GSI CRYOTARGET
SAFETY MANUAL
FRS1

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S U M M A R Y

1 - OVERVIEW OF THE SYSTEM

This document describes the cryogenic target to be used in G.S.I. for the isotope production study in 0.8 A GeV ^{238} U on proton reactions relevant for hybrid reactor system. The target, 1 cm long, and 3 cm in diameter, is delimited by titanium foils (20 µm thickness). Hydrogen is cooled and liquefied by contact with the expander module second stage of the 1020 CP closed-cycle refrigeration system C.T.I. This configuration limits liquid volume to 45 cm^3 : 7 cm^3 for target, 9 cm^3 for connecting tubes, 29 cm^3 for the bottom of condenser.

The target and the refrigeration system are in a residual 30 liters vacuum chamber, which provides a secondary containment volume in case of rupture of the target cell. When the target is in operation, it is connected to a 57 liters storage tank through two separate relief 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 (23.8 K for deuterium). Filling the target with hydrogen requires about 38 liters of gas at NTP (44 liters for deuterium). As a result, the storage tank is at a pressure of 1.7 bars before liquefaction for hydrogen (1.8 bars for deuterium).The total amount of hydrogen in use in the entire system is 97 liters at NTP (103 liters at NTP deuterium).

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, satisfying the US National Standard.
- the pumps RP02 used in the storage tank circuitry is leakproof (hermetic).
- the only other electrical equipment in direct contact with hydrogen are the heaters, temperature sensors and liquid level sensors.

2 - MECHANICAL SYSTEMS

2.1. - TARGET CELL

The target consists of a 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 (20 µm thickness and 3 cm in diameter : structural calculation in APPENDIX A2). When the two foils are assembled, the cell is secured by a Helicoflex elastic metal seal, 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.

One level sensor (470 carbon resistor) which allow detection of the thermal exchange difference between gas and liquid is used to determine the full state 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.

2.2. - CONDENSER

The condenser is a copper cylinder 5.6 cm long and 9 cm in diameter. 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 a Lakeshore 330 cryogenic temperature controller, which reads the temperature from a calibrated silicon diode DT 470 and drives a 50 ohms heater in a PID control loop. For additional safety, this instrumentation is duplicated, (condenser structural calculation is shown in APPENDIX A.1.3.)

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. When the target is operational, the pump is closed and vacuum is preserved by cryopumping (see APPENDIX A.1.2.. for structural calculation). The entrance and outlet windows, 3 cm in diameter, are made of titanium foil. The foil thickness is 20 µm (see APPENDIX A.2 for structural calculation and tests). The cell is secured by a Helicoflex elastic metal seal in a case of a target rupture and a deposition of liquid hydrogen in the bottom of vacuum chamber. Also, the final pressures in the vacuum chamber and the storage are respectively 1.17 bars and 1.1 bars for hydrogen (1.23 bars and 1.16 bars for deuterium).

There is no need relief valve to evacuate the vacuum chamber in a case of a target crash.

2.4. - STORAGE TANK

The hydrogen (deuterium) to be used in the target will be kept in storage tank, in a well ventilated area. It is a cylinder 45 cm long and 35 cm in diameter closed by two torispherical caps (11cm long), able to bear 17 bars and 12 bars internal and external pressure respectively (see APPENDIX A.1.1. for structural ASME calculation). The gas pressure in the tank will be approximately 1.7 bars when all the gas is in the tank, and slightly over 1 bar when the target cell is filled.

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 (deuterium) 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 tranmitters pressure and the M.K.S. flow controler to ensure safe operation of the target. Figure II, APPENDIX E, 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 APPENDIX E, Figure I.

3.2. - TARGET CELL CIRCUIT

NAME	TYPE	SETTING FOR PSV
MV03	Manual valve ½VCR (NUPRO)	
MV04	Manual Valve ½VCR (NUPRO)	
MV05	Manual valve ¼VCR (NUPRO)	
MV06	Manual valve ¼VCR (NUPRO)	
MV07	Manual control valve ¼VCR (NUPRO)	
MV09	Manual valve ¼VCR (NUPRO)	
RV01	Relief valve 4 MP (Circle Seal)	20 PSI
RV02	Relief valve 4 MP (Circle Seal)	20 PSI
RV04	Relief valve 4 MP (Circle Seal)	35 PSI
CV01	Check valve 4 PP (Circle Seal)	1 PSI
CV02	Check valve 4 PP (Circle Seal)	1 PSI
MKS	Flow controller (MKS)	5000 sccm N_2
PI04	Pressure indicator MIX5B (Bourdon)	-1 / +1.5 bars
PI05	Pressure indicator MIX5B (Bourdon)	-1 / +1.5 bars
PI06	Pressure indicator MEX3B (Bourdon)	-1 / +5 bars
PT02	Pressure transmitter 422C11266 (MKS)	ADF / 5 bars

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

The target circuit is evacuated by pump RP02 through valves MV03 and MV04. The target is filled through a flow control valve (MKS). The mass flow is regulated by an MKS controller 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 MV06 and MV07 in any case. The initial vacuum in the target circuit is controlled by gauge PG01, and the pressure under normal operating conditions (target full) is read out by gauges PT02, PI04 and PI05. Valve MV05 allows entry of nitrogen to restore atmospheric pressure in the target cell circuit.

3.3. - VACUUM CHAMBER CIRCUIT

NAME	TYPE	SETTING FOR PSV
Pump TP01	Turbo Pump serie 50 (Leybold 33 l/s)	
Pump RP01	Roughing pump (Alcatel 15 m^3/h)	
PV01	Pneumatic Valve DN 40 (VAT)	
IG01	Ion gauge(Balzers PK5250)	

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

The vacuum chamber is evacuated by primary pump RP01 and turbomolecular pump TP01 Gauge IG01 measures primary and secondary vacuum from 1000 mbar to 5×10^{-9} mbar (Balzers PK5 250).

3.4. - STORAGE TANK CIRCUIT

NAME	TYPE	SETTING FOR PSV
Pump RP02	Hermetic roughing Pump (Alcatel 2015H)	
MV01	Manual Valve DN 25 (VAT)	
MV02	Manual Valve DN 25 (VAT)	
MV08	Manual Valve ½VCR (NUPRO)	
MV10	Manual Valve ½VCR (NUPRO)	
MV11	Manual Valve ¼VCR (NUPRO)	
RV03	Relief Valve 4 MP (Circle Seal)	1 PSI
RV05	Relief Valve 4 MP (Circle Seal)	35 PSI
PI01	Pressure indicator MIX5D (Bourdon)	-1 / +1.5 bars
PI02	Pressure indicator MIX5D (Bourdon)	-1 / +1.5 bars
PI03	Pressure indicator MIX5B (Bourdon)	-1 / +1.5 bars
PI07	Pressure indicator MEX3B (Bourdon)	-1 / +5 bars
PG01	Pressure gauge (Alcatel)	10^{-3} 1200 mbars
PT01	Pressure transmitter 422C11266 MKS	ADF / 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 MV11 and to a supply line connecting it to the target circuit through manual valve MV08.

Vacuum is created in the supply line by a pump RP02 through valve MV10. The pressure in the hydrogen tank is controlled by pressure indicators PI01 or PI02, PI03 and pressure transducer PT01. Manual opening of the tank is performed with valves MV01 or MV02.

4 - SAFETY CONSIDERATIONS

4.1. - GAS HANDLING SYSTEM

4.1.1. - Target cell circuit

The titanium entrance and outside windows target (20 µm thick and 3 cm diameter) have been tested up to 7,5 bars (see APPENDIX A.2).

In the event of blockage of the supply line to the target cell, a *warm* return line is provided through valve CV01 to allow gas to flow back into the storage tank via MV01 or MV02 blocked open with a mechanical system.

In the event of a target warming due to a compressor stop or a loss of vacuum, gas returns into the storage tank via CV01 and CV02 (see venting calculations in APPENDIX B1).In the very unlikely case that one of valves MV01 or MV02 is closed, gas flows directly through RV01 in the vent line.

4.1.2. - Vacuum chamber circuit

The titanium entrance and outlet windows (3 cm in diameter) have been tested up to 7.5 bars. This value is the crash 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, RV02 and RV05. 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 CV01 and CV02. The tank can be isolated by a manual valve MV01 or MV02 which is 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 valve between the target and the storage :

- MV01 or MV02 : bolted open with mechanical system,
- however, in the case of closing of valves MV01 or MV02 the gas left in the target will be vented to the exhaust line through valve RV01 set to open at 1.4 bars (enough far 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 CV01 and CV02.

4.2.3. - Computer failure

The computer hasn't safety roll. Its utilization is pressure and temperature datums watch and synopses production.
The whole installation is protected by pressure safety valves. The target is controlled by an independent Lakeshore 330 cryogenic temperature controller which guarantees against solidification.

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 materiel

The target temperature is regulated by cryogenic temperature controller. Should the target nevertheless solidify, the pressure transmitter PT02 will fall below 1.05 bar and an alarm will inform the user. The action required to rectify this situation is to heat the target.

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 1020R is stopped,
- it is verified that MV03 and MV04 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 can be due to two causes :

<u>Leak in the vacuum chamber</u>

The target heats up in seconds by conduction with the intruding gas and returns naturally to the storage tank through valves CV01 and CV02, since MV03 and MV04 are closed. In that case, the pressure in the storage tank will end up to be about 1.8 bars (see APPENDIX B for venting calculations).

<u>Rupture of the target cell</u>

First of all, gaz flows back into the storage tank via CV01 and CV02. The maximum pressure in the vacuum chamber and the storage tank will be 1.17 bars and 1.1 bars respectively for hydrogen (1.23 bars and 1.16 bars for deuterium). The residual gaz in the vacuum chamber has to be evacuated manually with pump RP02.

In the case, very unlikely of closing of manual valves MV01 or MV02 occuring simultaneously with a target cell rupture, the maximum pressure in the vacuum chamber is 1.27 bars for hydrogen (1.47 bars for deuterium).

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

APPENDIX A : STRUCTURAL CALCULATIONS

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 tank	P_{inside} = 1,9 bar $P_{outside}$ = 1 bar Maximum Internal Pressure : MIP = 0.9 bar	P_{inside} = 0 bar $P_{outside}$ = 1 bar Maximum External Pressure : MEP = 1 bar
Vacuum chamber	P_{inside} = 0 bar $P_{outside}$ = 0 bar No Stress	**ACCIDENTAL WORKING** P_{inside} = 1.2 bar (crash target) $P_{outside}$ = 0 bar MIP = 1.2 bar
Cryostat	P_{inside} = 1.05 bar $P_{outside}$ = 0 bar MIP= 1.05 bar	P_{inside} = 1.8 bar $P_{outside}$ = 0 bar MIP = 1.8 bar

MATERIAL :

- Vacuum chamber is realized in stainless steel 304 L.

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

The maximum allowed stress is :

$$S = Min\ [2/3\ s_Y,\ \frac{1}{4}\ s_R]$$

Then :

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

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

$$s_Y = 2900\ PSI$$

$$s_R = 20300\ PSI$$

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

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

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

Certificate of test:
$s_Y = 10^5$ *PSI*
$s_R = 1.2\ 10^5$ *PSI*
E (modulus of elasticity) = $15,66\ 10^6$ *PSI*

Þ $\boldsymbol{S_{Titanium} = 30000}$ ***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] $\boldsymbol{PA = (4/3)B/Do/t}$

For a torispherical cap :

$$\boldsymbol{PA = MIN\ [PA_1 ; PA_2]}$$

[IV] $$\boldsymbol{PA_1 = (4/3)B/(Ro/t)}$$

$$\boldsymbol{PA_2 = 1.67\ SEt/0.885\ L + 0{,}1\ t}$$

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 tank -

- Cylindrical vessel : R inside = 6.69 inch.
  Length = 17.72 inch.

- Torispherical cap : L (inside radius) = 13.38 inch.
  Length = 4.33 inch.

The material is stainless steel 304 L.

- ***Internal pressure :***

The maximum internal pressure (MIP) is 13.05 PSI.
The weld efficiency is 0.8

t_{min} = 0.0065 inch. (for cylinder)
t_{min} = 0.0115 inch. (for cap)

In fact, we use t = 0.197 inch,

then	**t/t_{min} = 17**

- ***External pressure :***

MEP = 14,5 PSI

then	**PA = 181 PSI (for cylinder)**

with L = cylinder length + 2 x 1/3 cap length = 20.60 inch.

$\frac{L}{Do}$ = 1. 5 and $\frac{Do}{t}$ = 70 with Do = 13.78 in. and t = 0.197 in.

Þ A =1,5 10^{-3} Þ B = 9500 PSI

and	***PA = PA_1 = 190 PSI*** **(for cap)**

with $\frac{Ro}{t}$ ***= 70 and A = 1,8 10^{-3}*** *Þ* ***B = 10000 PSI***

PA_2 = 371 PSI (with L = 13.38 inch.)

then	$\frac{PA}{MEP}$ ***=12.48***

A.1.2. - Vacuum chamber

Two cylinders compose the vacuum chamber.

- ***Cylinder 1***

It's stainless steel 304 L
Length = 16,10 in.
inside radius = 5.04 in.

<u>Internal pressure</u>

MIP = 14.5 PSI Þ $t_{min} = 5.4\ 10^{-3}$ *in.*

in fact, we use **$t = 0.118$ inch.**

also **t/t_{min} =21.9**

<u>External pressure</u>

PA = 134 PSI

with $\frac{L}{Do}$ **= 1,60 and** $\frac{Do}{t}$ **= 85.42** Þ **$A = 10^{-3}$**

then *B = 8600 PSI*

MEP 14,5 PSI

then ***PA/MEP =9.25***

- ***Cylinder 2***

It's stainless steel 304 L.
Lenght : 16.85 in.
Inside radius : 2.46 in.

<u>Internal pressure</u>

MIP = 14.5 PSI Þ $t_{min} = 2.67\ 10^{-3}$ *in.*

in fact, we use **$t = 0.0787$ inch.**

also **t/t_{min} # 30**

<u>External pressure</u>

PA = 170 PSI

with $\frac{L}{Do}$ **= 3.42 and** $\frac{Do}{t}$ **= 62.50** Þ **$A = 7.5\ 10^{-4}$**

then *B = 8000 PSI*

then ***PA/MEP = 11.7***

A.1.3. - Cryostat

- **<u>The condenser</u>**, a cylinder 1.61 in. long and 3.39 in. in diameter is made of copper.

Internal pressure

The maximum internal pressure (MIP) is 27,55 PSI (accidental working).
The weld efficiency is 0.8
t_{min} = 0.030 inch.
In fact, we use : ***t = 0.078 inch***

also	***t/t_{min} = 2.6***

- ***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 = 86 PSI

with $\frac{L}{Do} = 0.45$ *and* $\frac{Do}{t} = 45$ Þ $A = 5\ 10^{-3}$

and *B = 2900 PSI (copper curve)*

PA/Atmospheric pressure # 6

A.2 - THIN WINDOWS

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 :

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

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 = 6.18 10^{-4} in. # 16 µm**
In fact we use e = 20 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 20 µm thickness.

Pressure (bars)	0.5	1	1.5	2	2.5	3	3.5	4	4.5
Deformation(mm) Test n°1	0.75	1.05	1.25	1.45	1.55	1.65	1.8	1.95	2.05
Deformation(mm) Test n°2	0.75	1	1.25	1.45	1.55	1.65	1.8	1.95	2.05

Pressure (bars)	5	5.5	6	6.5	7	7.5	8	8.5	9
Deformation(mm) Test n°1	2.25	2.4	2.65	2.8	3.05	crash	-	-	-
Deformation(mm) Test n°2	2.25	2.35	2.55	2.75	2.95	3.25	3.35	crash	-

This is at least 7 times the operationnal pressure required and 4.2 times the maximum allowed pressure. We consider this experimentaly tested safety factor as largely sufficient.

The maximum deformation in the window center is 1 mm for 1 bar.

APPENDIX B : VENTING CALCULATIONS

B.1. - VACUUM LOSS

Vacuum loss around super-isolated target will induce :

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

Surface seen by liquid is 320 cm² and maximum total heat flux is 640 W. Then venting time is 2.2 seconds and mass flow.

m = 11.3 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 = 11.3 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 = 0.030 sqin

Diameter = 0.194 in.

In fact, we use two safety valves, each ½ in. diameter. One is CV01 on the « varm » return line, the other is CV02 on the the entrance line.

APPENDIX C : ENERGY LOSSES

The energy losses E of a 0.8 A GeV ^{238}U through one centimeter liquid hydrogen and 20 µm titanium are respectively :

E_{H2} = 2.88 GeV

E_{Ti} = 130 MeV

Then for a 10^8 particles, the power losses in liquid hydrogen and one titanium foil are:

$P_{H2} = 2.88\ 10^9\ \ (10^8\ \ 1.6\ 10^{-19})$ 46 mWatts

$P_{Ti} = 130\ 10^6\ \ (10^8\ \ 1.6\ 10^{-19})$ 2 mWatts

APPENDIX D : 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	l	0.070 g/cm^3	0.1620 g/cm^3
Density variation (T)	dpT	-1.12 10^{-3} $g/cm^3/K$	-2.22 10^{-3} $g/cm^3/K$
Density variation (P)	dpP	-4 10^{-8} $g/cm^3/Pa$	-7.14 10^{-8} $g/cm^3/Pa$
1 liter of liquid liberates	l/ g	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 E : SCHEMATIC AND FLOW DIAGRAMS

	LEGENDS
I	List of instruments and valves.
II	Flow diagram of storage tank, target and vacuum chamber.
III	Electrotechnic circuit
IV	Picture of the target cell, condenser and vacuum chamber.
V	Photography of the cryostat.
VI	Photography of the vacuum chamber.
VII	Photography of the cryogenic rack.
VIII	Photography of the instrumentation rack.