see Rohacell chimical composition in figure X APPENDIX D).

The cylinder is manufactured in 6 parts glued each other with DP190 (see structural calculation and tests APPENDIX A.1.2).

2.3.3- VACUUM CHAMBER CAVE B (figure III APPENDIX D):

The entrance and outlet windows, 4 cm in diameter and 50 µm thickness are made of mylar. The lateral windows are also made of mylar (125µm thickness). They are rectangular in shape, 16 cm long and 9.5 cm high (see structural calculation and tests in APPENDIX A2).

The results of finite element calculations for the lower stainless steel vacuum chamber are shown in APPENDIX A.1.2.

2.4. - STORAGE TANK:

The hydrogen to be used in the target will be stored in a tank, in a well ventilated area. For S4 it is a stainless steel cylinder 35 cm long and 35 cm in diameter closed by two torispherical caps (7 cm long). S4 storage tanks are installed in the gas handling system rack. The storage tanks for S2 and Cave B are outside the rack.

For S2 it's a cylinder 98 cm long, 100cm in diameter closed by two caps (26 cm long) and for Cave B it's also a cylinder 63 cm long, 55 cm in diameter closed by two caps (11 cm long). The gas pressure in the tank will be approximately 1.5 bars for S4 (respectively 1.7 for S2 and

1.65 for Cave B). when all the gas is in the tank, and slightly over 1 bar when the target cell is filled. (see APPENDIX A.1.1 for structural calculations).

3 - GAS HANDLING SYSTEM:

3.1. - GENERAL DESCRIPTION:

The gas handling system for the G.S.I. cryotarget is composed of the plumbing, valves and controls necessary for transferring the hydrogen from the storage tank to the target cell and vice-versa. It also includes the pumps and valves for evacuating the vacuum chamber prior to filling the target.

The entire gas handling system will be housed in one rack. The system is equipped with manual valves, relief valves, indicators and transmitters pressure and the BROOKS flow regulator to ensure safe operation of the target. Figure IV, APPENDIX D, shows a schematic of the whole gas handling system. Components are labeled according to the abbreviations related in the complete list of instrumentation given in figureV APPENDIX D.

3.2. - TARGET CELL CIRCUIT:

NAME	TYPE	SETTING FOR PSV
MV08	Manual valve ¼ VCR (NUPRO)	
MV09	Manual control valve ¼ VCR (NUPRO)	
MV10	Manual valve ¼ VCR (NUPRO)	
MV12	Manual valve ½ VCR (NUPRO)	
MV13	Manual valve ½ VCR (NUPRO)	
MV15	Manual valve ¼ VCR (NUPRO)	
CV01	Check valve (NUPRO)	15 PSI
CV02	Check valve (NUPRO)	30PSI
CV04	Check valve (NUPRO)	15 PSI
CV06	Check valve (NUPRO)	1 PSI
CV07	Check valve (NUPRO)	1 PSI
FI01 FV01 EV01	Flow controller (BROOKS)	10000 sccm
PI07	Pressure indicator MIX5B (Bourdon)	-1 / +1.5 bars
PI08	Pressure indicator MIX5B (Bourdon)	-1 / +1.5 bars
PI12	Pressure indicator MEX3B (Bourdon)	-1 / +5 bars
PT02	Pressure transmitter (KELLER)	ADF / 2. 5 bars
PV03	Pneumatic Valve (ADAREG)	

Short list of instruments and valves for the target cell circuit.

The target circuit is evacuated by pump RP02 through valves MV12 and MV13. The target is filled through a flow control valve (BROOKS). The mass flow is regulated by the BROOKS regulator which reads the target pressure from a transducer PT02 and drives the flow valve in a PID control loop. The target may be filled by manual valves MV09 and MV10 in any case. The initial vacuum in the target circuit is controlled by gauge PG02, and the pressure under normal operating conditions (target full) is read out by gauges PT02, PI07 and PI08.

Valve MV15 allows entry of nitrogen to restore atmospheric pressure in the target cell circuit with no risk of overpressure by use CV04.

3.3. - VACUUM CHAMBER CIRCUIT:

NAME	TYPE	SETTING FOR PSV
Pump TP01	Turbo Pump ATP 80 (ALCATEL)	
Pump RP01	Roughing pump (Alcatel 5 m^3/h)	
PV01	Pneumatic Valve DN 50 (VAT) NC	
PV02	Pneumatic Valve (NUPRO) NC	0-1 BAR
MV16	Manuel Valve (NUPRO) ¼ VCR	0-1 BAR
PG01	Piezo gauge APR (PFEIFFER)	
IG01	Ion gauge PKR 250 (PFEIFFER)	
CV08	Check Valve (NUPRO)	1 PSI

Short list of instruments and valves for the vacuum chamber circuit.

The vacuum chamber is evacuated by the primary pump RP01 and the turbomolecular pump TP01 Gauge IG01 measures primary and secondary vacuum from 1000 mbar to $5x10^{-9}$ mbar (PFEIFFER PKR 250), valves PV02, MV16 allow entry of nitrogen to restore atmospheric pressure in the chamber with no risk of over pressure by use CV08. PV02 is piloted by PG01.

3.4. - STORAGE TANK CIRCUIT :

NAME	TYPE	SETTING FOR PSV
Pump RP02	Hermetic roughing Pump (Alcatel 2015H)	
MV01à MV05	Manual Valve DN 25 (VAT)	
MV06	Manual Valve ½ VCR (NUPRO)	
MV07	Manual Valve ½ VCR (NUPRO)	
MV11	Manual Valve ½ VCR (NUPRO)	
MV14	Manuel Valve ¼ VCR (NUPRO)	
CV03	Check Valve (NUPRO)	1 PSI
CV05	Check Valve (NUPRO)	35 PSI
PI01 to PI05	Pressure Indicator MIX 5D (BUORDON)	-1 /+1.5 bars
PI06	Pressure Indicator MIX 5B (BOURDON)	-1 /+1.5 bars
PI09	Pressure Indicator MEX 3B (BOURDON)	-1 /+1.5 bars
PI10	Pressure Indicator MEX 3B (BOURDON)	-1 /+1.5 bars
PI11	Pressure Indicator MIX 5D (BUORDON)	-1 /+5 bars
PG02	Pressure gauge (Alcatel)	10^{-3} → 1200 mbars
PT01	Pressure transmitter (KELLER)	ADF / 2.5 bars

Short list of instruments and valves for storage tank.

The storage tank is connected both to a supply bottle to fill it through MV14 and to a supply line connecting it to the target circuit through manual valve MV07.

Vacuum is created in the supply line by the pump RP02 through valve MV11. The pressure in the hydrogen tank is controlled by pressure indicators PI01 to PI05, PI06 and pressure transducer PT01. Manual opening of the tank is performed with valves MV01 to MV05.

4 - SAFETY CONSIDERATIONS:

4.1. - GAS HANDLING SYSTEM:

4.1.1. – TARGET CELL CIRCUIT:

⇒ For S4 :

The titanium entrance and outlet windows target (15 µm thick and 3 cm diameter) have been tested up to 5.5 bars (see APPENDIX A2). The Safety Manual of Fermilab (II.C.3.b) recommends a burst pressure of the least 1.5 x Maximum Allowable Working Pressure (M.A.W.P) that' it's to say 1.5 x 1.5=2.25 bars (differencial pressure).

⇒ For S2:

The mylar cell (125 µm thick and 6 cm in diameter) have been tested at 3 bars (see APPENDIX A.1.3). The Safety Manual of Fermilab (II.C.3.b) recommends a burst pressure for mylar flask of at least 2.8 bars (internal differential pressure).

⇒ For Cave B:

The mylar cell (100 µm thickness and 3 cm in diameter) glued on the Vespel piece have been tested at 3 bars (see APPENDIX A.1.3).

For the mylar part it's the same recommendation like S2.

For the Vespel transition piece the finite element calculations proves a maximum stress of 0.3 kg/mm² and no significant deformation for an internal pressure of 1 bar.(see figure IX APPENDIX D). The yield stress of Vespel is about 8 kg/mm². Also a very large safety factor is obtained.

For all targets:

In the event of blockage of the supply line to the target cell, a *warm* return line is provided through valve CV06 to allow gas to flow back into the storage tank via MV01 or MV02 for S4, MV06 and MV03 for S2, MV06 and MV04 for Cave B.

In the event of a target warming due to a compressor stop or a loss of vacuum, gas returns into the storage tank via CV06 and CV07 (see venting calculations in APPENDIX ??).In the very unlikely case that one of valves MV01 to MV06 is closed, gas flows directly through CV01 in the vent line.

4.1.2. – VACUMM CHAMBER CIRCUIT:

⇒ **For S4 :**

The titanium entrance and outlet windows (3 cm in diameter) have been tested up to 5.5 bars. (see APPENDIX A2). The Safety Manual of Fermilab recommends to test metallic windows up to 75 psid.

⇒ **For S2:**

The Rohacell vacuum chamber has been tested up to 6 bars (internal pressure) and 3.5 bars (external pressure). The Safety Manual of Fermilab recommends that the maximum allowable stress is 0.25 times the compressive stress (II.D.1.c). This safety factor of at least 4 is almost reached in fact : 3.4 (see APPENDIX A.1.2).

⇒ **For Cave B:**

The mylar entrance and outlet windows have been tested up to 2.5 bars , and lateral windows to 5 bars. The Fermilab Safety Manual (II.E.3.a) recommends to test thin mylar window for vacuum chamber up to 1.5 bars (differential pressure).

4.1.3. – STORAGE TANK CIRCUIT:

The storage tank and the low pressure manifold at the output of the supply gas bottle are protected by safety valves, CV02 and CV05. The exhaust from these valves is to be collected and evacuated through the safety exhaust line outside. In a case of a compressed air failure and/or electrical failure, the target is always connected to the storage tank via CV06 and CV07. The tanks can be isolated by manual valve MV01 to MV05 which are blocked open for added safety in normal operation.

4.2. – HANDLING OF EMERGENCIES:

4.2.1. – ACCIDENTAL CLOSING OF MANUAL VALVES:

There is only one or two valves between the target and the storage :

- MV01 or MV02 for S4 target,MV06 and MV03 for S2 target, MV06 and MV04 for S4 target: bolted open with mechanical system.
- however, in the case of closing of valves, the gas left in the target will be vented to the exhaust line through valve CV01 set to open at 1.05 bars differential (value far enough from the target crash pressure).

4.2.2. – POWER OUTAGE:

In case there is a power failure the compressor stops, the target heats up and gas returns to the storage tank through valves CV06 and CV07. The final pressure in the target is initial pressure in the tank.

4.2.3. – AUTOMATON FAILURE:

The automaton hasn't safety function. In case of failure, all organs will be in a safety position :

- compressor and pumps off

- valves PV01, PV02 closed
- valve PV03 opened

4.2.4. – BLOCKAGE:

Protection against a blockage due to the solidification of a contaminating gas, such as air, in the H_2 refrigeration circuit, no matter where the blockage occurs, is ensured by the fact that the entrance and return target lines are connected to pressure safety valves.

During the transfer operation the target condenser and cell are protected against blockage by the radiation shield which precools the gas to 40 K; all gases other than hydrogen will be trapped there. Blockage in the transfer lines at this location is very unlikely because the diameter of the piping is 6 mm.

4.2.5. – SOLIDIFICATION OF THE TARGET MATERIAL:

The target temperature is regulated by automaton. In case of a regulation loss there is a risk of an hydrogen solidification which could lead to target damaging. To avoid this major problem, the compressor is automatically stopped when the target pressure reaches a threshold value of 310 mbars (equivalent temperature 17K) which is given directly on pressure transmitter PT02.

4.2.6. – LOSS OF VACUUM IN THE CHAMBER:

Loss of vacuum in the chamber represents the highest level of emergency in the system because of the potential for a hydrogen leak. Immediate actions are taken automatically :

- every pump is stopped, if necessary,
- compressor HC8 is stopped,
- it is verified that MV12 and MV13 are closed (normal status) to avoid additional hydrogen (or deuterium) coming from the storage tank. The gaz will go back to the storage tank via pressure safety valves.

⇒ Loss of a vacuum may have two causes :

Leak in the vacuum chamber

The target heats up in few seconds by heat exchange with the intruding gas and hydrogen returns naturally to the storage tank through valves CV06 and CV07, since MV12 and MV13 are closed.

In that case, the final pressure in the storage tank and the corresponding target will be about 1.5 bars for S4 , respectively 1.7 for S2 and 1.65 for Cave B (see APPENDIX B1 for venting calculations).

In case of closing of storage tank manual valves occuring simultaneously with a target reheating hydrogen is discharged in the vent line via CV06,CV07 and CV01. The pressure for all targets will be about 2.1 bars.

Rupture of the target cell

First of all, there is a deposition of the flask contents into the vacuum space. After hydrogen flows back into the tank via CV06 and CV07. The maximum pressure in the vacuum chamber and the storage tank will be 0.32 bars and 1.05 bars for S4 (respectively 1.63 and 1.56 for S2, 1.33 and 1.26 for Cave B).The residual gas in the vacuum chamber has to be evacuated manually with pump RP02 (see APPENDIX B2 for venting calculations).

In the case, very unlikely of closing of storage tank manual valves occuring simultaneously with a target cell rupture, the maximum pressure in the vacuum chamber is always 0.32 bars for S4 (respectively about 2.1 bars for S2 by use CV06,CV07 and CV01 and 2.1 bars for Cave B).

In any case, there is no need check valves on the vacuum chamber to evacuate the gas. The final pressure is low enough. There is no risk to have a vacuum chamber failure.

A.1 - STORAGE TANK, VACUUM CHAMBER AND LH_2 CRYOSTAT

We discuss here the calculations to validate the design of the vacuum chamber and the LH_2 cryostat under normal or accidental operating conditions. The minimum required thickness of the walls of these vessels or the maximum pressure have been computed according to the procedures of the ASME code.

PRESSURE STRESS		
	NORMAL WORKING	**INITIAL PURGE**
Storage tanks	P_{inside} = 1,5 bar S4 (1.7 S2 and 1.65 Cave B) $P_{outside}$ = 1 bar Maximum Internal Pressure : MIP = 0.5 bar S4 (0.7 S2 and 0.65 Cave B)	P_{inside} = 0 bar $P_{outside}$ = 1 bar Maximum External Pressure : MEP = 1 bar
		ACCIDENTAL PRESSURE
Vacuum chambers	P_{inside} = 0 bar $P_{outside}$ = 1 bar MEP= 1 bar	P_{inside} = 0.32 bar S4 (1.63 S2 and 1.33 Cave B) $P_{outside}$ = 1 bar MIP< 0 for S4 (0.63 bar S2 and 0.33 Cave B)
Cryostats	P_{inside} = 1.05 bar $P_{outside}$ = 0 bar MIP= 1.05 bar	P_{inside} = 1.5 bar S4 (1.7 S2 and 1.65 Cave B) $P_{outside}$ = 0 bar MIP = 1.5 bar S4 (1.7 S2 and 1.65 Cave B)

MATERIAL :

- Storage tanks are realised in stainless steel 304 L.

The yield strength and tensile strength of 304 L are σ_Y = 25000 PSI and σ_R = 70000 PSI

The maximum allowed stress is :

$$S = Min\ [2/3\ \sigma_Y,\ 1/4\ \sigma_R]$$

Then :

$$S_{304L} = 16700\ PSI$$

- The condenser is realised in copper. At least, mechanical properties are :

$$\sigma_Y = 2900\ PSI$$

$$\sigma_R = 20300\ PSI$$

This leads to a nominal stress as defined in formula [1] :

$$S_{copper} = 1935\ PSI$$

- Thin windows S4 are realised in titanium. We use T40 titanium manufactured by TELEDYNE RODNEY METALS:

Certificate of test:

σ_Y =1.07 10^5 PSI
σ_R = 1.2 10^5 PSI
E (modulus of elasticity) = 15,3 10^6 PSI

$S_{titanium}$ =30000 PSI

. Thin windows Cave B and H2 liquid cells Cave B and S2 are realized in mylar . The yield strength is 15500 PSI and for plastic the maximum allowable stress is S= 0.633 σY:

S_{mylar} = 9811 PSI

ASME CODE :

- ***Internal pressure***
  The minimum thickness, t, for a cylindrical vessel can be determined from :

$$[I] \qquad t = \frac{PR}{SE - 0.6P}$$

where P is the internal pressure (P<0.3385 SE)
R the inside radius
S the allowable stress
E the weld efficiency.
The minimum thickness, t, for a torispherical cap is :

$$[II] \qquad t = \frac{0.885PL}{SE - 0{,}1P}$$

where L is the inside radius of the spherical cap.

- ***External pressure***
  The maximum working pressure must be smaller than the maximum allowable pressure PA.

For a cylindrical vessel :

$$[III] \qquad PA = (4/3)B/Do/t$$

For a torispherical cap :

$$[IV] \qquad PA = MIN\,[PA_1\,;\,PA_2]$$
$$PA_1 = (4/3)B/(Ro/t)$$
$$PA_2 = 1.67\,SEt/0.885\,L + 0{,}1\,t$$

Where the stress B is given by factor A which depends :

- for a cylindrical vessel :

  L/Do and Do/t ratios (Do = outside diameter ; L = cylinder length)

- for a torispherical cap :
  A = 0.125/(Ro/t) (Ro = outside radius of the spherical cap).

A.1.1 - Storage tanks :

		S4	S2	Cave B
Cylindrical vessel	R inside (inch)	6.89	19.69	10.83
	Length (inch)	13.78	38.58	24.80
Torispherical cap	L inside radius (inch)	13.78	39.38	21.66
	Length (inch)	2.76	10.24	4.33

The material is stainless steel 304 L.

- ***Internal pressure :***

The weld efficiency is 0.8

	S4	S2	Cave B
MIP (PSI)	7.25	10.15	9.4
t min (cylinder)	0.0037	0.015	0.0076
t min (cap)	0.0066	0.026	0.0135
t used	0.157	0.236	0.197
t used / t min	24	9	14.6

- ***External pressure :***

MEP = 14.5 PSI

⇒ Tank S4:

Then	***PA = 136 PSI (for cylinder)***

with L = cylinder length + 2 x 1/3 cap length = 15.62 inch.

$\frac{L}{Do} = 1.13$ and $\frac{Do}{t} = 88$ with Do = 13.78 in. and t = 0.157 in.

$\Rightarrow A = 1,2\ 10^{-3} \Rightarrow B = 9000\ PSI$

And	***PA= PA_1 = 144 PSI (for cap)***

with $\frac{Ro}{t} = 88$ and $A = 1,4\ 10^{-3} \Rightarrow B = 9500\ PSI$

PA_2 = 287 PSI (with L = 13.78 inch.)

Then	***PA / MEP = 9.4***

⇒ Tank S2:

Then	***PA = 56 PSI (for cylinder)***

with L = cylinder length + 2 x 1/3 cap length =45.41 inch.

$\frac{L}{Do}$ = 1.15 and $\frac{Do}{t}$ = 167 with Do = 39.38 in. and t = 0.236 in.

⇒ A =5 10^{-4} ⇒ B = 7000 PSI

And	***PA = PA_1 = 64 PSI (for cap)***

with $\frac{Ro}{t}$ ***= 167 and A = 7.5 10^{-4} ⇒ B = 8000 PSI***

PA_2 = 151 PSI (with L = 39.38 inch.)

Then	***PA / MEP = 3.8***

For this storage tank a finite element calculations (ACORD program) gives a maximum stress of 1.9 kg/mm2 for an applied external pressure of 1 bar. For stainless steel this value is very acceptable (see figure XI APPENDIX D).

⇒Tank Cave B:

Then	***PA = 103 PSI (for cylinder)***

with L = cylinder length + 2 x 1/3 cap length =27.69 inch.

$\frac{L}{Do}$ = 1.28 and $\frac{Do}{t}$ = 110 with Do = 21.66 in. And t=0.197 in.

⇒ A =9 10^{-4} ⇒ B = 8500 PSI

PA = PA_1= 109 PSI (for cap)

with $\frac{Ro}{t}$ ***= 110 and A =1.13 10^{-3} ⇒ B = 9000 PSI***

PA_2 = 229 PSI (with L = 21.66 inch.)

Then	***PA / MEP = 7.1***

A.1.2. - Vacuum chamber :

We introduce here the calculations concerning the Rohacell vacuum chamber for S2 and the lower inox vacuum chamber for Cave B.

⇒ Rohacell vacuum chamber S2:

In this case, the minimum thickness t for a cylindrical vessel is :

$$t_{mini} > \quad Ro \times \frac{[\sigma_u / (\sigma_u - 2P)]^{1/2} - 1}{[\sigma_u / (\sigma_u - 2P)]^{1/2}}$$

where Ro is the external radius of the vessel and σu the compression strength:
Ro = 2.07 inch
σu = 217 PSI
P (external pressure) = 14.5 PSI

⇒ t_{mini} > 0.143 inch

In fact we use t= 0.49 inch that it 's to say:

⇒ t / t_{mini} = 3.4

We have tested two samples at 3.5 bars external pressure and 6 bars internal pressure without problem.

⇒ Lower vacuum chamber Cave B:

By using a program of finite element calculations (ACORD) the maximum stress is 3.8 Kg/ mm2 and maximum deformations localized near the lateral windows are 0.17 mm for an applied external pressure of 1 bar.

These values are very acceptable (see figure VII APPENDIX D).

A.1.3. - Cryostat

⇒ The condenser, a cylinder 3.43 in. long and 5.55 in. in diameter is made of copper.

- . ***Internal pressure***

The maximum internal pressure (MIP) is 21.75 PSI for S4 during an accidental working (respectively 24.65 for S2 and 24 for Cave B).

The weld efficiency is 0.8
t_{min} = 0.040 inch.
In fact, we use : ***t = 0.078 inch***

Also	***t / t_{mini} =2***

- ***External pressure***

There is no external stress in normal or accidental working. But it is necessary to know the maximum allowable pressure PA because during vacuum test, atmospheric pressure acts on the condenser (14,5 PSI).

PA = 45 PSI

with $\frac{L}{Do} = 0.62$ *and* $\frac{Do}{t} = 71 \Rightarrow A = 2\ 10^{-3}$

and *B = 2400 PSI (copper curve)*

PA / Atmospheric pressure ≅ 3

A finite element calculation (ACORD) gives a maximum stress of 0.5 Kg/mm² and a maximum deformation of 2.10-³mm for an applied external pressure of 1 bar (see figure VIII APPENDIX D). This result is very similar with the above result : 2400 PSI ≈ 1.65 Kg/ mm² for 3 bars.

⇒ Mylar cells S2 and Cave B :

	S2	***CAVE B***
MIP	24.65	24
Weld efficiency	1	1
Cylinder : t min (µm)	75	35
Cap :t min (µm)	130	65
t used	**125**	**100**

We have tested at room temperature and 77 K, two duplicates of each target cell with an internal pressure 3 bars. No rupture or mesurable creep have been notice . The Safety Manual of Fermilab recommends that the burst pressure is greater than 40 PSI d or 2.8 bars (II.C.3.b).

A.2 - THIN WINDOWS

- **S4 target :**

The vacuum chamber and the target are closed on the both faces by two thin titanium circular windows.
The minimum thickness of circular window is :

$$e = 4.19 \ a \ [E/\sigma_Y^3]^{1/2} \quad \textit{[Fermilab Safety Manual, II.E.1.c]}$$

Where :
e = thickness of window, in.
a = diameter of window.
E = Yound's modulus of window material, psi.
σ_Y = yield strength of window material, psi.

This thickness will give a maximum working stress in the center of the window of 0.633 σ_Y at 15 psid. (66600PSI).

a = 1.18 in. ⇒ **e = 5.52 10^{-4} in. ≈ 14 µm**
In fact we use e =15 µm.

However, the final design shall be based upon burst testing which is presented in the next section. It's very important to optimise the window thickness in order to reduce background producted in the window by the beam.

THIN WINDOW TESTING :
We have pressure tested two samples under a constant flow of water, to demonstrate a burst pressure of at least 75 psid for all samples (Safety manual of Fermilab II.E.3.a).
Test results are recapitulated in these following tables :

Titanium T40 window : 3 cm in diameter and 15 µm thickness.

Pressure (bars)	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5
Deformation (mm) Test n°1	1.2	1.4	1.5	1.7	1.8	2	2.2	2.4	2.6	2.8	3
Deformation (mm) Test n°2	1	1.4	1.6	1.8	2	2.2	2.4	2.6	2.7	3	3.2

This is at least 5.5 times the operationnal pressure required and 3.7 times the maximum allowed pressure. We consider this experimentaly tested safety factor as largely sufficient.
The maximum deformation in the window center is 1.4 mm for 1 bar.

- **<u>Cave B target :</u>**

The vacuum chamber are closed by two circular and two rectangular mylar windows.

⇒ The minimum thickness of circular windows is :

$$e = 4.19 \ a \ (E / \sigma_y^3)^{½}$$

with : a= 1057 inch
E= 5.6 10^{+5} PSI
σy= 15500 PSI

e= 2.54 10^{-3} inch or 65 µm

In fact we use e= 50 µm and tests have been proved that burst pressure is > 2 bars (the Fermilab Safety Manual recommends to test mylar window for vacuum chamber up to 1.50 bars : II.E.3.a).

⇒ The minimum thickness of rectangular window is :

$$e = 30.59\ K\ H\ \left(E / \sigma_y^3\right)^{½}$$

with : H= 3.74 inch (height of window)

$$L/H = 6.3/3.74 = 1.68 \Rightarrow K= 0.195$$

Also :

e= 8.6 10^{-3} inch or 220 µm

In fact we use e= 125µm and tests have demonstrated that burst pressure is 5 bars.

APPENDIX B : VENTING CALCULATIONS

B.1. - VACUUM LOSS

Vacuum loss around super-isolated target will induce :

- 1,5 bar overpressure
- a 2 W/cm² maximum heat flux (W.Lehmann and G.Zahn).

In order to determine the discharge area of the safety valve in case of a vacuum loss it's enough to do this calculation for the biggest target in this case S2 target.
Surface seen by liquid is 800 cm² and maximum total heat flux is 1.6 kW. Then venting time is about 15 seconds and mass flow.

m = 28 Lb/h (1 Lb = 453 g)

Discharge area of the safety valve in sq in is :

$$A = \frac{m\sqrt{T/M}}{CK\, P_{max}}$$

m = mass flow = 28 1b/h
C = constant for gas or vapor which is a function of the ratio of specific heats, k = Cp/Cv
$C_{hydrogen}$ = 357 with K = 1.408
K coefficient of discharge = 0.809
P_{max} = 21,75 PSI
M = 2
T = 540 °R (300 K room temperature)

A = 0.073 inch 2

Diameter = 0.30 inch.

B2 – CRASH TARGET :

There is a deposition of the liquid hydogen on the botton of the vacuum chamber. Fermilab Safety Manual advises that the heat flux to the liquid hydrogen shall be taken as 20 W/cm² for a vacuum chamber made in stainless steel.

Vacuum chamber surface seen by liquid is about 130 cm² for S4 (respectively 900 cm² for S2 and 260 cm² for Cave B). Then maximum heat flux is obtained for S2 target that it's to say 18 kW.

Time evaporation is very short (2 seconds max) and mass flow :

m= 315 lb/h

Then A= 0.82 inch²

D ≈ 1 inch

In order to decrease the heat flux it's possible to put an isolating material (like Klegecell or Rohacell) in the bottom of the vacuum chamber . The thermal conductivity of this type of material is typically 3.10^{-4} W/cm K and the heat flux to liquid hydrogen shall be taken as 0.1 W/cm². Then maximum heat flux is 90 W.

Time evaporation is about 4 minutes and mass flow :

m = 1.66 Lb/h

Then A= 0.005 inch²

D ≈ 0.1 inch

In fact, we use two safety valves, each ½ inch in diameter. One is CV06 on the « varm » return line, the other is CV07 on the the entrance line. This device is greatly capable to collect the mass flow and to limit the pressure at a reasonable value for these two occurrences.

APPENDIX C : A FEW PROPERTIES OF LIQUID H2 AND D2

Quantity	Symbol	Values	
		H2 20.39 K and 101.3 kPa	D2 23.67 K and 101.3 kPa
Freezing Pt	Tf	13.868 K	18.73 K
Boiling Pt	Tb	20.39 K	23.67 K
Density	ρl	0.070 g/cm^3	0.1620 g/cm^3
Density variation (T)	dρl/ dT	-1.12 10^{-3} $g/cm^3/K$	-2.22 10^{-3} $g/cm^3/K$
Density variation (P)	dρl/dP	-4 10^{-8} $g/cm^3/Pa$	-7.14 10^{-8} $g/cm^3/Pa$
1 liter of liquid liberates		840 liters of gaz (15 °C; 1 bar)	974 liters of gaz (15 °C; 1 bar)
Heat of vaporization	Hv	450 J/g	300 J/g

APPENDIX D : DIAGRAMS AND PICTURES

PICTURE	*LEGENDS*
I	Target and vacuum chamber S4
II	Target and vacuum chamber S2
III	Target and vacuum chamber Cave B
IV	Flow diagram of the gas handling system
V	List of instrumentation

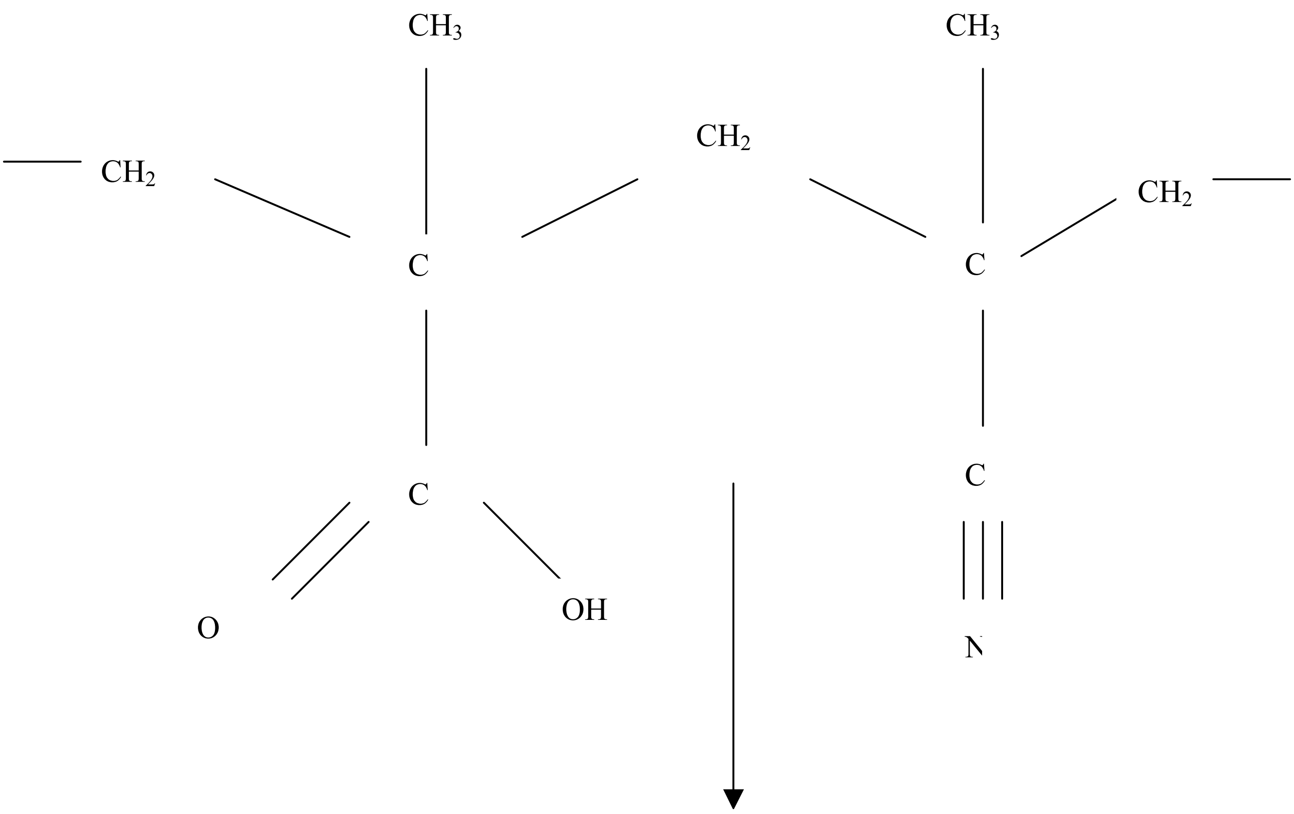
PICTURE OF THE FINITE ELEMENT CALCULATIONS

VI	Storage tank S2
VII	Lower vacuum chamber Cave B
VIII	Condenser
IX	Vespel piece
[illegible]	[illegible]

Rohacell chimical composition

Acide méthacrylique

Nitrite méthacrylique



Imide méthacrylique