ZEPHYR Tritium System

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Reprint of ZEPHYR-Report No. 6a of July 1980

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
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+) Sandia Laboratories, Livermore, Calif.

Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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Abstract

The ignition experiment ZEPHYR will need tritium as an essential component of the fuel. The ZEPHYR Tritium Systems are designed as to recycle the fuel directly at the experiment.

An amount of tritium, which is significantly below the total throughput, for example 10^5 Ci will be stored in uranium getters and introduced into the torus by a specially designed injection system.

The torus vacuum system operates with tritium-tight turbomolecular pumps and multi-stage roots pumps in order to extract and store the spent fuel in intermediate storage tanks at atmospheric pressure. A second high vacuum system, similar in design, serves as to evacuate the huge containments of the neutral injection system.

The spent fuel will be purified and subsequently processed by an isotope separation system in which the species D_2, DT and T_2 will be recovered for further use. This isotope separation will be achieved by a preparative gaschromatographic process.

All components of the tritium systems will be installed within gloveboxes which are located in a special tritium handling room. The atmospheres of the gloveboxes and of the tritium rooms are controlled by a tritium monitor system. In the case of a tritium release - during normal operation as well as during an accident - these atmospheres become processed by efficient tritium absorption systems.

All ZEPHYR tritium handling systems are designed as to minimize the quantity of tritium released to the environment, so that the stringent German laws on radiological protection are satisfied.

ZEPHYR Tritium Systems

Contents

A. Introduction

1. Tritium Data

For ignition experiments ZEPHYR will need tritium as one component of the fuel. Though tritium belongs to the radio nuclei with low radiotoxity it has to be handled very carefully. The human body contains a high hydrogen concentration and therefore the exchange between protium and tritium has a high probability. Tritium will mainly be incorporated in the form of water. Nearly all of the inhaled HTO, DTO or T_2O will be retained for a mean biological half-life of 9 days. In the case of HT, DT or T_2 the incorporation is a factor of about 10^{-4} smaller. The incorporation can be reduced by increased consumption of liquids. The most important properties are listed in Table 1.

Table 1 Properties of tritium

radioadtive decay	$H^3\ (\beta^-)\ He^3$
half life	12.26 a
max. energy	18.6 keV
max. range in air	0.6 cm
mean energy	5.7 keV
mean range in air	0.05 cm
biological half life	9 d
ionization in tissue	$47\ \mu^{-1}$
energy loss in tissue	$3.3\ \mathrm{keV}\ \mu^{-1}$
specific activities:	1 g tritium = 9.58×10^3 Ci
	1 cm^3 (STP) = 2.58 Ci

Table 2 presents the values specified by the German radiological regulations.

Table 2 Radiological regulations for tritium

max. allowable activity in human body	2×10^{-3} Ci
limits on annual dose for ingestion	1.6×10^{-4} Ci/a
for inhalation	7.2×10^{-5} Ci/a

limits on mean annual concentration	
in air for public area	10^{-8} Ci/m^{3}
for control area	4.8×10^{-6} Ci/m^{3}
for supervision area	4.8×10^{-7} Ci/m^{3}
limits on surface contamination	
for public area	10^{-7} Ci/m^{2}
for control area, on clothing	10^{-5} Ci/m^{2}
for supervision area, on clothing and utensils	10^{-6} Ci/m^{2}

2. General Remarks

Although the experimental phase of ZEPHYR will not start with tritium, the radioactive isotope of hydrogen poses severe additional problems and their solutions may increase the difficulties in other areas.

In this section questions concerning the permissions given by the authorities are not addressed. This section will deal only with a listing of technical problems and proposals for their solution.

At present the T-supply and return is believed to be highly uncertain. It should be possible to get the necessary T-supply for the total of three years which the experiment is estimated to run. First contacts with suppliers have already been made.

As it is not intended to introduce more T-handling into the experiment than is necessary to serve the demands of ZEPHYR it would be desirable to give the whole T-exhaust back to an external manufacturer. For this purpose it is only necessary to store the torus exhaust in an intermediate storage tank. External recycling of smaller quantities of tritium than the total 10^6 Ci to be processed would reduce the on-site T-inventory.

As mentioned it is not possible to make contracts at the present time. In this study the following proposal is made:

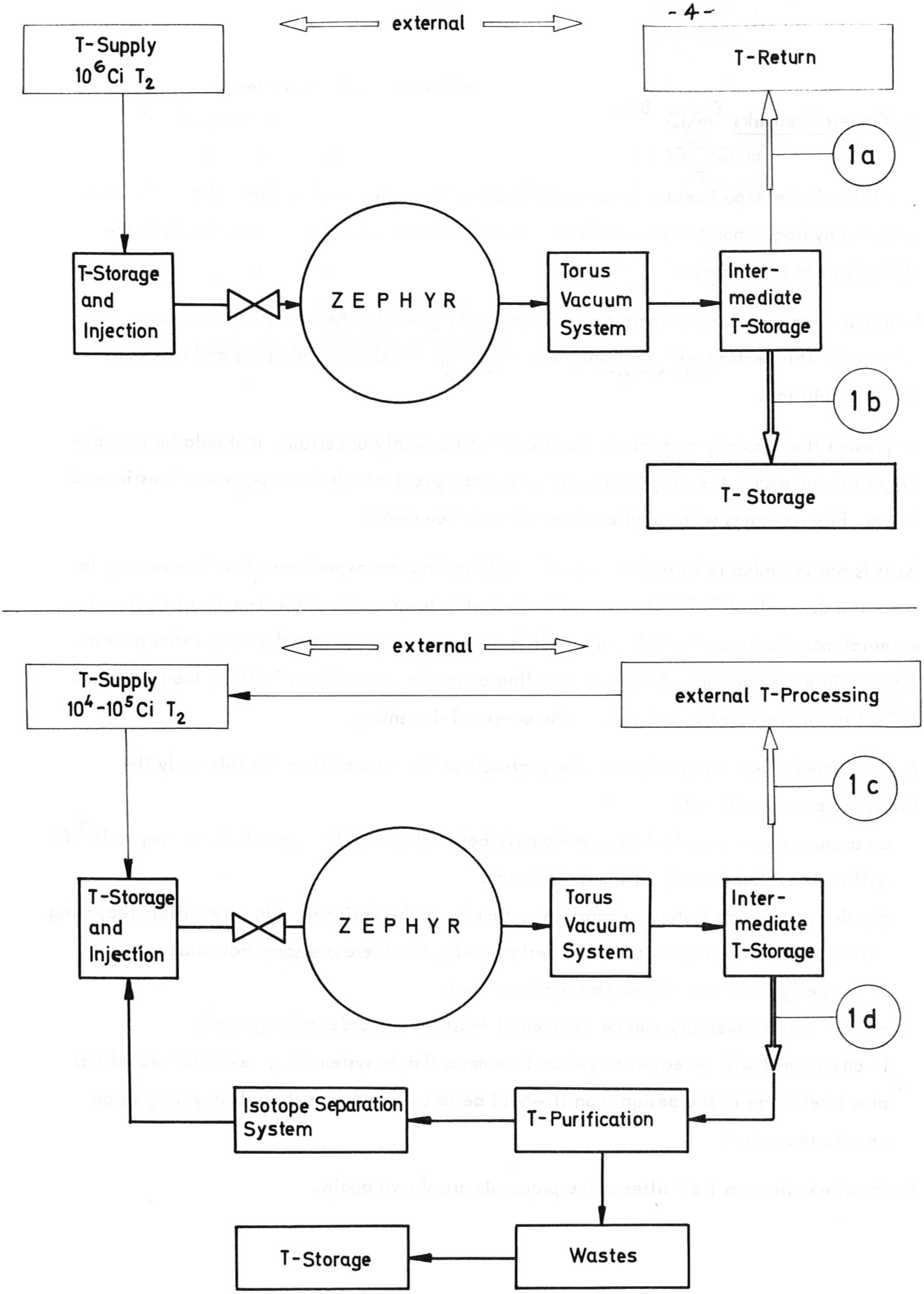
an amount of tritium which is significantly below the total throughput, for example 10^5 Ci will be recycled directly at the experiment.

For this purpose an isotope separation system has to be designed. On-site tritium recycling will increase the complexity of the design study, but there are some advantages.

- the design will not rely on (foreign) contracts
- the on-site inventory can be reduced at least by one order of magnitude.

In any case it will be easier to switch to a more simple system (e.g. external recycling) at a later stage in the design than it would be to switch from external recycling to an on-site recycling.

In the block diagram 1 all alternative proposals are shown again.



Block Diagram 1

4 alternative Tritium Systems

Fig. 1

1a shows the once through process with external supply and return

1b shows also an once through process but with final storage of the T_2 on-site (this case shall be excluded in this study)

1c here the flow-diagram of an external T-recycling process is shown and in

1d the recycling scheme described in the following pages.
Here one can see that this proposal demands additional processes.

In this report four subsystems are described:

a) the tritium storage and injection system TSI-S

b) the torus vacuum system TVS

c) the fuel cleanup and isotope separation system (FCU and ISS)

d) the tritium absorption systems TAS

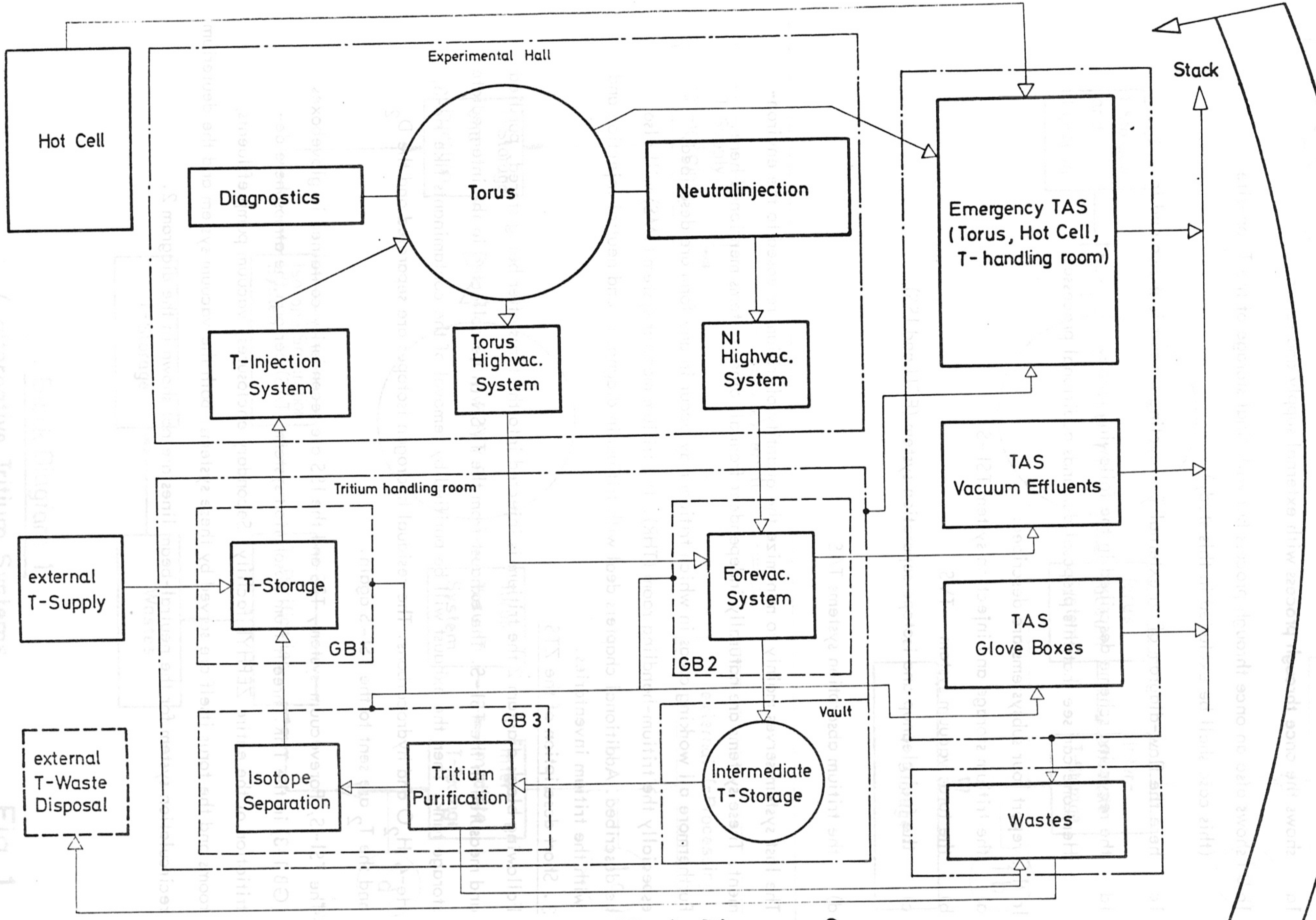
The last system serves mainly to minimize the quantity of tritium released to the environment. These systems are naturally independent from all other systems mentioned here.

Furthermore all working areas in which tritium may occur in any form are described, especially the tritium-handling room (THR). The tritium monitor system (TMS) will also be described. Additional chapters deal with tritium in diagnostic and neutral injection and with the tritium inventories.

3. Short description of the ZTS

Following block diagram 2 the tritium is injected into the torus after being stored, purified and measured in the TSI-S. The exhaust from the TVS will be collected in the intermediate storage tank. Then the exhaust will be purified by removal of the contaminants like He-3, He-4, H_2O and hydrocarbons. The residual hydrogen isotopes are separated and the D_2 and the T_2 are sent to the TSI-S again.

The TSI-S, Forevacuum-system, TPS and the ISS are secondarily contained in gloveboxes (GB 1-3) in the THR. Three tritium absorption systems (TAS) perform the atmosphere detritiation of the entire ZEPHYR facility. Secondary enclosures, vacuum pump effluents, rooms and the torus itself are served by these systems. Both the vacuum system and the deuterium recirculation system for the neutral-beam lines are not shown in the diagram 2.



Block Diagram 2

Tritium-Systems

Fig. 2

The systems to monitor tritium concentrations in all critical enclosures and rooms are shown schematically.
Tritium in neutral injection and diagnostics will be described in separate chapters of the paper, but interconnections between these and T-systems are shown when necessary.

4. Tritium Containment Philosophy

The German laws on radiological protection stipulate that a facility using or producing radionuclides must take precautions to ensure that:

1) uncontrolled releases will be avoided
2) the released activity is as low as possible
3) the maximum radiation dose to people residing beyond the site boundaries is $<$ 30 mrem per year.

Dose calculations done for the proposed ZEPHYR site indicated that even for an annual release of a few hundred thousand curies of HTO through a 100 m stack, the dose to a person living at the site boundary would be less than 30 mrem. However, to satisfy the requirements that uncontrolled releases should be avoided and other releases minimized, an extensive tritium scheme has been developed which relies on the extensive application of secondary containment of tritium sources. Tritium collected in these secondary containers will be captured by state-of-the-art tritium absorption systems (catalytic oxidation of the tritium followed by adsorption of the resulting water on molecular sieves). In certain high hazard areas, tertiary containment will be employed. Air from the tritium absorption system and from the building complex will be exhausted to the atmosphere through a tall stack.

The section of this report dealing with tritium absorption systems has curves showing the quantity of tritium leaked from and remaining in secondary enclosures as a function of time for various tritium release scenarios. The annual average tritium concentration in the stack will obviously depend on the frequency and magnitude of postulated releases, but the total annual releases will be of the order of a few hundred curies.

B. Description of Subsystems

1. Tritium Storage and Injection System

1.1 Purposes of the System

1. Storage of tritium in safe and solid form.

2. Limitation of impurities in the tritium to be injected.

   For TFTR, for example, the following limitations on the impurity concentration are given:

Impurities with $Z < 2$	less than 1% ,
Impurities with $2 < Z < 10$	less than 0.1% ,
Impurities with $Z > 10$	less than 0.01% ,

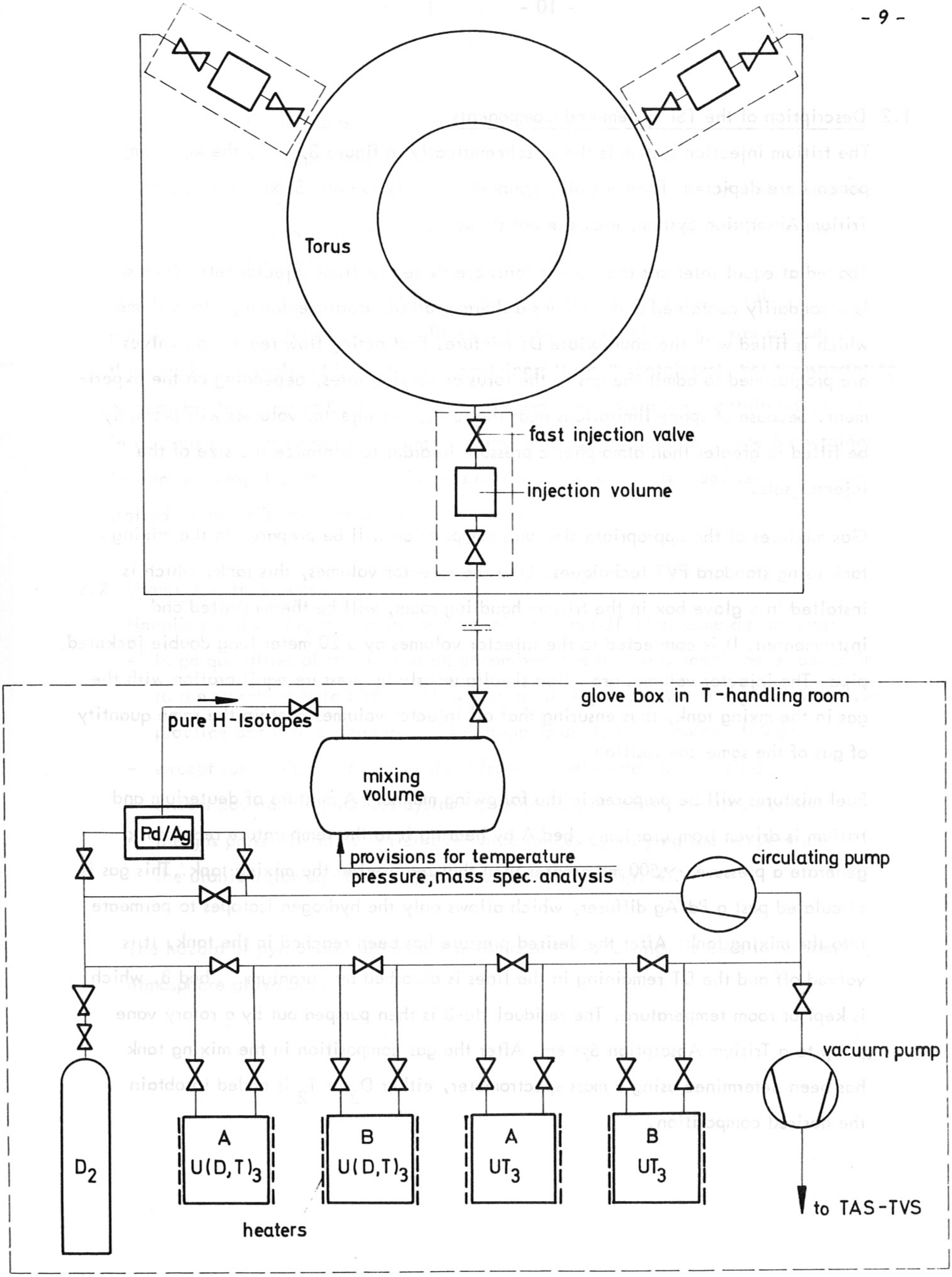
   or as low as possible.

   By means of suitable filters or frits it has to be ensured that no particulate impurities larger than $5\,\mu$ get into the plasma.

3. Transportation of tritium and a deuterium-tritium mixture (50 : 50) into the torus via an injection system in the quantity required by the tokamak system and in the given time sequence.

4. Supplying at least 4000 pulses (at least 1000 of them fully ignited) with the appropriate quantities of fuel during the experimentation period of about 3 years:
   quantity of tritium per discharge approx. 250 Ci,
   shot frequency about 1 shot/h,
   total tritium requirements approx. 10^{6} Ci $\hat{=}$ 100 g.

5. Reliable prevention of tritium release from storage tanks and the injection system and compliance with official regulations on permissible values.



Tritium Injection System
Schematic

Fig. 3

1.2 Description of the TSI System and Components

The tritium injection system is shown schematically in figure 3. Only the key components are depicted. For example, connection to the Isotope Separation System, Tritium Absorption System, etc. are not shown.

Spaced at equal intervals around the torus are three identical injector sets. Each set is secondarily contained and includes a thermostatted, instrumented injector volume which is filled with the appropriate DT mixture. Fast acting flow regulating valves are programmed to admit the gas to the torus at varying rates, depending on the experiment. Because of space limitations near the torus, the injector volumes will probably be filled to greater than atmospheric pressure in order to minimize the size of the injector sets.

Gas mixtures of the appropriate size and composition will be prepared in the mixing tank using standard PVT techniques. Like the injector volumes, this tank, which is installed in a glove box in the tritium handling room, will be thermostatted and instrumented. It is connected to the injector volumes by a 20 meter long double jacketed pipe. The injector volumes are filled simultaneously by pressure equilibration with the gas in the mxing tank, thus ensuring that all injector volumes contain the same quantity of gas of the same composition.

Fuel mixtures will be prepared in the following manner. A mixture of deuterium and tritium is driven from uranium bed A by heating it to the temperature required to generate a pressure ∼500 mb greater than that required in the mixing tank. This gas is circulated past a Pd/Ag diffuser, which allows only the hydrogen isotopes to permeate into the mixing tank. After the desired pressure has been reached in the tank, it is valved off and the DT remaining in the lines is absorbed by uranium bed B, which is kept at room temperature. The residual He-3 is then pumped out by a rotary vane pump to a Tritium Absorption System. After the gas composition in the mixing tank has been determined using a mass spectrometer, either D_2 or T_2 is added to obtain the desired composition.

Description of Components

1.2.1 Transport tanks for supplying tritium

In accordance with the Radiation Protection Regulations (Strl. Sch.V.) of the Federal Republic of Germany radioactive materials such as tritium gas have to be transported in tanks which prevent the release of radioactivity.

Tanks for tritium gas can only be sealed quantitatively by means of metal.

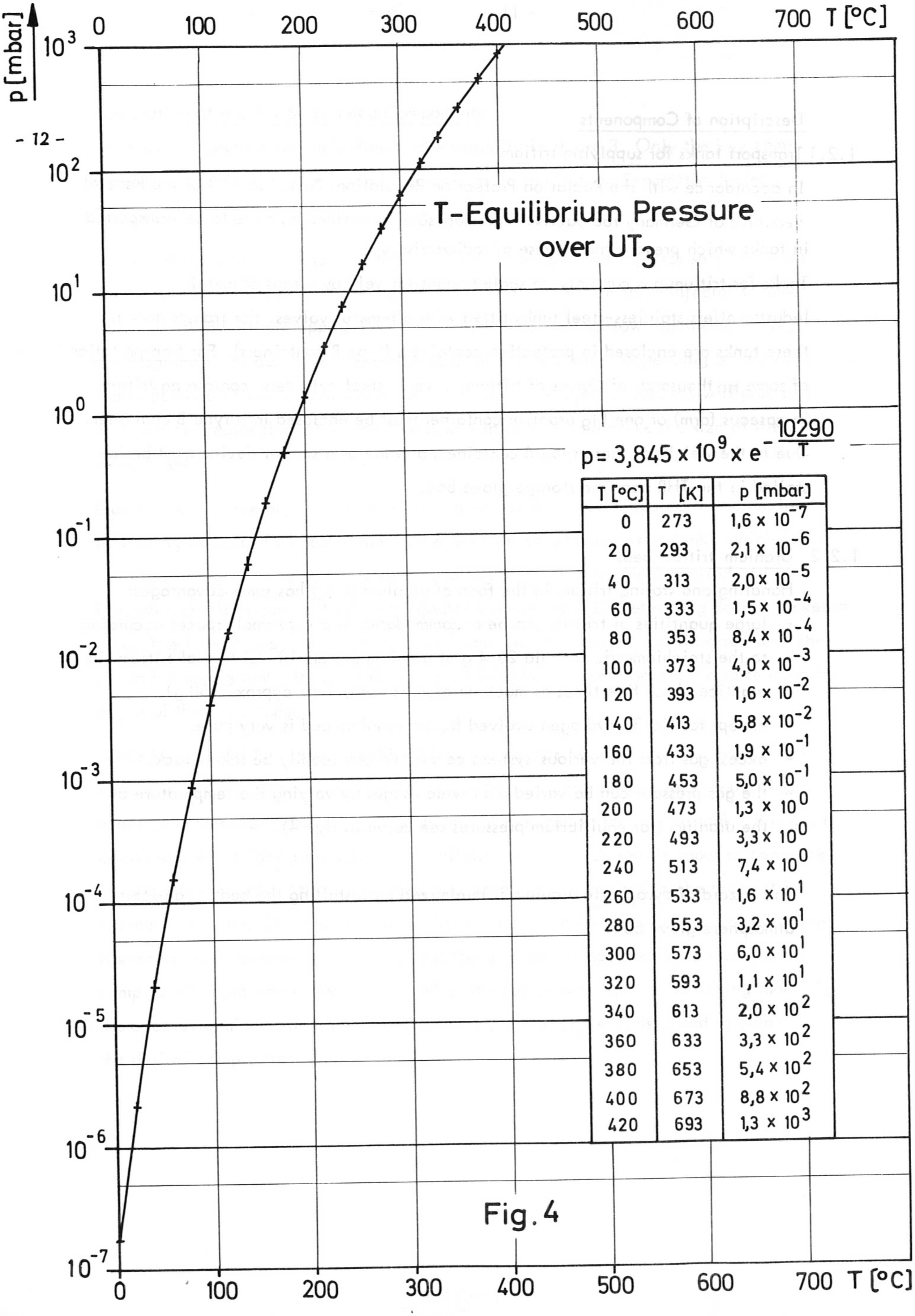
Industry offers stainless-steel tanks fitted with all-metal valves. For transportation these tanks are enclosed in protective containers (type B containers). For transportation of some ten thousands of Curies of tritium, several steel cylinders (containing tritium in gaseous form) or one big uranium container must be enclosed in a type B container. Due to the weight of these type B containers a crane or a similar device must be installed in the THR near the storage glove box.

1.2.2 Uranium tritide beds

Handling and storing tritium in the form of uranium (UT_3) has some advantages:

- large quantities of tritium can be accommodated in a very small space; according to the stoichiometric formula 26·4 g of uranium getters 10^4 Ci (1g) of tritium (in practice about five times as much uranium is used, i.e. approx. 150 g).
- except for He-3, hydrogen evolved from a uranium bed is very pure.
- excess gas from the various systems connected can readily be taken back.
- the gas pressure can be varied over wide ranges by varying the temperature of the uranium (for equilibrium pressures see curve in fig. 4).

The hazard of pyrophoric uranium is minimized by installing the beds in an inert atmosphere glove box.

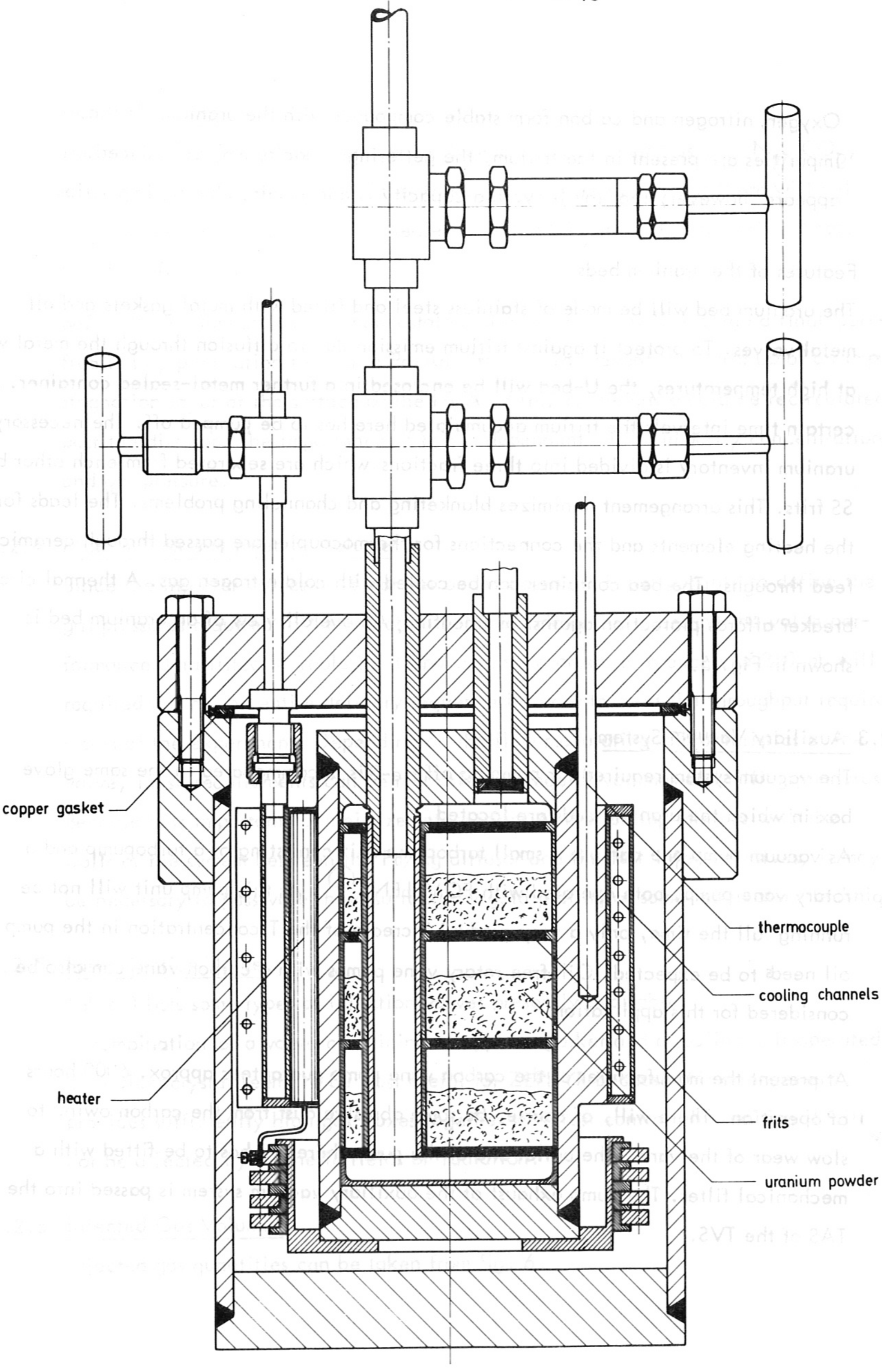


T-Equilibrium Pressure over UT_3

$$p = 3{,}845 \times 10^{9} \times e^{-\frac{10290}{T}}$$

T [°C]	T [K]	p [mbar]
0	273	$1{,}6 \times 10^{-7}$
20	293	$2{,}1 \times 10^{-6}$
40	313	$2{,}0 \times 10^{-5}$
60	333	$1{,}5 \times 10^{-4}$
80	353	$8{,}4 \times 10^{-4}$
100	373	$4{,}0 \times 10^{-3}$
120	393	$1{,}6 \times 10^{-2}$
140	413	$5{,}8 \times 10^{-2}$
160	433	$1{,}9 \times 10^{-1}$
180	453	$5{,}0 \times 10^{-1}$
200	473	$1{,}3 \times 10^{0}$
220	493	$3{,}3 \times 10^{0}$
240	513	$7{,}4 \times 10^{0}$
260	533	$1{,}6 \times 10^{1}$
280	553	$3{,}2 \times 10^{1}$
300	573	$6{,}0 \times 10^{1}$
320	593	$1{,}1 \times 10^{1}$
340	613	$2{,}0 \times 10^{2}$
360	633	$3{,}3 \times 10^{2}$
380	653	$5{,}4 \times 10^{2}$
400	673	$8{,}8 \times 10^{2}$
420	693	$1{,}3 \times 10^{3}$

Fig. 4



sectional drawing of an uranium bed
(similar to Sandia design)

Fig. 5

Oxygen, nitrogen and carbon form stable compounds with the uranium. If these impurities are present in the tritium, the gettering capacity may be reduced. It appears, however, that the recycling capacity is not impaired by the impurities.

Features of the uranium beds

The uranium bed will be made of stainless steel and fitted with metal gaskets and all-metal valves. To protect it against tritium emission due to diffusion through the metal wall at high temperatures, the U-bed will be enclosed in a further metal-sealed container. At certain time intervals the tritium accumulated here has to be pumped off. The necessary uranium inventory is divided into three fractions which are separated from each other by SS frits. This arrangement minimizes blanketing and channeling problems. The leads for the heating elements and the connections for thermocouples are passed through ceramic feed throughs. The bed container can be cooled with cold nitrogen gas. A thermal circuit breaker affords protection against overheating. An overall view of an uranium bed is shown in Fig. 5.

1.2.3 Auxiliary Vacuum System

The vacuum system required for pumping off He-3 is accommodated in the same glove box in which the uranium beds are located.

As vacuum pump one can use a small turbopump unit consisting of a turbopump and a rotary vane pump, both operated with FOMBLENE®. As this pump unit will not be running all the time, only a very gradual increase of the T concentration in the pump oil needs to be expected. Oil-free rotary vane pumps with a carbon vane can also be considered for this application.

At present the manufacturer of the carbon vane pump guarantees approx. 6000 hours of operation. There will, of course, be some abrasive dust from the carbon owing to slow wear of the vane. The outlet end of the pump therefore has to be fitted with a mechanical filter. The pump exhaust of the auxiliary vacuum system is passed into the TAS of the TVS.

Tritium cleaning

The tritium leaving the uranium beds is free of impurities such as O_2, N_2, CO_2, H_2O and hydrocarbons. Most of the He-3 can be pumped off, but there will still be some residual He-3 which is released from the UT_3-lattice as the bed is heated to drive off the tritium.

Before the tritium enters the thermostated mixing tank, it will undergo a final purification by permeation through a Pd/Ag diffusor. To prevent the build up of an impurity stagnation layer at the surface of the Pd/Ag diffusor, the gas should be recirculated past the diffusor. The importance of this is dependent on the impurity concentration and gas pressure.

1.2.4 Mixing Tank and Injector Volumes

Since the injector valves have not yet been chosen, it is not possible to define the gas pressures required in the injection volumes. However, based on the valve performance data listed in Table 3, it appears that a pressure in excess of 260 mb will be required during the entire delivery sequence in order to meet the throughput requirements of the experiment. Depending on the flow modulating characteristics of the valve, these requirements can be met using a range of volumes and filling pressures. Because it is important to minimize interactions of the fueling mixture with the walls of the system between the Pd/Ag diffusor and the fast injector valves, it may be necessary to passivate these surfaces by gold plating or some equivalent technique.

1.2.5 Fast Injection Valve

Table 3 lists some types of injection valves presently available.
A combination of a valve containing a sapphire-gasket and a sealing bolt operated by a piezocrystal seems to be most useful for ZEPHYR because this arrangement provides sufficiently high gas fluxes together with fast control. In addition it will not be affected by magnetic fields or radiation.

1.2.6 Injected Gas Volumes

Injected gas quantities can be taken from fig. 6.

Table 3 Gas inlet valves

Type	drive	throughput $p = 1000$ mb	opening/ closing time	sealing	stroke	possible constr. variations
Granville Phillips APC 216	servomotor	10^{-10} - 100 mb ℓ/s	10 s / 10 s	metallic bakeable	3 mm needle valve	
Balzers UD 135	mechanical bimetallic	0 - 600 mb ℓ/s 8 - 100 mb ℓ/s 10^{-9} - 1 mb ℓ/s	3 - 30/10 - 30 s with magnetic driver 0.25	metallic counter plunge	0.3 mm disk valve	piezomotor
Virod LV 3	mechanically	0 - 600 mb ℓ/s	with magnetic driver 0.25	metallic bakeable	0.5 mm disk valve	piezomotor
Phys. Int.	piezomotor	0 - 700 mb ℓ/s	1 / 2 ms	O - ring	cone valve	
Veeco PV 10	piezomotor	0 - 4 mb ℓ/s	2 / 2 ms	O - ring	25 um	
IPP /W VII	eddy curvent	125 mb ℓ/s	$8 \cdot 10^{-5}/10^{-3}$ s	O - ring	0.2 mm disk valve	
IPP / OB	electro magnetic	800 mb ℓ/s	2 / 3 ms	O - ring	1 mm	

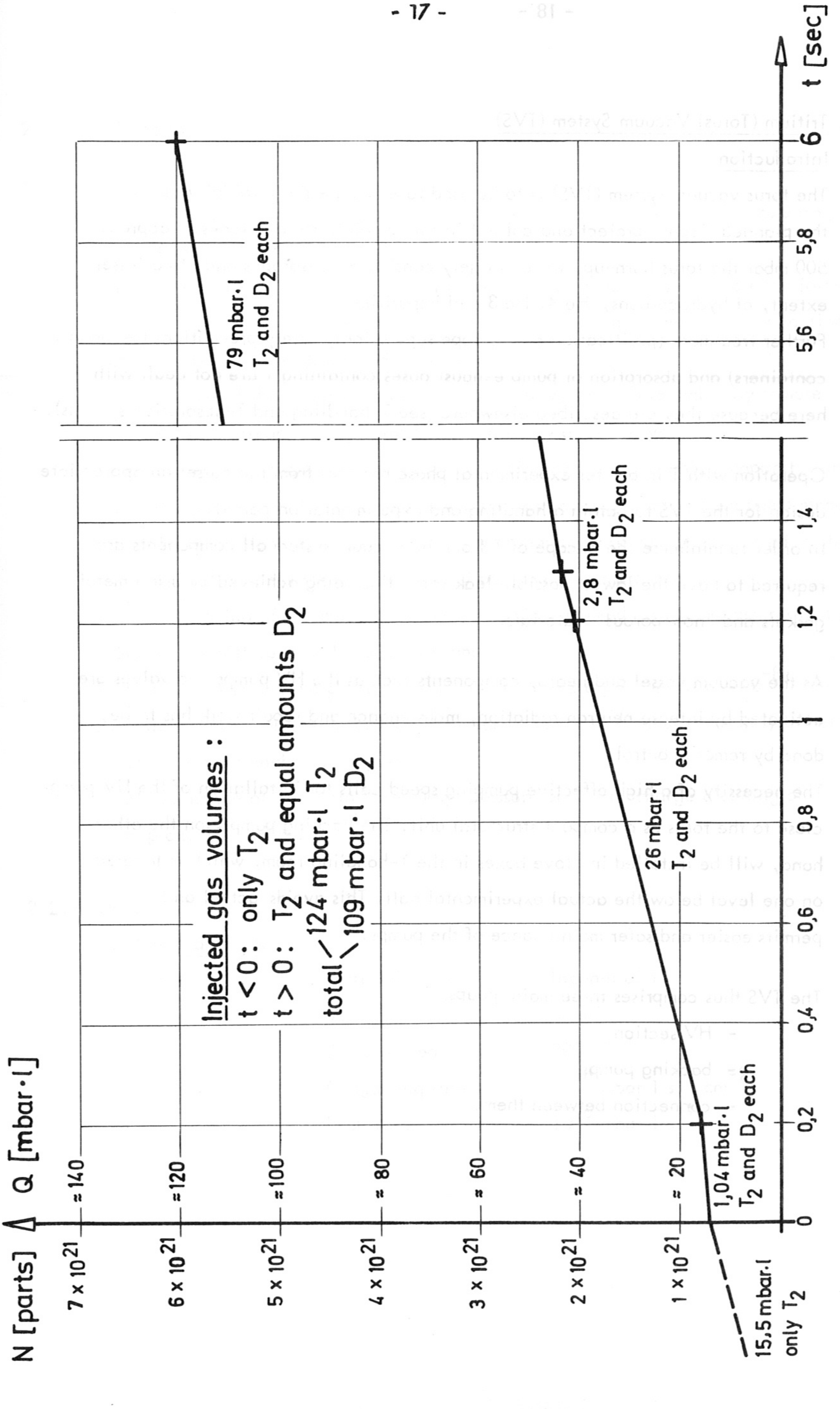

N [parts]
Q [mbar·l]
7 x 10^21
6 x 10^21
5 x 10^21
4 x 10^21
3 x 10^21
2 x 10^21
1 x 10^21
≙ 140
≙ 120
≙ 100
≙ 80
≙ 60
≙ 40
≙ 20
t [sec]
0
0,2
0,4
0,6
0,8
1
1,2
1,4
5,6
5,8
6
Injected gas volumes :
t < 0 : only T2
t > 0 : T2 and equal amounts D2
total 124 mbar·l T2
109 mbar·l D2
15,5 mbar·l only T2
1,04 mbar·l T2 and D2 each
26 mbar·l T2 and D2 each
2,8 mbar·l T2 and D2 each
79 mbar·l T2 and D2 each

Fig. 6

2. Tritium (Torus) Vacuum System (TVS)

2.1 Introduction

The torus vacuum system (TVS) is to be used to evacuate the toroidal vessel of the planned Zephyr project and collect in intermediate storage tanks at approx. 500 mbar the torus burn-up, which largely consists of H isotopes and, to a lesser extent, of hydrocarbons, He 4, He 3 and impurities.
Further treatment (purification and isotope separation), safety precautions (secondary containers) and absorption of pump exhaust gases containing T are not dealt with here because they are described elsewhere (see T-handling and T-absorption systems).

Operation with T in a later experimental phase requires from the outset an appropriate design for the TVS to obtain a handling and experimentation permit.
In order to minimize the excape of T from the vacuum system all components are required to have the lowest possible leak rate, this being achieved by using metal gaskets and "non-porous" materials.

As the vacuum vessel and nearby components such as the HV pumps and valves are activated by intense neutron radiation, maintenance and repair work has to be done by remote control.
The necessity of a high effective pumping speed calls for installation of the HV pumps close to the torus as a compact structural unit. The backing pumps, on the other hand, will be installed in glove boxes in the T-handling room, which is located on one level below the actual experimental hall. This avoids actual and permits easier and safer maintenance of the pumps.

The TVS thus comprises three main groups:

- HV section
- backing pumps
- connection between them.

2.2 HV Section

2.2.1 Description

For the HV section there are four rectangular pump ports available (H = 620 mm, W = 420 mm, L = 1200 mm).

These pump ports, which are an integral part of the vacuum vessel, are each joined by a short circular pipe (W = 630 mm, L = 1000 mm) which provides the connection to the HV pumps through the radiation shield.

On both sides of the radiation shield the pipes have to be detachable by remote control, the pump-side disconnecting point being sealed by a HV-valve.

At each pump port there is a pump unit consisting of one or two high-capacity turbomolecular pumps (TMP) with a Roots pump (RP) as backing pump. These pump modules should be replaceable as a unit, so that maintenance work can be performed in the hot cell. Oil changes for the TMP should be done by remote control.

The dimensioning of the pumps is governed by the required ultimate pressures and gas yields in the different modes of operation:

1. Evacuation from atmospheric pressure to an ultimate pressure of $p = 10^{-8}$ mbar
2. Evacuation of torus from 2.5×10^{-2} mbar to 1.6×10^{-6} mbar (or lower) in half an hour after each plasma pulse
3. Maintenance of a certain "cleaning" pressure during discharge cleaning at approx. 10^{-2} mbar.

2.2.2 Data

1. Vessel and Pipes

Vessel	Material:	Inconel 625
	Volume:	20 m^3
	Surface area:	200 m^2
	Outgassing rate:	10^{-8} mbar l s^{-1} cm^{-2}
	Leak rate:	10^{-6} mbar l s^{-1}

Pipes Material: Stainless steel
Diameter: 100 mm
Length: 15 and 23 m
Volume: $0.6\ m^3$
Manifold volume: $0.4\ m^3$

Conductance of 1st pipe to TMP: $5000\ 1\ s^{-1}$

2. Filling quantities

Plasma pulse

Time varying gas intake quantities in T operation result in the following total quantities to be pumped off per pulse:

T: 30 mg = 10^{-2} Mol = 250 mbarl (300 K) ≈ 290 Ci
D: 20 mg = 10^{-2} Mol = 250 mbarl (300 K)

Impurities

As no data of our own are available, an estimate is made on the basis of the residual gas partial pressures of other experiments:

	H_2O	CO	CO_2	CH_4
TFR 400	$8\cdot10^{-7}$	$5\cdot10^{-7}$	$1\cdot10^{-6}$	$8\cdot10^{-7}$
TFR 600	$2\cdot10^{-9}$	$1\cdot10^{-9}$	-	-
DITE	-	$1\cdot10^{-6}$	-	$1\cdot10^{-7}$
JFT 2	$3\cdot10^{-7}$	$7\cdot10^{-7}$	-	$6\cdot10^{-7}$
PLT	$5\cdot10^{-7}$	$2\cdot10^{-6}$	-	$6\cdot10^{-7}$
ZEPHYR	$5\cdot10^{-7}$	$2\cdot10^{-6}$	$1\cdot10^{-6}$	$6\cdot10^{-7}$ mbar

ASDEX-experiments will give information about the impurities and gas consumption when Ti-surfaces are applied.

3. Miscellaneous

Magnetic field strength at TMP
perpendicular to torus plane: 1.3×10^{-1} T
parallel to torus plane: 9.0×10^{-2} T

Timing: $t_{pulse} = 10\ s$

$t_{interval} = 1800\ s$

With improved magnetic shielding the interval between pulses could be reduced.

Pumping speeds and conductance

4 TMP with $4500\ l\ s^{-1}$ or

4 TMP with $6000\ l\ s^{-1}$

Conductivity (TMP - torus) $5000\ l\ s^{-1}$

thus S_{eff} $12000\ l\ s^{-1}$

Neutrons per pulse: 2×10^{20}

Limiter material: not yet decided, but possibly graphite, SiC in the shape of small discs

2.2.3 Choice of High Vacuum Pumps

Table 4 lists the essential properties of various pumps suitable for producing the HV. The decision in favour of the TMP is due to the fact that off-the-shelf turbo-pumps are available which have the required pumping characteristics. All other pumps have greater disadvantages or require further development.

At present it is assumed that a total of four pump ports will be available in the torus. The HV system described thus ensures sufficient redundancy.

2.3 Backing System

2.3.1 Purposes

The backing system serves, on the one hand, for evacuating the vessel and all pipes from atmospheric pressure to the operating pressure of the HV system and for maintaining the backing pressure of the TMP that is necessary for operation. On the other hand, the burn-up has to be transported via the backing system into the intermediate storage tanks, where it is kept at a pressure of approximately 500 mbar till further

	TMP	Cryosorption pump (15 K)	Getter Pump ZrAl
Pumping Speed per Pump total	 $5000\ \text{ls}^{-1}$ (4) $20000\ \text{ls}^{-1}$	air: $8000\ \text{ls}^{-1}$ H_2: $5500\ \text{ls}^{-1}$	N_2: $2250\ \text{ls}^{-1}$ H_2: $11250\ \text{ls}^{-1}$
Throughput	$J = p \cdot S$ $50\ \text{mbar ls}^{-1}$	air: $5\ \text{mbar ls}^{-1}$ H_2: $1.5\ \text{mbar ls}^{-1}$	
Which gases are pumped	all gases	all gases	all besides inert gases
Supply Systems	air cooled	He-compressor	heater
Maximum backing pressure	10^{-1} mbar	10^{-1} mbar	10 mbar
Total Capacity	unlimited	$100\ \text{mbar} \cdot \ell/\text{g}$ sorption agent	$2500\ \text{mbar} \cdot \ell$ (for N_2) $22000\ \text{mbar} \cdot \ell$ - embrittlement limit

Table 4 Properties of High Vacuum Pumps

	TMP	Cryopump	Getter Pump ZrAl
Maintenance Work "remote"	exchange of oil	cleaning of compressor exchange of activated charcoil	none
Intervals	every 5000 h	every 6000 h	-
Materials	SS, Cu, Al	SS, Cu, activated charcoal	SS, Zr Al

Table 4 continued

Type of Pump Properties	Normal Rootspump	Gas cooled Rootspump	Alcatel-Turbomolecularpump
Max. Pumping Speed	$S_{th} = 500\ m^3 h^{-1}$	$S_{th} = 125\ m^3 h^{-1}$	$450\ ls^{-1}\ (H_2)$
Max. Compression ratio	50	30	$1.5 \cdot 10^6$
Ultimate Pressure	10^{-3} mbar +)	mbar	10^{-3} mbar
Exhaust Pressure	p 50 mbar	1000 mbar	1000 mbar
Seals: internal external	piston seals metal seals	piston seals metal seals	dynamic seals
Cooling	none	H_2O, 200 lh^{-1}	none
Heating	none	none	none
Bearings	ball bearing	ball bearing	gas bearing
Lubrication	oil	oil	none
Material	SS	SS	SS, Al
Maintenance Work	exchange of oil 1.5 l	exchange of oil 1.5 l	none
Intervals	5000 h	5000 h	-
Leakage Rate	10^{-7} mbar ls^{-1}	10^{-7} mbar ls^{-1}	T mixed with bearing gas

Table 5 Properties of Roughing Pumps

+) when multi-stage pumping sets are applied

Type of Pump / Properties	DUO 60 A oil lubricated rotary pump	TF 80/16 +)	TF 63/4 2-stage	KNF NV 400·3ED	KNF N 770·3AN18 membrane pump
Max. Pumping Speed	60 m^3h^{-1}	16 m^3h^{-1}	4 m^3h^{-1}	9 m^3h^{-1}	2.4 m^3h^{-1}
Max. Compression ratio	10^6	5	100	50	500
Ultimate Pressure	6.5×10^{-3} mbar	200 mbar	10 mbar	20 mbar	2 mbar
Exhaust Pressure	1000 mbar	1000 mbar	1000 mbar	1000 mbar	1000 mbar
Seals: internal	oil sealed	-	-	-	-
external	rubber seals	metal seals		metal seals	
Cooling	none	none	none	none	none
Heating	none	none	none	none	none
Bearings	ball bearing	ball bearing		membran special grease	
Lubrication	oil	none	none	none	none
Material	Steel	St, carbon vane			
Maintenance Work	exchange of oil 4.5 l	exchange of vane		none	
Intervals	3500 h	6000 - 10000 h		-	
Leakage Rate	10^{-9} mbar ls^{-1}	10^{-9} mbar ls^{-1}		10^{-9} mbar ls^{-1}	

Table 5 continued

+) 1-stage non oil lubricated rotary pump

The mentioning of manufacturers\`names does not imply recommendation.

Type of Pump Properties	Cryopump +)	SAES 15 WP 875/2 Zr Al Getter	Hg - ejector pump
Max. Pumping Speed	4000 ls^{-1} (H_2)	11 250 ls^{-2}	12 ls^{-1}
Max. Compression ratio	-	-	10^6
Ultimate Pressure	$2x10^{-10}$ mbar	reversible at 10^{-5} mbar	$1x10^{-6}$ mbar
Exhaust Pressure	-	-	1 mbar
Seals: internal	-	-	-
external	metal seals	metal seals	rubber seals
Cooling	He-evaporation	none	H_2O, 50 lh^{-1}
Heating	possible	yes	yes 450 W
Bearings	none	none	none
Lubrication	none	none	none
Material	SS, Al, Cu, Ag	SS, Cu, ZrAl	SS, Hg
Maintenance Work	exchange of activated charcoal	exchange of ZrAl-getter, if capacity is reached	exchange of Hg
Intervals	6000 h	-	
Leakage Rate	10^{-9} mbar ls^{-1}	10^{-9} mbar ls^{-1}	10^{-9} mbar ls^{-1}

Table 5 continued

+) Flow through 20 K cryopump backed by a rotary vane pump.

	mechan. pump	oil-free mechan. pump	normal Rootspump	gas-cooled Rootspump	membrane pump	Alcatel	Cryopump	ZrAl	Hg-ejector pump
$P_{end} \leq 10^{-2}$ mbar	yes	no	yes	yes	no	yes	yes	yes	yes
$P_{ab} \geq 500$ mbar	yes	yes	no	yes	yes	yes	yes/no	yes/no	no
throughput 20 - 500 ls^{-1}	yes	yes	yes	yes	no	yes	yes	yes	no
T-compatible									
a) oil free	no	yes	yes	yes	yes	yes	yes	yes	yes
b) leakage rate 10^{-7} mbar ls^{-1}	yes	yes	yes	yes	teflon memb.	no	yes	yes	yes
pumping behaviour	transport	transport	transport	transport	transport	transport	collecting reversible	collecting rev. irrev.	transport
use of pump	1)	yes, 2)	no	yes	no	3)	yes	yes	no

1) yes, if T-contaminated oil can be stored

2) in case of minimum gas-throughput

3) this pump cannot be used because the T_2 will be mixed with about 2 m^3/h bearing gas

Table 6 Vacuum technology requirements of different backing pumps treatment. This procedure is intended to ensure that alternative ways of further processing the torus burn-up are kept open. Special attention is being paid at present to recycling (purification and isotope separation) since there are only faint prospects as yet of either storage of the used tritium on site or return of the contaminated tritium to the supplier.

Each TMP unit is fitted with a Roots pump as first stage of the backing system. This RP is connected to the main backing system, which is in the tritium handling room, by a long (~ 20 m) pipe.

There are various types of pumps that may be suitable for the backing system. Their special features and data are listed in Table 5. The vacuum technology requirements are listed in Table 6, and all relevant pump types are compared to these requirements. It is also possible to combine different types of pumps if this provides the desired properties. This applies particularly to series connection of several pumps of the same or different types to achieve a certain final pressure (e.g. gas-cooled plus normal RP). The backing system should also be accompanied by a redundant one.

2.3.2 Choice of Backing Pumps

By these criteria the following systems can be applied:

- Zr Al getter pumps with rotary vane pump
- RP set comprising gas-cooled and normal RP
- flow through 20 K cryosorption pumps backed by rotary vane pump for helium.

a) Zr Al getter pumps, in conjunction with rotary vane pumps for the helium, are attractive only if there is no intention to recycle the tritium. Quantitative removal of tritium from Zr Al requires that the getter be heated above 900° C, in which case the getter will be destroyed. Partial regeneration results at 700° C, but even then only about 25 regeneration cycles are possible before the getter is destroyed. Because the tritium partial pressure at room temperature is only 1.7×15^{-15} torr, Zr Al affords major advantages over other storage methods from the standpoint of safety.

b) According to the manufacturers, multi-stage RP sets can pump the torus burn-up into the intermediate storage tank at the required pressure.

As such pump units have not yet been tested under conditions similar to those of Zephyr, relevant experience is not available. The RP under consideration at present have been designed and tested for operation with UF_6. At present at the TSTA (LASL) one RP is being tested for the first time to pump tritium.

The leak rates specified will have to be confirmed. In particular, the additional pump-off of bearing oil from labyrinth gaskets, which separate the pump volume of the RP from the bearing oil, indicates that the tightness is possibly unfavourable. At any rate it has to be expected that the oil will be contaminated by tritium. The servicing frequency according to the manufacturers is 40 000 h. An oil change is due about 1 to 2 times/a; during the entire experimentation period about 250 ℓ of contaminated oil are accumulated.

c) An alternative backing system consists of redundant cryosorption pumps, each in series with an oil-free rotary vane pump. The cryosorption pump is held at a sufficiently low temperature to trap everything but the helium, which passes through the cryopump and is pumped into the TVS tritium absorption system by the rotary vane pump. Since the hydrogen isotopes can be desorbed from one cryopump while the other is on-line, the quantity of tritium held up in the pumps can be minimized by regenerating often. The desorbed gas is transferred into the storage tank by the rotary vane pump.

In the course of the second design phase the suitability of cryosorption pumps for collecting torus burn-up is to be investigated more intensively, if possible experimentally.

2.4 Pump Performance, Numerical Treatment

Of particular interest are pumping times and variations and distributions of pressure during different pumping phases as a function of the types of gases pumped.

The pumping time from atmospheric pressure to the ultimate pressure is made up of the components for the rough and high vacuum regions.

In the former region the pumping time is governed by the volume to be evacuated, whereas in the high-vacuum region it is the desorption and leak rates of the individual components that are essential.

Depending on the size of the backing pumps, the rough vacuum region is reached after a pumping time of 2 to 4 hours.

Calculation of the pumping time taken to reach the HV region yields a time of some minutes, depending on the desorption from the walls.

The time taken to evacuate the torus from the filling pressure to the ultimate pressure after a plasma discharge can be determined by calculating the quantity of residual gas Q_R left in the torus. The pressure drop is plotted in fig. 7 versus time for air and H_2. A distinction can be made between three ranges I, II and III.

While in region I the pumping speed of the TMP depends on the pressure in the torus (i.e. it drops with rising pressure), the pumping speed in region II is constant.

The quantity of residual gas is given by the equation

$$Q_{R_i t_i} = Q_{t_i - 1} \cdot K \text{ with } K = 1 - \frac{S \cdot (t_i - t_{i-1})}{V} \quad \text{and } S \cdot (t_i - t_{i-1}) \qquad V$$

As the pumping speed S depends on both the type of gas and the torus pressure, Q_R is successively determined for small time intervals ($t = 1$ s). The residual pressure p is then obtained by dividing by the volume V.

In region II the constant desorption rate determines the attainable ultimate pressure according to the equation

$$P_{final} = Q_{des} / S_{eff}$$

For desorption rates of $q = 10^{-8}$ mbar 1 s^{-1} cm^{-2} and an effective pumping speed of 12 000 1 s^{-1} one gets a possible ultimate pressure of $p = 1.6 \times 10^{-6}$ mbar.

By means of special cleaning processes it might be possible to reduce the desorption rate to $q = 10^{-10}$ mbar 1 s^{-1} cm^{-2}, thus affording an ultimate pressure of the order of 10^{-8} mbar.

The dimensioning of the backing system is governed by the quantities of gas to be pumped per unit time and by the backing pressure of less than 1 mbar required for the TMP.

As it is assumed that $Q = p \cdot S = \text{const.}$ is valid for the entire backing system, the pumping speed of the backing pumps may decrease towards the intermediate tank with rising pressure. A possible configuration is shown in fig. 8.

The bottom curve is valid for maintaining an ultimate pressure in the torus with a constant, small gas release from the vessel walls. The pressure calculations are based on the maximum compression ratios K_{max} (for zero gas throughput) according to the supplier`s specifications.

After each plasma pulse the torus burn-up has to be pumped off for a certain time (pump-down time according to fig. 7). The top curve in fig. 8 shows the pressure variation for the larger gas yield.

If it is assumed that the respective effective pumping speeds are always smaller than half the nominal speeds, and the compression ratios smaller than K_{max}, one obtains the pressures listed in fig. 8. This produces a laminar flow, particularly in the long backing vacuum line, thus preventing any noticeable conductance losses.

2.5 Tentative Design

As shown in fig. 9 a total of four HV modules, each consisting of a TMP and a RP will be applied.

There are TMP available in series production which after special treatment comply with the requirements of ZEPHYR, but there are also completely new designs. All the TMP and RF of the HV pumping sets are air-cooled and all maintenance can be done by remote control. Additional shielding prevents undue stress caused by the magnetic fields prevailing at the pump site.

The backing system should consist of a T-tight multi-stage Roots pump set with two ordinary and three gas-cooled Roots pumps. This pumping set is able to compress H isotopes from 0.1 mbar to 800 mbar. All these Roots pumps are equipped with slotted tube motors, and leak rates of less than 10^{-7} mbar ls^{-1} are ensured if the housing of the pumps is made of stainless steel. These pumps are equipped either with piston sealings or labyrinth sealings to separate the working area from their gearing housing which is oil lubricated. At present it seems to be necessary to pump at the sealing space because otherwise oil vapour may enter the pumping area. In this field further development is necessary. A second pumping set ensures sufficient redundancy and additionally enhances the pumping velocity.

The TVS may be completed by cryopumps (CP). It is thus possible to achieve selective pumping in the presence of high T concentrations. A cryocondensation pump CP I with a working temperature of 30 K is able to pump all impurities except He and the H-isotopes. The following two cryosorption pumps CP II work at 15 K and will be applied for pumping and regenerating alternately.

In case discharge cleaning with a D-T gas mixture will be applied the CP I will purify the circulating gas by collecting all impurities. The capacity of the CP I should be high enough so that regeneration need not be done during the discharge cleaning process.

The use of cryopumps as described here will have to be tested to ensure that all requirements can be met.

2.6 Vacuum Measurement in the Torus Vacuum System

2.6.1 Measuring System for the 10^{-8} - 10^{-3} mbar Pressure Range

Ionization measuring systems (hot cathode measuring systems)

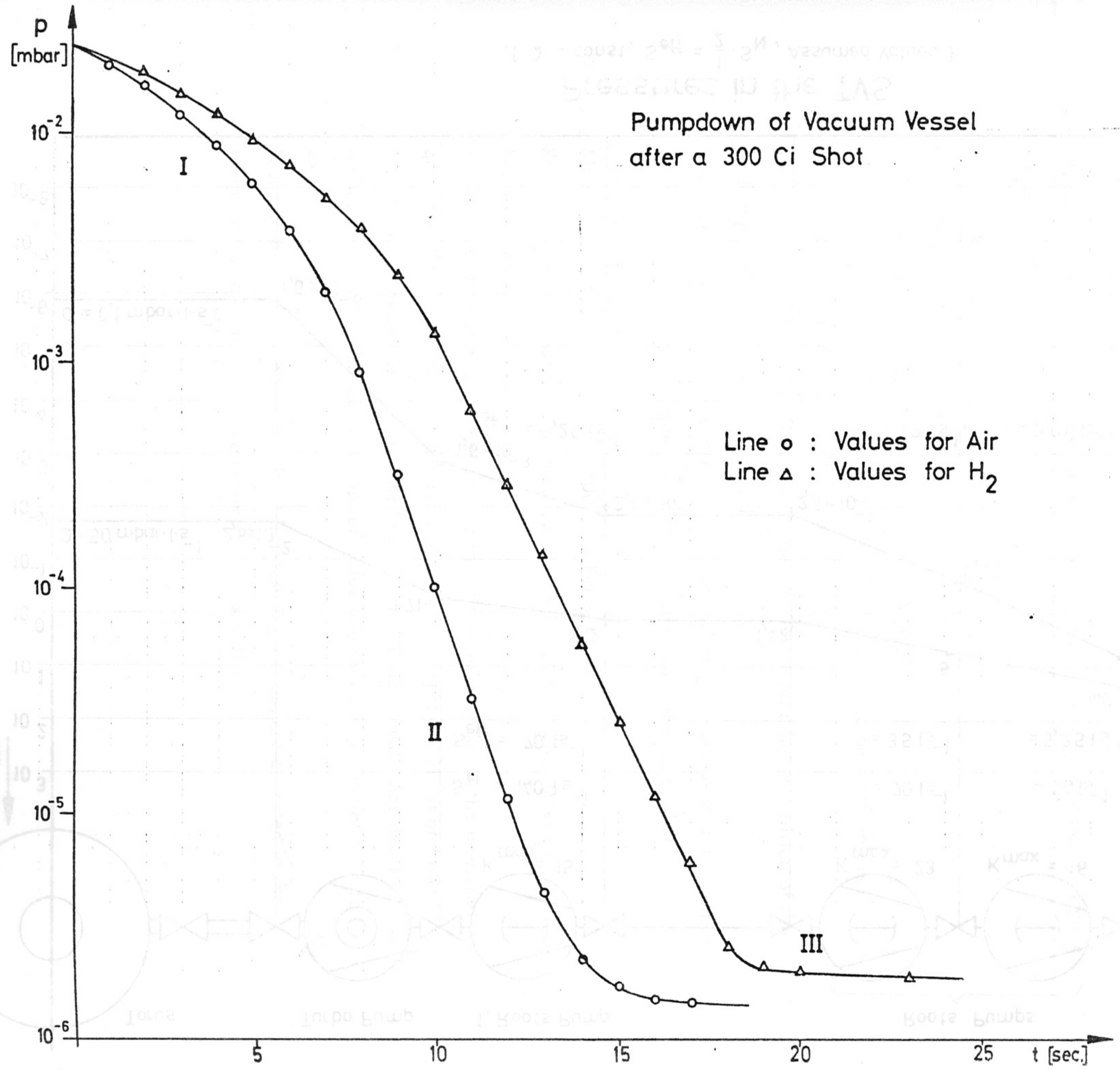
Measuring system on CF flange, bakeable, ceramic ducts, two separate emission surfaces for I_{em} - 10 mA

Disturbances expected: I_{em} = 10 mA

a) Residual gas ionization due to ß decay of tritium. However, owing to the small tritium inventory in the measuring system, 1.4 x 10^{-4} Ci, and the low ionization probability of the 18 keV electrons, the influence of residual gas ionization is negligible in operation with an emission current of 10 mA down to a tritium partial pressure of a few times 10^{-3} mbar.

b) Positive X-ray effect (Compton effect and pairing effect)

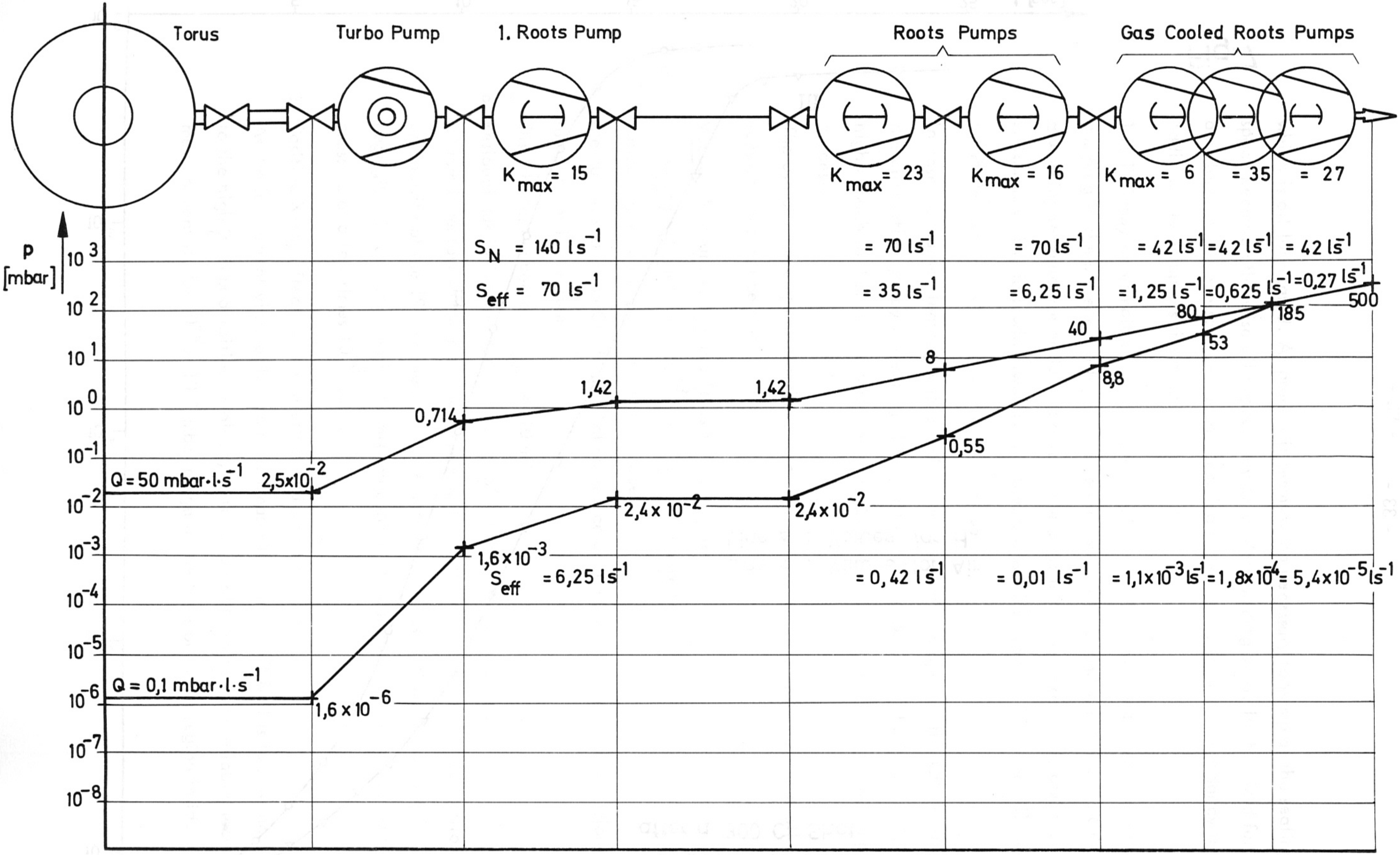
As the ion current yield of hot cathode measuring systems (HCMS) is low owing to the high γ flux densities involved, it is not possible to perform reliable vacuum measurement in the 10^{-8} - 10^{-3} mbar range in the torus or in the region inside



Pumpdown of Vacuum Vessel
after a 300 Ci Shot

Line o : Values for Air
Line Δ : Values for H_2

Fig. 7



Pressures in the TVS

(Q = const, $S_{eff} = \frac{1}{2} \cdot S_N$, Assumed Values)

Fig. 8

the first shield. The disturbances in this region may be up to 10^4 times as high as the test value. For HCMS it is thus necessary that the γ flux densities at the application site be lower than $10^9\ \gamma/\mathrm{cm}^2\ \mathrm{s}$.

Quantitative data on the disturbances in the HCMS outside the first shield can only be obtained after the locally expected γ flux density and its spectral energy distribution, have been determined.

Disturbances due to neutron radiation were not taken into account since the HCMS are switched off during the shot.

Measuring cycle:

I. Measurement of disturbances $I_{EM} = 0$

II. Measurement of total values $I_{EM} = 1$ or 10 mA

III. Determination of true values by taking the difference between values I and II and display of result

The supply voltages to the measuring system are interrupted before ignition of the discharge and during the burning cycle.

The cycle I to III has to be continually repeated during the pump-down time since the disturbances keep changing owing to the decay time after each shot.

2.6.2 Measuring System for the 10^{-3} - 100 mbar Range

Resistive measuring system with metal gaskets suitable for tritium (thermotron)

Disturbances:

As these systems use the thermal conduction of the residual gas as the measured quantity, the current fed to the measuring branch is approx. 10^{-3} A and the mass of the measured element exposed to radiation is very small (approx. $10^{-5}\ \mathrm{cm}^3$), no noticeable distortion of the measured value due to ß and γ radiation is to be expected.

It should be ensured, however, that the measuring systems are operated in the temperature compensated range between 273° and 313°.

2.6.3 Measuring System for the 10 - 1500 mbar Range

For this pressure range it is possible to use wire strain pressure gauge. These systems afford the advantage that their display is independent of the residual gas composition and the measuring range is linear. Integrated into the measuring system is a DC-coupled amplifier which yields a signal of +5 V at the final value of the measuring range so that a resolution of up to 1×10^{-3} of the final value is possible. An all-metal version with metal gasket is possibly suitable for tritium operation.

Disturbances:

The structure should be free of vibration. Distrubances due to resonant frequencies up to approx. 2 kHz. No data is available on the influence of γ radiation on the integrated amplifier.

2.6.4 Radiation Insensitive Measuring System for the 10^{-4} - 10^{4} mbar Range

M.K.S. Baratron Type 317

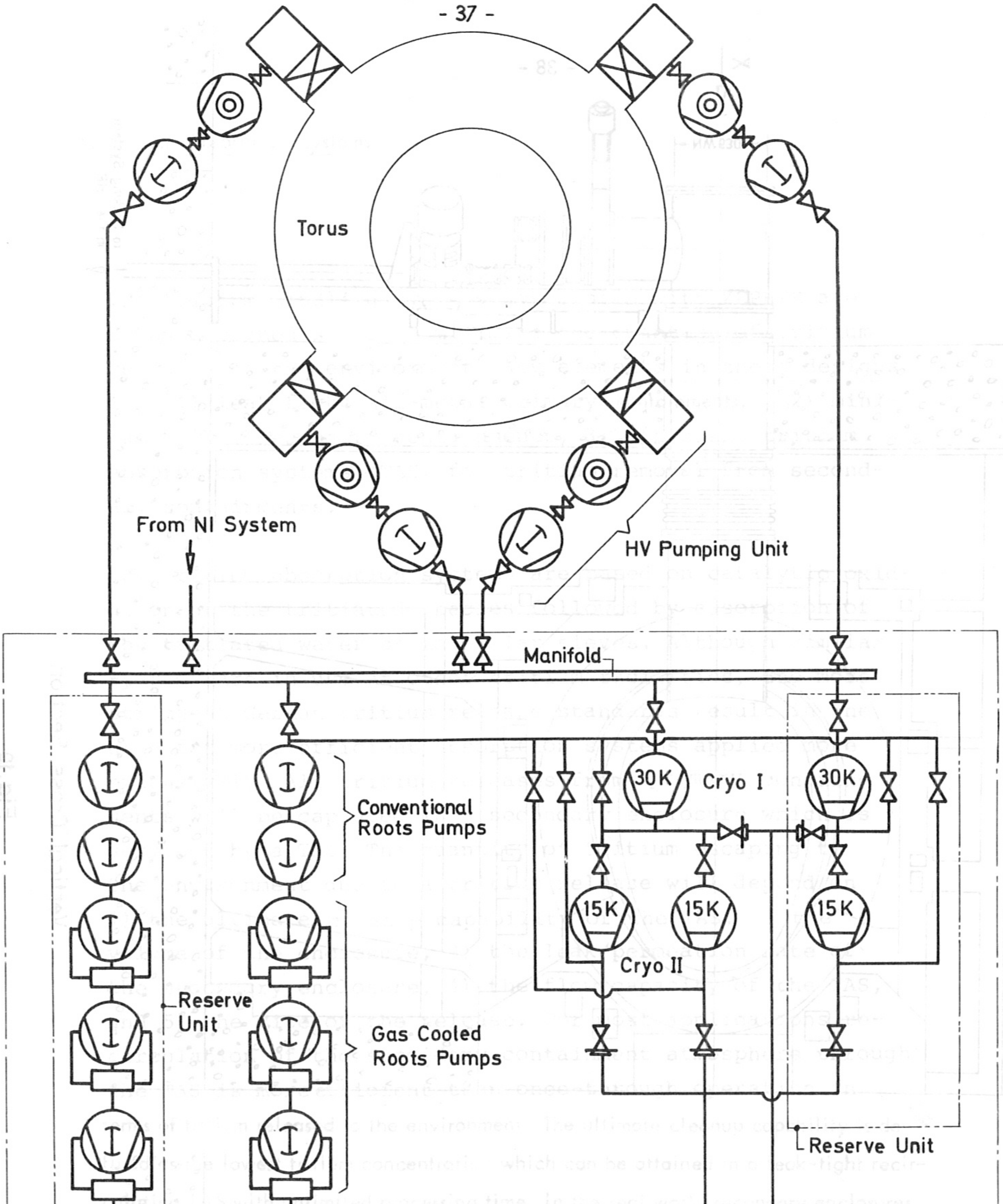
These sensors allow absolute pressure measurement independent of the type of gas.

The sensors are available for a measuring range from 1 mbar ascending in powers of ten to 10^{4} mbar and have an resolution amounting to 10^{-4} of their final value. It would thus be possible to cover the total range of 10^{-4} - 10^{3} mbar, with two sensors having limiting values of 1 mbar and 10^{3} mbar by providing sufficient range overlap.

The accuracy of the system is ± 1 % to ± 10 % of the measured value, depending on the pressure range.

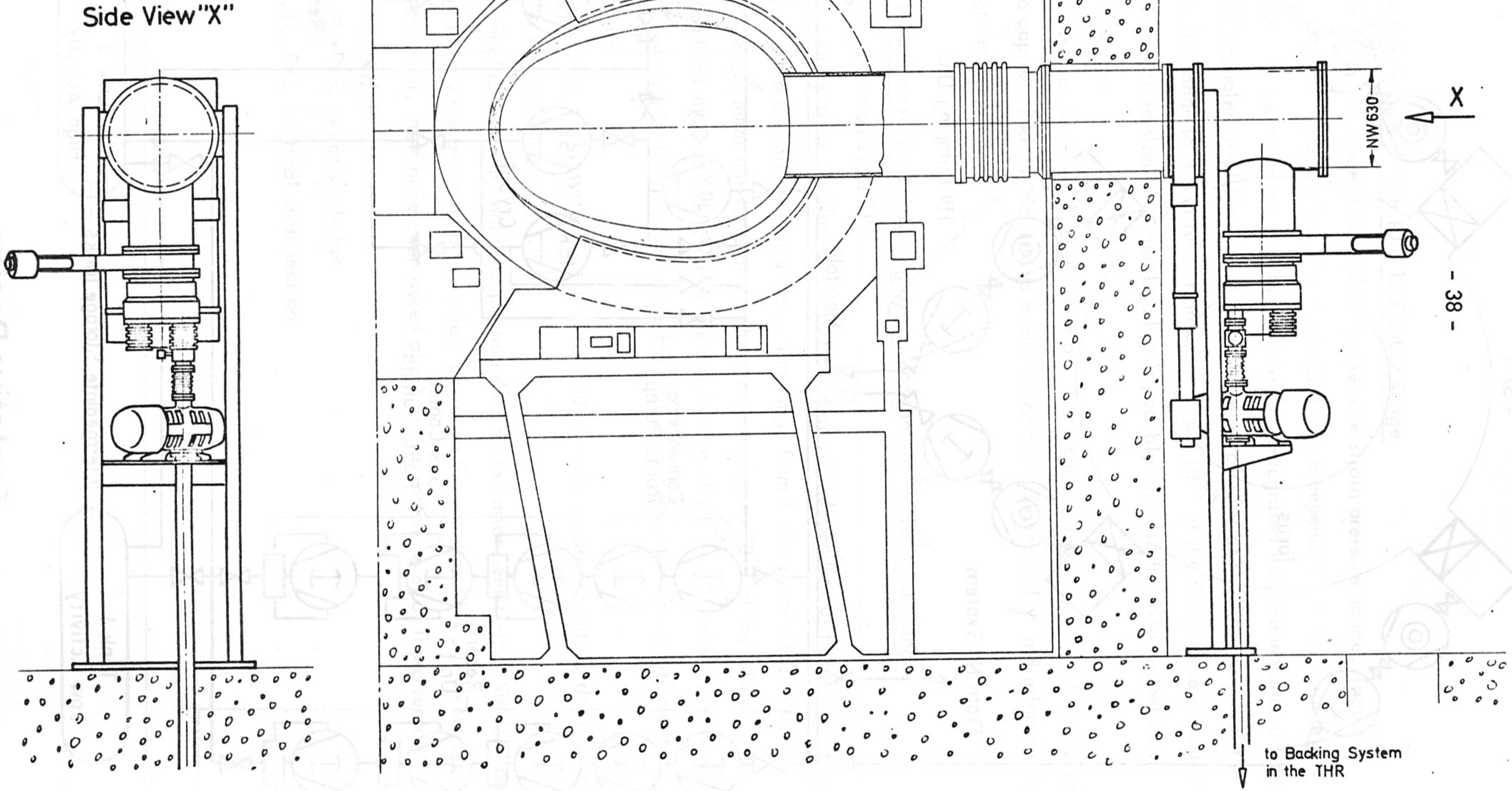
The manufacturer was unable to provide data on radiation sensitivity. Since, however, these sensors are being used in nuclear power stations and at KFA Jülich for pressure measurement, users have been asked about the radiation level of these sensors.

2.7 List of Figures



Tentative Design

Fig.9



Vertical Cross Section

Fig.10

3. Tritium-Absorption-Systems

3.1 Introduction

The tritium handling systems associated with ZEPHYR are being designed so as to minimize the quantity of tritium released to the environment. Key elements in these designs are: 1) leak tight all-metal primary containments, 2) minimum volume secondary containments, 3) efficient tritium absorption systems (TAS) for tritium removal from secondary containments.

The tritium absorption systems are based on catalytic oxidation of the tritiated species followed by adsorption of the tritiated water on molecular sieves. Although similar systems are in use at other tritium facilities, the more stringent German tritium release standards result in the need for more efficient absorption systems applied more extensively. All tritium releases from primary containments will be captured in a secondary enclosure which is serviced by a TAS. The quantity of tritium escaping to the environment due to a tritium release will depend on 1) the ultimate cleanup capability of the TAS, 2) the volume of the enclosure, 3) the leak/permeation rate of the secondary enclosure, 4) the flow capacity of the TAS, and 5) the size of the release. For most applications recirculation of the secondary containment atmosphere through the TAS is more efficient than once-through operation in terms of tritium released to the environment. The ultimate cleanup capability is defined as the lowest tritium concentration which can be attained in a leak-tight recirculating TAS with unlimited processing time. In the real world secondary enclosures have a finite leak/permeation rate. Therefore the tritium released to the environment will be equal to the ultimate cleanup capability of the TAS times the volume of the enclosure plus the tritium which leaks from the enclosure during processing by the TAS. Trade-offs among these factors will be discussed in the section on TAS design.

Most present day systems use Pd/Pt catalysts although some use copper oxide or other metal oxide combinations. Copper oxide is effective only at elevated temperatures but some of the precious metal catalysts will oxidize hydrogen near room temperature, though not as efficiently as at higher temperatures. This is particularly important for an emergency system which is likely to stand idle for months yet is expected to respond within seconds to a tritium release. Although elevated temperatures ($>$ 600 K) are required to oxidize hydrocarbons with reasonable conversion efficiencies, this is relatively unimportant during the early stages of cleanup when tritium to tritiated hydrocarbon ratios are very large. Most of the tritium leakage from an enclosure occurs during the first minutes after a release (when tritium concentrations are highest) so it is very important that a TAS responds quickly, whether operating at peak efficiency or not.

Molecular sieves (types 4A, 5A and 13X) at ambient temperature are the most commonly used water adsorbants in these systems. The best existing tritium absorption systems will remove tritium to a level of about 5×10^{-5} Ci/m^3. Most users are satisfied with this performance and have not attempted to improve it or to determine whether the catalyst or the molecular sieve is limiting further reductions in outlet concentrations. In the section on TAS design it will be shown that improvements in ultimate cleanup capability would be very desireable for systems operating on large volumes, ($>$ 1000 m^3). For glove boxes ($\sim$ 10 m^3) present systems are more than adequate.

3.2 Potential Sources of Tritium Release

The number, sizes and performance requirements of the tritium absorption systems were determined after careful consideration of the potential sources of tritium release /1/. The factors considered were: the quantity of tritium at risk, the probability of release (based on the integrity of the primary containment, the nature and complexity of the process, frequency of operation, etc.) and the volume and integrity of the secondary containments.

The primary potential sources are: 1) torus, 2) vacuum pump effluents, 3) tritium contaminated equipment in the hot cell, 4) tritium-contaminated equipment in maintenance tents, 5) tritium injection system, 6) fuel cleanup and isotope separation systems, 7) tritium storage, 8) tritium absorption systems, 9) pumping systems. Vacuum pump effluents can be collected in storage tanks and processed periodically. All other potential sources listed above can be secondarily contained and the containment atmospheres can be recirculated through tritium absorption systems.

While each of these sources could be serviced by a dedicated TAS, that would be a very costly solution. It was concluded that three separate, fully redundant tritium absorption systems could perform all of the gas detritiation tasks for ZEPHYR. Tritium sources having compatible cleanup requirements will be joined to a common manifold serviced by a TAS. The individual sources will normally be valved off from the manifold, but in the event of a tritium release in any one of the secondary enclosures, the valves will automatically open and the atmosphere of the containment vessel will be recirculated through the TAS until the tritium level in the enclosure is within desired limits.

The three system, their tasks, and approximate volumetric flow capacities are:

TAS I	torus, hot cell, tritium vault, tritium handling room, maintenance tents, room containing tritium absorption systems - 3000 m^3/hr
TAS II	all low volume, non-evacuable enclosures (e.g. glove boxes for tritium injection system, fuel cleanup and isotope separation system). - 300 m^3/hr
TAS III	tritium-containing effluents from all vacuum pumps in the facility - 10 m^3/hr.

Before describing the model used to size the individual systems it may be useful to discuss the rationale for grouping the various sources.

3.3 Allocation of TAS Duties

TAS I

This, the largest of the three tritium absorption systems (~ 3000 m^3/hr), will process the atmosphere of the hot cell and maintenance tents and will service the torus and tritium handling room in emergency situations. The torus will contain in and on its walls perhaps several thousand curies of tritium. The torus also contains ~ 300 curies of tritium at ~ 10^{-3} torr just before a discharge.

Of the possible way to deal with a large hole in the torus, one of the worst would be to allow the tritium to escape into the reactor hall before trying to capture it. The large volume of the hall (~ 3×10^4 m^3) would result in the need for a very large TAS (~ 3×10^4 m^3/hr for cleanup in 10 hours) and a relatively leak tight hall (< 1.2 m^3/hr). With an ultimate cleanup capability of 5×10^{-5} Ci/m^3, several curies of tritium would still remain in the hall atmosphere after cleanup and would have to be released through the stack.

Another solution, which does not depend on a secondary container, is to draw air into the torus (through the hole) at a velocity sufficient to prevent the back-diffusion of tritium into the hall (about 1 m/sec). This tritium-contaminated air, the quantity of which depends on the size of the hole, would be discharged into the inlet of a high efficiency TAS operating in a closed loop. A corresponding volume of decontaminated air would be extracted from the downstream side of the TAS and discharged into the stack. For small leaks, most of the gas is recirculated and very little is discharged to the stack. However, if the volumetric flow rate of air coming into the torus becomes equal to the maximum flow capacity of the GAS, no recirculation occurs. For this reason, TAS I must have a much higher single-pass conversion efficiency than the other systems.

The hot cell is the largest volume into which tritium will be intentionally released. These low level releases (fractions of a curie to tens of curies if welding is performed) will result from desorption and outgassing during the repair of large pieces of contaminated equipment.

The tritium handling room will contain a number of glove boxes (4 to 6, each $\sim 10\ m^3$ in volume). These glove boxes will contain the torus roughing pumps, the fuel cleanup system, the isotope separation system, the tritium supply for injection to the torus, etc. Since people will often be working in this room, it will normally be ventilated by a once-through air supply. In the event of a tritium release into the room, the normal ventilation system would be valved off after all persons have left the room and the atmosphere would be recirculated through a TAS. The room would be functioning as a tertiary container in this case and since the glove boxes themselves are serviced by another TAS, it is unlikely that a significant quantity of tritium will ever escape into the room unless a serious accident breaches the primary containment and the glove box simultaneously. The volume of the tritium handling room is about 400 to 500 m^3.

The term "maintenance tent" refers to any temporary enclosure which is erected over a large piece of equipment which is likely to release tritium during a planned maintenance or disassembly operation. The atmosphere of the tent would be continuously processed during the maintenance operation to prevent the excape of tritium into a larger volume such as the reactor hall or the TAS room.

TAS II

Four to six glove boxes, each having a nominal volume of $\sim 10\ m^3$, will be connected to the TAS II manifold. The operations contained within these glove boxes, such as fuel cleanup and isotope separation, involve large quantities of high concentration tritium ($\sim 10^5$ curies), high temperatures, and pressures near atmospheric. Even though primary containments of the highest quality will be utilized, the potential for a large tritium release is greatest within some of these glove boxes.

TAS II is designed with a higher ratio of flow rate to enclosure volume than the other systems. This is necessary because of the large amount of tritium which would leak/permeate out of the glove box if the tritium release were not cleaned up within a matter of minutes. The glove boxes will be valved off from the TAS manifold during normal operation. In the event of a tritium release within a glove box, the valves connecting that box to the TAS manifold will be opened and the atmosphere of the box will be recirculated through the system until the tritium concentration is within allowable limits.

Although TAS II may be considered an emergency system in some respects, it will also be used to periodically remove relatively small concentrations of tritium from the boxes. The tritium concentration in a glove box can be expected to rise gradually as a result of permeation and small leaks and also from breaking connections to change sample volumes and maintain or replace equipment. The contamination level in this system will eventually be quite high.

It was mentioned earlier that these tritium absorption systems were to be fully redundant. This means that all prime function components such as blowers, heaters, catalyst beds, and dryers will be duplicated and interconnected so that failure of a single component will not disable the system. A control computer will automatically establish a workable flow path through the system, if one exists. It is obvious that if continuous processing of the glove box atmospheres is not required, it is more cost-effective to service the boxes with a single, high capacity, fully-redundant system than with dedicated systems for each glove box.

TAS III

The smallest of the three systems will remove tritium from the effluents of all vacuum pumps in the facility. Pumps which normally would exhaust to the stack will instead exhaust into a manifold which is connected to several stainless steel storage tanks. The tanks will be sized to collect gas for perhaps a week before processing is necessary. This allows for the anticipated large variation in gas load and also permits TAS III to be less than fully redundant since excess storage capacity allows time for repairs. Also, the system need not be maintained in a stand-by condition for fast start-up.

3.4 TAS Design

As mentioned earlier, the quantity of tritium escaping to the environment due to a tritium-release will depend on 1) the ultimate cleanup capability of the TAS, 2) the volume of the enclosure, 3) the leak/permeation rate of the secondary enclosure, 4) the flow capacity of the TAS, and 5) the size of the tritium release. There are obviously some trade-offs which can be made to minimize the amount of tritium lost. A fast responding, high flow rate TAS can compensate for a leaky enclosure. Conversely, flow rate is not important if the secondary enclosure is a leak-tight stainless steel tank. Ultimate cleanup capability is very important for large volume enclosures and may have to be improved over present day systems. For once-through systems single pass tritium removal efficiency is, of course, very important. To aid in sizing these systems a simple model was developed for recirculating systems which incorporates the variables listed above. The system is assumed to remove a constant fraction of the tritium on each pass until an ultimate concentration is reached. This concentration is determined by the amount of tritium in a penetrating form (e.g. tritiated methanes or ammonia which may pass through certain catalysts without being converted to water), by the vapor pressure of tritiated water over the molecular sieves, or by a combination of these factors.

Expressions were derived for T / 2 /, the quantity of tritium remaining in the enclosures as a function of time and T ` , the quantity of tritium leaked from the enclosure as a function of time.

$$T = fT_o e^{-\lambda_1 t} + (1-f)T_o e^{-(\lambda_1 + \varepsilon\lambda_R)t} + \frac{\varepsilon\lambda_R}{\lambda_1 + \varepsilon\lambda_R} \cdot U_v \left(1 - e^{-(\lambda_1 + \varepsilon\lambda_R)t}\right)$$

and

$$T' = fT_o\left(1 - e^{-\lambda_1 t}\right) + \frac{(1-f)}{\lambda_1 + \varepsilon\lambda_R} \cdot \lambda T_o \left(1 - e^{-(\lambda + \varepsilon\lambda_R)t}\right) + \frac{\varepsilon\lambda_R}{\lambda_1 + \varepsilon\lambda_R} \cdot \lambda_1 \cdot U_v \cdot t - \frac{\varepsilon\lambda_R}{(\lambda_1 + \varepsilon\lambda_R)^2} \cdot \lambda_1 \cdot U_v \left(1 - e^{-(\lambda_1 + \varepsilon\lambda_R)t}\right)$$

T_o = quantity of tritium initially present in the enclosure
t = time, hours
λ_R = removal time constant, hr^{-1} (volumetric flow rate of TAS divided by volume of the enclosure)
λ_1 = leak time constant, hr^{-1}
ε = single pass tritium removal efficiency
f = fraction of tritium in penetrating form
U_v = residual quantity of tritium remaining in enclosure due to vapor pressure of tritiated water over molecular sieves or similar process.

For a recirculating system the single-pass conversion efficiency is relatively unimportant compared to the flow rate, so $\varepsilon = 0.99$ was chosen for all cases. It was also assumed that the fraction of penetrable species was zero. For glove boxes the leak time constant was set to 5×10^{-6} hr^{-1}. This was based on data for existing glove boxes. The leak time constant for the various rooms was set to 4×10^{-5} hr^{-1}. This number is very difficult to estimate because it depends not only on the construction of the room but also on the pressure maintained within the room. The maintenance of a negative pressure sufficient to prevent tritium diffusion out of the room will also result in the need to release air to the stack to balance in-leakage. U_v was based on a residual tritium concentration of 5×10^{-5} Ci/m^3. This may be difficult to sustain in practice.

3.4.1 TAS I

Earlier it was decided that a hole in the torus would be dealt with by drawing air into the torus at a sufficient velocity to prevent the diffusion of tritium out of the torus. Tritium hoods generally have a face velocity between 0.5 and 1.0 m/sec /3/. A TAS with a flow rate of 3000 m^3/hr would be sufficient to maintain a velocity of 1.05 m/sec through a hole one meter in diameter. If the maximum credible accident is the destruction of a 30 cm diameter diagnostic window, the 3000 m^3/hr system would have sufficient capacity to recirculate a large fraction of the gas while still maintaining > 1 m/sec flow through the hole. The trade-off to be made here is between flow rate and single-pass tritium removal efficiency. If the TAS is sized so that it can service a 30 cm diameter hole only on a once-through basis, then it must have a higher single-pass removal efficiency than a larger, partially recirculating system if it is to maintain the same tritium release rate to the stack. In making this trade-off, the other duties of the TAS must also be considered. For recirculating systems, flow rate is much more important than single-pass removal efficiency in minimizing clean-up time.

TAS I will also be used to service the hot cell (2500 to 3000 m^3), the tritium-handling room, and maintenance tents.

Figure 11 shows results for the release of 10 Ci into a 3000 m^3 volume ($\lambda_R = 1.0$). Leakage from the hot cell does not appear to be significant (if the assumed leak time constant is correct to within a factor of a hundred), but because of the large volume, several tenths of a curie could be released through the stack every time something is taken into or out of the hot cell.

3.4.2 TAS II

Since the glove box volumes are so much smaller than those serviced by TAS I it is possible to use a much higher removal time constant and still have a reasonable-sized absorption system. Fig. 12 shows results for a tritium release of 10^5 curies into a 10 m^3 glove box serviced by a 300 m^3/hr TAS ($\lambda_R = 30$). It can be seen that even after a 10^5 curie release only 10^{-2} Ci of tritium leaks from the box. This assumes that the gloves are capped so that permeation of tritium through the large surface area of the gloves is not a factor. The residual concentration after cleanup is less than 10^{-4} Ci/m^3. Since it is possible to work in glove boxes with tritium concentrations orders of magnitude greater than this, the residual tritium need not be vented to the stack as it is for the rooms.

3.4.3 TAS III

The amount of tritium released to the environment through TAS III depends only on the quantity of gas processed and the ultimate cleanup capability of the system. Since

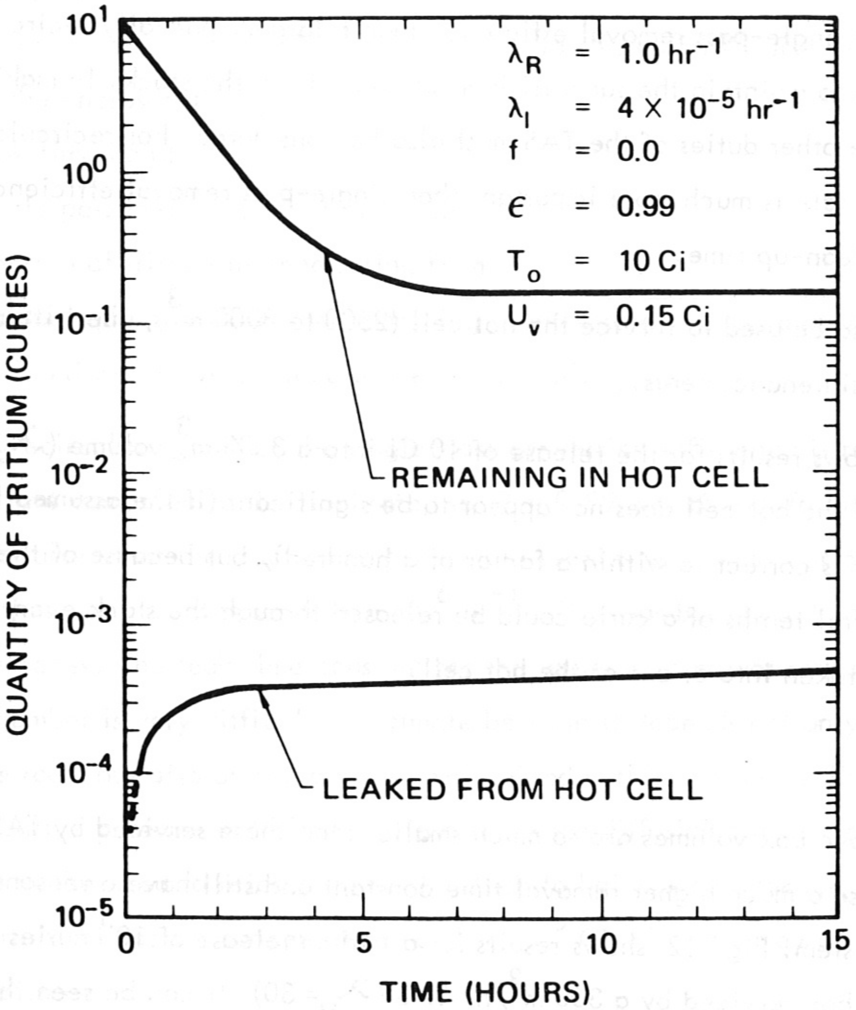


Fig. 11 Results for a tritium release of 10 Ci into a 3000 m^3 hot cell serviced by a 3000 m^3/hr TAS.

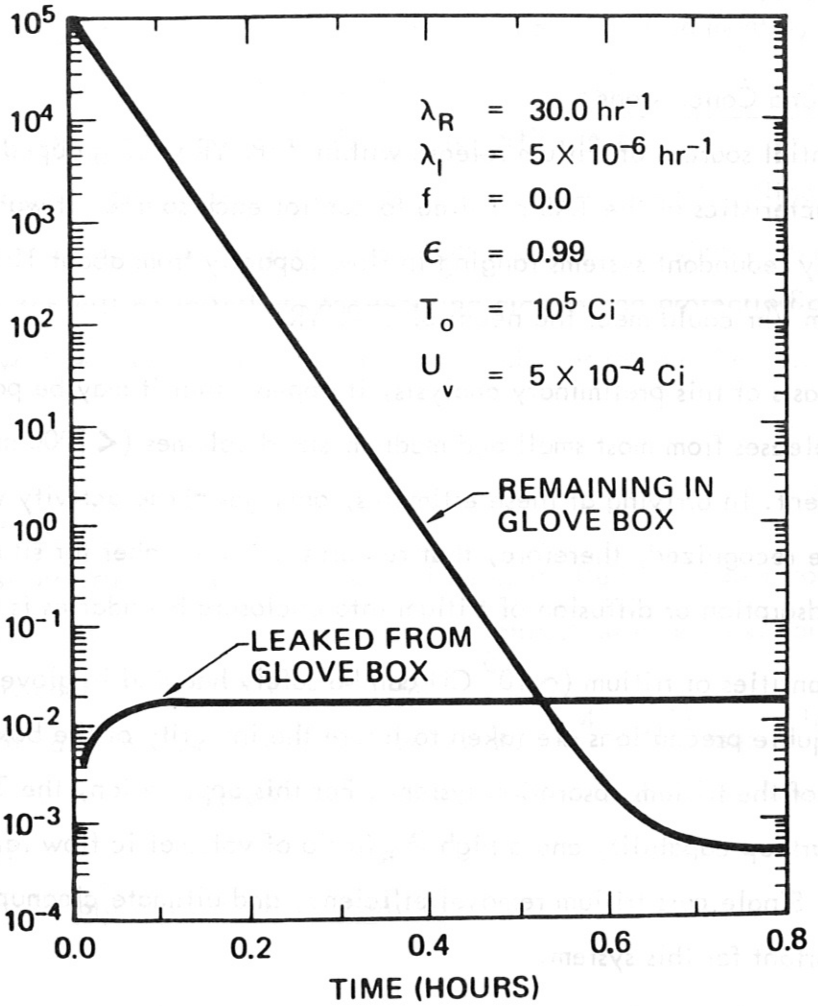


Fig. 12 Results for a tritium release of 10^5 Ci into a 10 m^3 glove box serviced by a 300 m^3/hr TAS.

the storage tanks can be made leak-tight, the size of the system has no effect on the amount of tritium released.

3.5 Summary and Conclusions

The potential sources of tritium release within ZEPHYR were grouped according to the characteristics of the TAS required to control each source. It was determined that three fully redundant systems ranging in flow capacity from about 10 m^3/hr to < 3000 m^3/hr could meet the needs of ZEPHYR.

On the basis of this preliminary analysis, it appears that it may be possible to limit tritium releases from most small and medium-sized volumes (< 1000 m^3) to < 1 Ci per incident. In arriving at these estimates, only gas phase activity was considered. It must be recognized, therefore, that releases will be higher for situations where tritium adsorption or diffusion of tritium into enclosure boundaries is significant.

Large quantities of tritium ($\sim 10^5$ Ci) can be safely handled in glove boxes provided that adequate precautions are taken to insure the integrity of the boxes and the reliability of the tritium absorption systems. For this application, the TAS should have a fast start-up capability and a high λ_R (ratio of volumetric flow rate to glove box volume). Single pass tritium removal efficiency and ultimate cleanup capability are less important for this system.

For large volumes which must be vented to the stack after clean-up, ultimate cleanup capability is very important in determining the amount of tritium released. More work needs to be done to improve the ultimate cleanup capability of tritium absorption systems and to understand the limiting processes.

4. Tritium Monitoring System

4.1 Control of Persons

All persons subject to possible tritium exposure have to be controlled monthly by measuring the tritium activity in their urine. When higher activities are expected these controls should be done daily to obtain a better estimate of the absorbed dose. The numbers must be recorded and preserved. The entrance of the tritium handling rooms is provided with a lock area, containing a restroom and a shower. Furthermore, a surface contamination monitor will be installed. The working clothes and protection clothes with oxygen apparatus will be placed here. The protection clothes reduce the absorbed dose by a factor of 10^3.

4.2 Control of the Rooms

All rooms with possible tritium contamination will be controlled by tritium monitors with different sensitivities. For more than 10^{-6} Ci/m^3 air ionization chambers, for less than 10^{-6} Ci/m^3 proportional counters will be applied.

In the experimental hall and its basement the radionuclei Ar^{41}, N^{13} and N^{16} will be produced, in addition, by neutron radiation. Table 7 lists their data. Their activities must also be controlled.

Table 7 Radionuclei produced in air by neutrons

Isotope	half-life	rad. energy in MeV , (%) /5/ ß		activity per pulse/6 / Ci	activity after one hour Ci/m^3	allowed mean annual concentration Ci/m^3 /4/
N^{13}	9.96 min	ß$^+$1,2 (100%)	0,511 (200%)	0,5	2.6x10^{-7}	2.8 x 10^{-9}
N^{16}	7,35 s	10.4(26) 4.3 (68) 3.3 (5)	7.12 (5) 6.13(68)	120	after 3 min practically decayed	7.8 x 10^{-12}
Ar^{41}	1,83 h	1.2(99) 2.5 (1)	1,3 (99)	5 x 10^{-2}	1.1 x 10^{-6}	2.2 x 10^{-9}

Above a given radiation level in the contaminated room a visual and acoustic alarm will warn of the tritium release and workers must leave the room. If possible, the ventilation of this room will be automatically taken over by a tritium absorption system (not possible for the experimental hall and its basement).
During discharges the experimental hall and the basement will be barred.

The suction tubes of the monitors should be installed near the possible tritium release and at the exit of the ventilation system inside the room. Table 8 specifies the monitors needed.

Table 8 Tritium monitors

	10^{-6} Ci/m^3	10^{-6} Ci/m^3	Tritium and other radiating isotopes
Inside 1. shielding	1	2	x
exp. hall	1	2	x
exp. hall basement	1	2	x
lock area hot cell	1	1	x
hot cell	1	2	x
hot waste room	1	1	x
lock area tritium handling	1	1	
tritium handling room	1	2	
tritium absorption system	1	2	x
tritium waste room	1	1	
glove boxes	-	7	
tank room	1	1	
stack	1	2	x

4.3 Measuring Systems

Tritium radiates only soft $ß^-$ - rays, and owing to the low range of the ß`s the contaminated air must flow through the measuring system. This allows us to install a good shielding around the monitors against the γ - radiation from the activated tokamak and shielding structure.

High tritium concentrations cause contamination of the chambers (memory effect). Subsequent flushing with clean gases will reduce this effect.

In rooms with neutron radiation one has to discriminate between tritium and the above mentioned radionuclei, which emit ß and γ - rays and simultaneously enter the measuring chamber.

For tritium concentrations of less than 10^{-6} Ci/m^3 the application of proportional counters, for more than 10^{-6} Ci/m^3 the application of ionization chambers is recommended. The proportional counter according to Fig. 13 has 3 chambers in series through which a mixture of air and methane in a ratio of 1 : 2 flows. It is assumed that ß`s of tritium in the middle chamber 1 have no effect in the shielding chambers 2. But the higher energy ß`s of the other radionuclei produce counts in the neighbouring chambers. To eliminate the effect of Ar^{41} and N^{13} the counts of the middle chamber 1 will be measured in anticoincidence with the chambers 2. The probability that nontritium ß`s will be counted only in chamber 1 is only a few per cent and can be neglected because the real tritium concentration will be smaller than the measured one. The sensitivity for tritium is of the order of magnitude of 10^{-9} Ci/m^3. With smaller chambers and changed mixtures the upper limit can be increased to 10^{-1} Ci/m^3. The memory effect then prevents further measurements at low concentrations.

At such high tritium levels the influence of Ar^{41} and N^{13} can be neglected. The tritium could be measured by an ionization chamber which has a compensation volume for background radiation. The inner surface of these chambers should be gold-coated except for the insulator to reduce the memory effect.

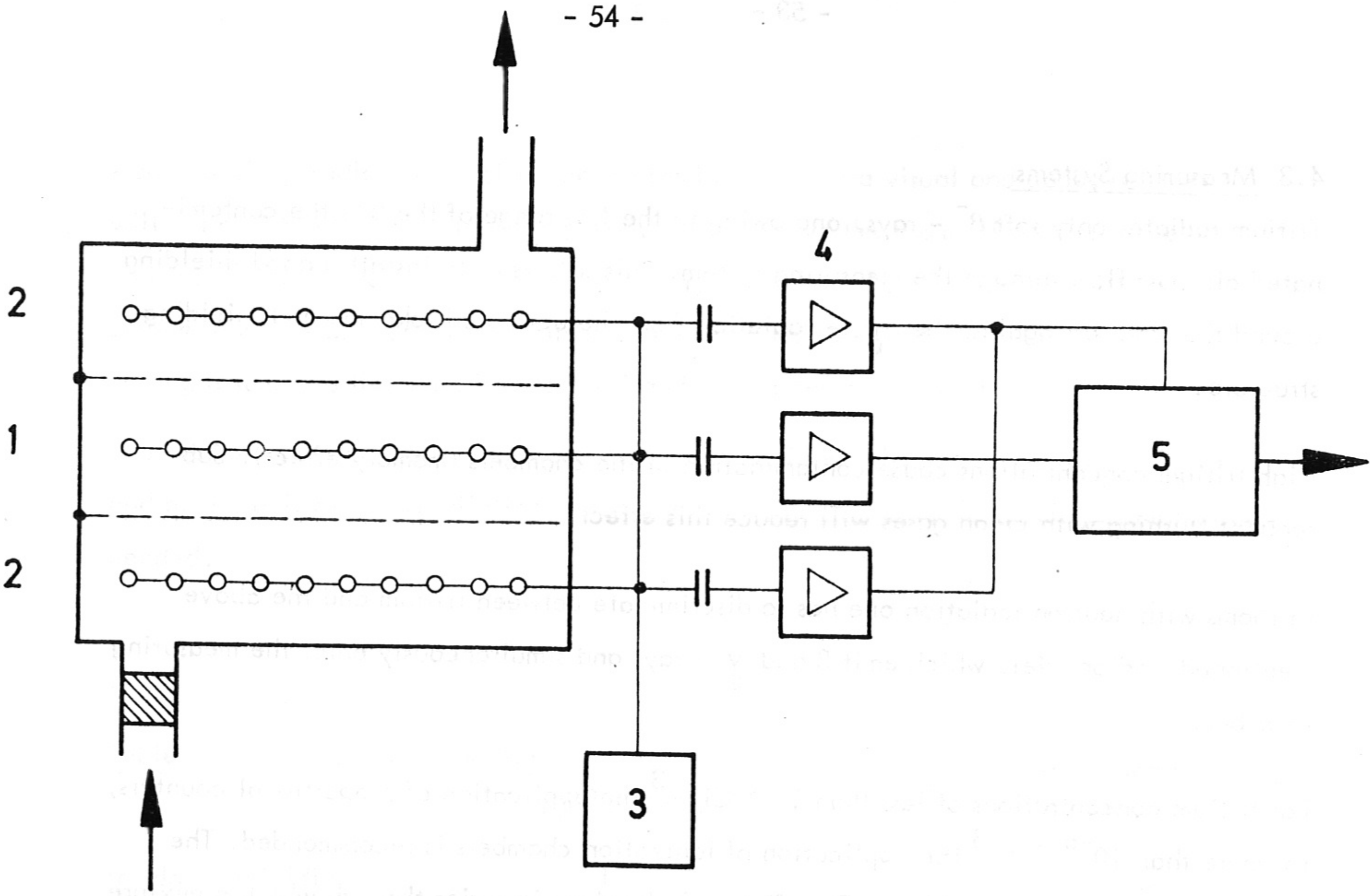


Fig. 13 Measuring of tritium in air with a 3 chamber proportional counter

1 measuring volume
2 shielding volume
3 high voltage supply
4 amplifier and pulse shaping
5 anticoincidence counter

Surface contamination with tritium or tritium containing water or other compounds can be measured with windowless proportional counters. The sensitivity is about 2×10^{-8} Ci/m^2. The permissible value is 10^{-6} Ci/m^2. Ar^{41} or N^{13} play no part because after a ventilation time of one hour their activity is negligible.

Contamination of liquids can be checked with liquid scintillation counters, where the scintillation liquid will be mixed in a known volume ratio with the contaminated water or other liquids.

5. Tritium Waste

5.1 Introduction

Tritium waste is considered to be all material which contains sufficient tritium to preclude its storage outside of a controlled area but from which it is impossible or economically unreasonable to extract the tritium. These materials range from tritiated water and tritiated pump oil having fairly high specific activities to rubber gloves.

In the following discussion no attempt will be made to estimate the quantity of waste which will be generated or to formulate a specific waste handling and storage program although this will be done during the design phase. The issue of radioactive wastes is particularly important for ZEPHYR because the wastes must be stored on site. Because there is at present no possibility to dispose of the wastes, every attempt must be made to minimize the quantity generated.

5.2 Categories of Tritium Waste and Methods of Handling

Most of the waste will be in solid form (e.g. contaminated equipment, protective clothing) or can be converted to solid form (e.g. tritiated water can be absorbed on molecular sieves, tritiated oil can be absorbed by clay). Solid waste should be compacted, where possible, to minimize storage volume. Low level liquid wastes generated by cleaning the floors or washing protective clothing will probably meet the standards for discharge into the sewage system.

5.2.1 Tritiated Water

Most of the tritiated water will be generated by the TAS (Tritium Absorption System). Depending on the TAS and its duties, the specific activity of tritiated water driven off the molecular sieves could cover a very wide range. For example, if a large tritium release were to occur in an inert atmosphere glove box served by a TAS whose molecular sieve beds had recently been regenerated, it is quite likely that the water could be processed by the Fuel Cleanup and Isotope Separation Systems with almost total recovery of the tritium. A few curies released into the hot cell, however, would be unrecoverable due to the large quantity of normal water in the hot cell atmosphere and on the TAS molecular sieve beds. The amount of waste tritiated water generated will depend on many factors; the most important being the volume of gas processed by the TAS`s and the humidities of the gas streams.

5.2.2 Tritiated Oils

A great deal of tritiated oil, much of it contaminated with water, will be produced by the mechanical vacuum pumps in the facility. These include rotary vane pumps, turbo-pumps, and Roots pumps. This oil, even if it is of very low specific activity, must be stored on site.

5.2.3 Contaminated Components

It is possible to decontaminate surfaces by chemical treatment. Most of the surface tritium occurs in the form of THO, and therefore aqueous solutions are adequate. Applying this treatment will yield tritiated water and/or solvents. The problems connected with waste disposal will only be transferred.

During warm-up of metals in which tritium is dissolved emissions might occur; even during cutting processes T-releases are possible.

Re-usable components should be heated to 150 - 200 °C within specially designed glove boxes in order to release the THO molecules absorbed at the surface of these parts. With this procedure the parts will be sufficiently decontaminated to continue with mechanical work.

The main portion of the tritium which is not dissolved in materials might be released by vacuum degassing. Parts of the experiment which carry the 14 MeV neutron load must be processed corresponding to that activity. Processes for remote tritium degassing must therefore be envisaged. These processes have to be performed in the hot cell. Limiters, shielding components and some diagnostic equipment which are exposed directly to the fusion plasma may contain significant amounts of dissolved tritium within a depth of a few times 1/1000 mm.

5.2.4 Tritium Contaminated Solid Waste

Of the categories mentioned, this could occupy the largest volume but contain the lowest total tritium activity. It would include such items as discarded pipes and flanges, broken parts from contaminated equipment, rubber gloves, shoe covers, other protective clothing, gaskets, spent getter materials, etc. Every effort will be made to minimize the volume of this waste by using washable protective clothing times, for example, and compacting other material where possible.

5.3 Dimensions of the T-Waste Storage Room

At present it is difficult to make estimates with sufficient accuracy concerning amounts of solid and/or liquid waste. Within the next few years some further information will be available owing to progress with the operation of other T-experiments and the like.

In general, there must be sufficient space to store a complete Roots pump module (1000 x 1500 x 1500 mm).

Loaded molecular sieves constitute a storage problem; it seems to be a good solution to store these columns within the TAS room itself.

Max. dimensions of a molecular sieve: height 5 m; diameter 1.4 m.

For storage of ordinary waste drums (200 l volume each) at least 20 m^2 area must be available. In these containers cleaning aids, gloves, seals, solidified pump oil and solidified THO (from regeneration devices) can be stored.

Furthermore, a small supply of concrete and polymers should be stored in this room and a space should be made available for the manipulation of containers and drums.

At present the waste room shows the following dimensions: ground area

height of the room: 5 m (see /7/).

There should also be pathway for transportation which connect this room both with the THR and the TAS room.

6. Tritium in Neutral Injection

6.1 Introduction

The cryopanels located in the neutral beam lines will receive significant amounts of tritium by back diffusion with each shot. Also during D-D operation tritium will be generated in the beam lines itself. Following data given in /8 / up to 170 Ci per day per beam line will be accumulated in the beam lines. The tritium will be spread over surfaces of the beam lines and mainly collected at their cryopanels. After a certain number of discharges the cryopanels must be regenerated and the tritium is pumped off together with a surplus of deuterium $(1 : 10^3)$. For the regeneration of the cryopanels an external vacuum system (NBVS) has to be installed.

Presently it is believed that a maximum T-concentration of about 1% in the deuterium will be tolerable; this means that the deuterium load to be regenerated from the cryopanels could be recirculated. The same restriction is valid for the hydrogen concentration in the deuterium.

Other impurities like tritiated methanes and so on occuring at the same time in the gases to be pumped off from the cryopanels must be removed from the recirculated deuterium. Therefore a cleanup process must be foreseen. Removal of these impurities might be done by cryogenic processes.

There might be an additional reason for recirculating the deuterium; as there is a necessity of conditioning shots between normal discharges about 100 ℓ(STP) of D_2 will be spent per day. Trade-off studies of deuterium costs and of the costs of a cleanup device should be started in order to evaluate both choices.

If the concentration of tritium and protium in the recirculated deuterium exceeds the tolerable limit the gases must be stored in an intermediate tank. Processing them by an absorption device (TAS) results in a fairly high load on its molecular sieves. Therefore a high number of molecular sieve regeneration cycles will result. A solution may be to oxidize the D_2 (T_2) directly by a catalytic oven to tritiated D_2O.

This liquid waste can either be stored on site or given to an external processing facility. There are separation facilities which are designed to separate small quantities of T_2 from heavy water by means of catalytic exchange between tritiated water vapor and gaseous D_2, followed by subsequent cryogenic distillation.

Even in case of a higher concentration of T_2 or H_2 in the D_2 an isotope separation process on site is not envisaged; due to the high dilution of both the isotopes in the deuterium, the ISS for the fuel cannot be used.

Totally some percent of the overall tritium consumption of ZEPHYR will be lost with the NI-effluents to be processed in the described manner by the NBVS.

6.2 Requirements of the NBVS

The neutral beam vacuum system (NBVS) on the one hand must be designed to evacuate each neutral beam line from atmospheric pressure to a base pressure of 10^{-5} torr or lower. On the other hand the NBVS must be able to pump off the deuterium from the crypanels of the neutral beam lines during their regeneration. It is expected that this regeneration cycle will occur once a day and that the amount of deuterium to be pumped off will be in the order of magnitude of about 100 ℓ (STP) per day. Due to the fact that during neutral injection operation a certain amount of tritium will diffuse back into the beam lines the NBVS must be designed tritium compatible. Therefore the NBVS will be designed similar to the TVS and will be based on turbomolecular pumps which are fitted directly at the NI housing and on roots pumps for the four vacuum systems which are located in the THR.

6.3 NB Vacuum System Components

6.3.1 The choice of turbomolecular pumps for the HV section of the NBVS follows the decision made for the HV pumps for the TVS (see Table 4, pages 23 ff).
The pumps are designed to be all metal sealed, oil lubricated, the oil can be replaced by remote operation; they operate without water cooling.

At each beam line there is a pump unit consisting of a high-capacity turbomolecular pump (pumping speed of about 5000 l s^{-1}) with a roots pump as backing pump. These pump modules should be replaceable as a unit, so that maintenance work can be performed in the hot cell.

6.3.2 Backing system

The backing system serves on the one hand as a redundant system for the TVS and for evacuating the beam lines and the connecting pipes from atmospheric pressure to the operating pressure of the NB high vacuum unit and for maintaining the backing pressure of the TMP that is necessary for their operation.

On the other hand, the regenerated gases from the cryopanels of the neutral-beam lines have to be transported via the backing system into the intermediate storage tank for the NI-effluents, where the gases are kept at a pressure of approximately 500 mbar till further operation. (Removal of impurities and recycling to the beam lines).

The decision for roots pumps for the backing system follows again the arguments discussed while designing the TVS. (Choice of pumps see table 5, pages 25 ff).

6.4 Removal of Impurities from the Recycled Deuterium

As it is not intended to separate the tritium from the recycled deuterium it is also not worthwhile to extract the tritium in the impurities by cracking them by chemical treatment. Therefore the impurities will be treated like wastes and will be separated in the simplest way.

One solution might be to conduct the recirculation gases into a series of cryogenic traps in a steady flow process.

6.5 Intermediate Storage Tanks

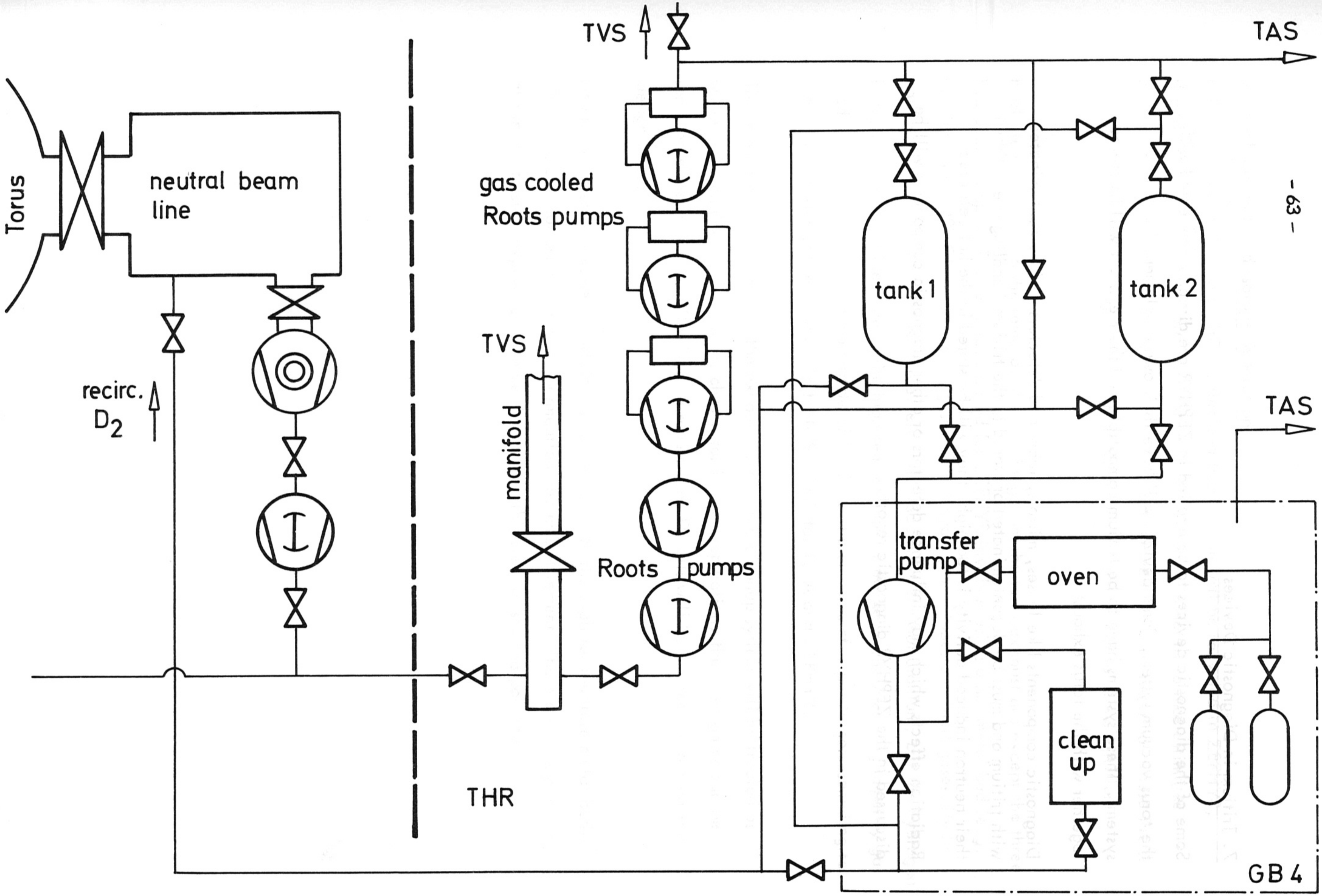
The gases pumped off the neutral-beam lines during regeneration of the cryopanels will be transferred by the NBVS into two intermediate storage tanks. The holding capacitiy of each tank should be high enough to collect the 100 ℓ(STP) output of an experimental day. So a capacity of 400 l at a pressure of 500 mbar will be installed.

There are two reasons to install two of these intermediate tanks: on the one hand for redundancy and on the other to be able to proceed with ZEPHYR operation during removal of impurities in the recirculated deuterium and during final treatment of the deuterium enriched with tritium.

6.6 Catalytic Oven

When the deuterium regenerated from the NI cryopanels is highly (about 1 %) contaminated with tritium it is not possible to recirculate it further. Then the trititated deuterium will be conducted through a catalytic oven (CuO or precious metal catalyst) in order to convert it to tritiated water. This unit must be placed in a glovebox in the THR due to the more hazardous THO which results from this process. The tritiated heavy water will be collected in steel cylinders which will be transferred - if possible - to an external facility.

In Fig.14 an overall view of the NBVS together with the additional equipment is shown.



NI Vacuum System

Fig. 14

7. Tritium in Diagnostic Devices

Some of the diagnostic devices to be applied in ZEPHYR are directly connected with the torus vacuum system. Some devices will have their own supplemental pumping systems. These systems have to be tritium compatible and their exhaust will be stored together with the torus exhaust.

Diagnostic components like lenses, mirrors, tubes and detectors will be contaminated with tritium and must be decontaminated or stored in the tritium handling area. When their neutron induced activity is too high, they will be stored in the hot cell area.

Radiation effects which may influence detectors or other diagnostic components will be discussed in the ZEPHYR diagnostic report.

8. Fuel Cleanup and Isotope Separation

Although it has not been definitely decided that tritium will be recycled in ZEPHYR, it will be necessary to explore relevant recycling schemes in detail so that estimates can be made of tritium inventories, risks, costs and glove box space required. These facts will be essential in making a technical decision on whether or not to recycle tritium.

8.1 Fuel Cleanup

Fuel cleanup refers to the removal of everything from the torus exhaust gas except the three hydrogen isotopes. The technique aimed for ZEPHYR involves using a hot metal bed (e.g. uranium at $\sim 700^{\circ}$ C) to remove all gases except hydrogen isotopes and inert gases. Hydrocarbons, ammonia, carbon monoxide, etc. will react with the hot uranium, but the hydrogen isotopes are not retained due to the high temperature of the bed. The incoming impurity gas load will be in the order of magnitude of 1 - 2%. The amounts of impurity corresponding to the different elements are shown in table 9 both for TSTA and ZEPHYR.

The impurities separated from the exhaust fuel by the cleanup system will be treated as wastes. Depending on the process chosen for isotope separation, the inert gases can be removed either before or after isotope separation. Details will be worked out during the design phase.

At present there are some uncertainties connected with the high temperature metal beds. These include corrosion, stresses, permeation and embrittlement. Therefore it is planned at the IPP to start experimental investigations in this field as soon as possible.

Table 9 Impurities to be processed by a fuel cleanup facility

1	2	3	4	5
element	atom %	molecule	amount in g	amount in g +)
H	1	HD, HT	7.2	0.33
C	0.02-0.1	$C(D, T)_4$	1.7-8.6	0.078-0.398
O	0.5	DTO	57.6	2.66
N	0.1	$N(D, T)_3$	10.1	0.46
Ar	0.0006-0.05	Ar	0.17-14	0.0078-0.05
			TSTA /9/	ZEPHYR

+) Data for a total throughput of 10^6 Ci T_2

8.2 Isotope Separation

8.2.1 Introduction

Important considerations in choosing a process and sizing the apparatus are the quantity of gas to be separated and the degree of separation required. It is not clear at this point that all of the gas for filling the torus has to be initially separated into pure T_2 and pure D_2. If a significant portion of the fuel could be injected as DT, it would have a great impact on the separation process. Further definition of the isotope separation system will occur as these answers becomes available.

8.2.2 Cryogenic Distillation

Cryogenic distillation is favoured by most fusion reactor studies and is going to be used at TSTA /10/. At present a system is under construction at LASL. It will make the required separation by means of a system of four interlinked, cryogenic fractional distillation columns. The throughput of the TSTA device is more than 10^3 higher than needed for ZEPHYR. As it is not possible to reduce the size of the columns a high T-inventory will be accumulated in the system. Therefore it is not a reasonable technique for ZEPHYR. A separation device at Grenoble, constructed by SULZER /11/ has been working for several years; this facility mainly separates small quantities of T_2 from heavy water. It achieves the separation by means of catalytic exchange between D_2 and heavy water vapor and subsequent D_2 cryogenic distillation.

At Ispra a report was prepared which summarizes the results of feasibility studies carried out on three processes for the regeneration of exhaust plasma in fusion reactors /12/. The first process follows the TSTA design but with some modifications. The second is based on the catalytic oxidation of the hydrogen isotopes to their respective oxides and on their separation by distillation. The DTO is subsequently electrolyzed for its conversion to DT-mixtures. The third process is a modification of the previous one in order to reduce the T inventory. Cryogenic distillation of hydrogen isotopes or distillation of oxidized hydrogen isotopes are processes which result in a high tritium inventory in the columns and are therefore not suitable for an experiment with the throughput and inventory requirements of ZEPHYR.

8.2.3 Gas Chromatography

A great deal of interest has been shown in the sixties (1958 - 1963) in attempts to separate the isotopes of hydrogen by the methods of gas chromatography. Glueckauf and Kitt /13/ separated pure D_2 from H_2 by displacement chromatography in a column containing palladium black, Japanese scientists separated HD and D_2 by employing a molecular sieve column /14/ and Smith and Hunt separated H_2, HD and D_2 in 1960 by using a chromia-alumina column operated at 77 K with neon as carrier gas. Results of a quantitative separation of all hydrogen isotopes (H_2, HD, HT, D_2, DT and T_2) were reported by R. Schott in 1973 / 15 / and R. Wagner / 16 / gave in his dissertation retention times of the different species.

At the IPP all hydrogen isotopes and their mixtures were separated by using an alumina column at 77 K with helium as carrier gas (flux = 26.6 ml per min). The diameter of the column was 2.2 mm and the length 1500 mm. Within 60 min a quantitative separation of 10 µl H_2, 5 µl HD, 5 µl D_2 and 1 µL T_2 was done (see fig. 15).

The retention times were similar to those given by Carter and Smith / 17 / referred to in the internal status report / 18 / for comparison.

First attempts to separate greater amounts than usually applied in analytical processes were made by F.B. Hill et al. / 19 / applying modified elution- chromatography on vanadium hydride and by Chadwick / 20 / who separated T_2 from a hydrogen-stream using Pd. The processed volumes were 0.2 - 2 ℓ(STP).

Experimental investigations have been started at the IPP in 1980 in order to evaluate large-scale gas chromatography for separation of the hydrogen isotopes. Presently the

Chromatogram of Hydrogen Isotopes and their Mixtures

Column Length	1.5 m
Column Diameter	2.2 mm
Column Packing	Al_2O_3
Carrier Gas	He
Flow Rate	26.6 ml/min (11.6 cm/sec)
Column Temperature	- 196 °C
Detector	He-ionisation detector (200 m Ci T)

ca. Amounts of Isotopes in μl

H_2	10
HD	5
HT	1
D_2	5
DT	0.5
T_2	1

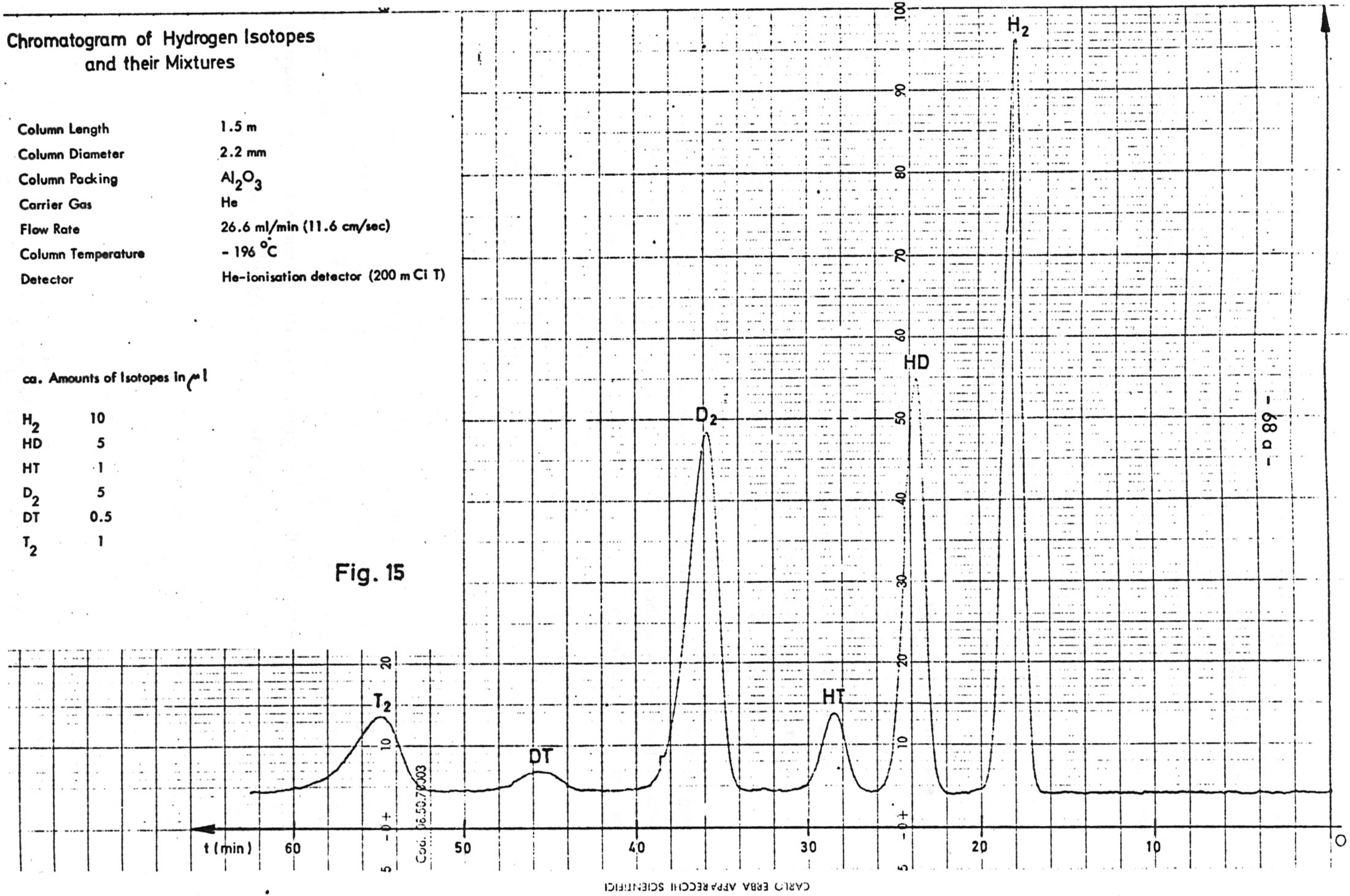


Fig. 15

experiments are being run with H_2 and D_2 in order to avoid tritium handling in this preliminary phase of the experiment.

There are some parameters of the gas chromatography process which influence the quantity of gaseous mixtures to be separated:

- diameter of the column
  with increasing diameter the volume of the gas sample increases; at the same time the separation efficiency decreases.
- length of the column
  increasing length of the column increases the separation effects, but at the same time the separation time increases too;
- velocity of the carrier gas
  an increasing carrier gas velocity decreases both the separation time and the separation efficiency, especially of those species whose retention time are close together.
- stationary phase of the column
  the stationary phase of the column must be pre-conditioned (purging with noble gas, heating to fix certain amounts of water at the surface, adding of additional compounds like chromium or iron oxides). This special treatment influences both the separation efficiency and the separation time.
- temperature of the column;
- type of carrier gas;

First results of the investigation show that the maximum sample volume which can be processed by the analytical column with a diameter of 2.2 mm is $\sim 1 \times 10^{-5}$ ℓ (STP). This corresponds to 1.3×10^{-2} Ci of T_2 when an equimolecular mixture of D_2 and T_2 is applied and protium (and HD, HT) occurs only in the order of magnitude of impurities (below some percent). This separation was achieved within one hour.

Then a larger column was used; the diameter was increased to 12 mm while the length was kept at 1500 mm.

The maximum sample volume processed by this column was 10 ml. This is a factor of 10^3 greater than the sample separated with an analytical column but is still smaller than is needed for ZEPHYR. But the separation time increased too, due to the fact that the carrier gas flux had to be reduced because otherwise it was not possible to keep the temperature of the column constant. Investigations are continuing to further develop this technique.

Presently the following conclusion can be drawn:
Gaschromatography appears to be an excellent process to separate all hydrogen isotopes quantitatively. Preliminary investigations show that the method can be scaled up to a preparative scale. Further investigations are necessary to establish the parameters for this application. At the moment these experiments can be done simply with H_2 and D_2.

9. Tritium Inventories in the ZEPHYR Tritium Systems

9.1 General

It is important to have knowledge of the amounts, whereabouts, and chemical forms of tritium in ZEPHYR because these facts will be necessary to evaluate the risks connected with certain operations and to design processes and equipment.

9.2 Tritium Inventory in Uranium Beds

In the tritium storage and injection system the necessary tritium supply for the experiments will be stored in safe and solid form as $U\,T_3$ (see 1.2.2).

The inventory will be in the order of magnitude of 6×10^4 Ci. As mentioned earlier, this tritium supply constitutes no safety problem because the isotope is kept in two independent all-metal containments and will only be released by controlled processes.

9.3 Tritium Inventory in the Injection System

In the injection system the tritium occurs in gaseous form. Special precautions like double-walled pipes and a secondary containment for the whole unit (see fig. 3) must be foreseen in order to prevent uncontrolled tritium releases in emergency cases.

The total amount of the tritium inventory in the injection system immediately before injection will be about 1000 Ci.

9.4 Tritium in the Torus

In order to achieve the desired plasma parameters about 300 Ci tritium must be injected into the torus. During the discharge only a few per cent of the fuel will be burned, so that the gaseous tritium inventory will remain in the same order of magnitude. But some of the gaseous tritium will disappear due to interactions with the walls of the vessel. There are several mechanisms which may occur at the same time:

a) tritium exchange with hydrogen or deuterium adsorbed at the walls and dissolved in the material;

b) tritium permeation through the walls (negligible at the low operation temperatures of ZEPHYR);

c) tritium diffusion and subsequent solution of tritium in the walls;

At present no evaluation of the amounts of tritium which are covered by items a-c could be made. Up to now, there is no tokamak existing with comparable energy load of the walls, therefore reasonable data will be available only during the experimental operation of ZEPHYR with tritium. Computer modelling of the above processes will be started in the near future.

9.5 Tritium Inventory in TVS and NBVS

All gases which interact with metal surfaces will be bound for a more or less indeterminate time.

The H-isotope-metal system also shows absorption in addition to adsorption. This is the reason why non-negligible amounts of T collect in the TVS and other peripheral systems. During the experimental phase T will be collected and this "dead inventory" has to be additionally conveyed to the TVS. The "dead inventory" contains adsorbed and absorbed gases and also the tritium left as residual gas in the torus and pipes, this quantity being given by the product of the pressure and volume.

9.5.1 Estimate of quantity of tritium adsorbed

For the general case where various molecular (physisorption) and dissociative (chemisorption) adsorption states are superposed the deposition n is given according to / 21/ by

$$n = \frac{n_m b_i P}{1 + b_i P} + \frac{n_m (b_k P)^{1/2}}{1 + (b_k P)^{1/2}}$$

The total quantity n_m due to monomolecular deposition can readily be determined by simple geometric estimation. If the atomic diameter of a H isotope is assumed to be 1 Å, a metal surface of 1 m^2 with complete monomolecular deposition can adsorb about 12 Ci of tritium.

The factors b_i and b_k are essentially dependent on the adsorption heats of the various states and are in units of inverse pressure, so that bP is a dimensionless number.

Only at very low pressures, i.e. where $\frac{1}{b} \gg P$ is valid, does n show a distinct dependence on b. At "high" pressures n can be taken as the limiting value $n = n_m$. In this context the high vacuum region is already considered to be "high".

In the case of H isotopes the second term of the above equation predominates owing to dissociative adsorption, so that the total quantity of tritium adsorbed, Q_{ads}, can be estimated as follows:

$$Q_{ads} = 4 \cdot n_m \cdot A_g = 4800 \text{ Ci}.$$

The factor 4 originates from the ratio of the physically effective to the geometrical surface, which can be assumed to be 8 /22/, and takes into account the fact that a 50 to 50 mixture of T and D is present.

9.5.2 Estimate of the quantity of tritium absorbed

The solubility of tritium in stainless steel is given according to /23/ by

$$S = S \cdot P^{1/i}$$

where j = 2 is taken for T in metals. The quantity S is dependent on the gas-metal combination and, according to /24/, has the value

$$S = 6.8 \cdot 10^{-2} \exp\left(- \frac{1094}{T}\right) \frac{cm^3 \, T_2}{cm^3 \, SS} \cdot (\text{torr.})^{-1/2}$$

To estimate the quantity of T absorbed, it is assumed that the above mentioned solubility is valid to a depth of 1 mm but is then negligible owing to the low diffusion rate.

The mean pressure in the system is assumed to be 10^{-2} mbar. This means that in a volume of 100 m^2 by 1 mm (10^5 cm^3) at a wall temperature of 100 °C about 110 Ci is dissolved. An additional factor which has to be considered in the future is the effect of implanted tritium.

9.5.3 Permanent inventory pV

The pressure in the TVS as shown in Table 5 of Sec. 2 exclusively describes the partial pressure of the H isotopes. The product of the pressure p and volume V then yields 2700 Ci as the quantity of tritium permanently present. The greater part of this inventory is located, however, at the end of the FVS and in the pipe to the TAS. Between the torus and the gas-cooled Roots pumps there is only approx. 140 Ci.

9.5.4 T inventory in the NBVS

The surfaces of the NBVS are of the same order of magnitude as those of the TVS. In this system tritium only appears as an undesirable addition to the deuterium and should not exceed a few per cent of the total quantity. The "dead inventory" is accordingly a few hundred Ci.

9.6 Tritium in the Fuel Cleanup and Isotope Separation System

The TVS transports about 300 Ci/shot out of the torus to an intermediate storage tank. This tank has a capacity of about 3000 - 10 000 Ci (10 - 30 shots respectively). This number will represent the maximum amount of tritium to be processed both by the FCU and the ISS

In both processes the tritium will occur in gaseous form so far as is known at present.

For safety reasons the FCU as well as the ISS will be kept in glove boxes in the THR, so that the T-inventory of these systems will be secondarily contained.

9.7 Tritium Inventory in the Neutral-Beam Lines

Per day and beam line about 170 Ci T_2 will be accumulated on the cryopanels of the NB-lines. With a total of six beam lines a t-inventory of about 1000 Ci T_2 will be built up during an experimental day.

Primarily this amount will be trapped cryogenically, then it will be pumped off by the NBVS and finally it will be processed. During all these processes this amount of tritium will be "diluted" by a surplus of deuterium ($1 : 10^3$).

9.8 T-Inventory in the TAS

It is not intended that a substantial tritium inventory will exist in any of the TAS for any length of time. The molecular sieve beds can be regenerated whenever desired and the tritiated water will be transferred either to waste storage or to the fuel cleanup unit, depending on its specific activity.

9.9 T-Inventory in Wastes

Although every attempt will be made to minimize the T-inventory in wastes, it is impossible with the information vailable at present to make good estimates. Important considerations are the size and efficiency of the FCU and ISS, postulated accident scenarios, the number of oil lubricated pumps in use, the capabilities of the decontamination facility, residual moisture left on the TAS molecular sieve beds after regeneration, etc.

C. Description of the Tritium-Areas

1. Definitions

Due to the different tasks of the T-systems at the one hand and to their relatively high varying T-inventories and to the highly different potential of danger of these systems at the other hand, the T-subsystems have to be installed in several separated rooms.

Depending on the duties of the systems in these rooms, they must be placed more or less near to the torus, in or out of the shielded section of the building and are commonly within the controlled area. They must be closed for the public and only controlled persons may work in these rooms.

2. The T-Handling Room THR

2.1 Common Description

The THR is located in the basement of the NB power supply building.

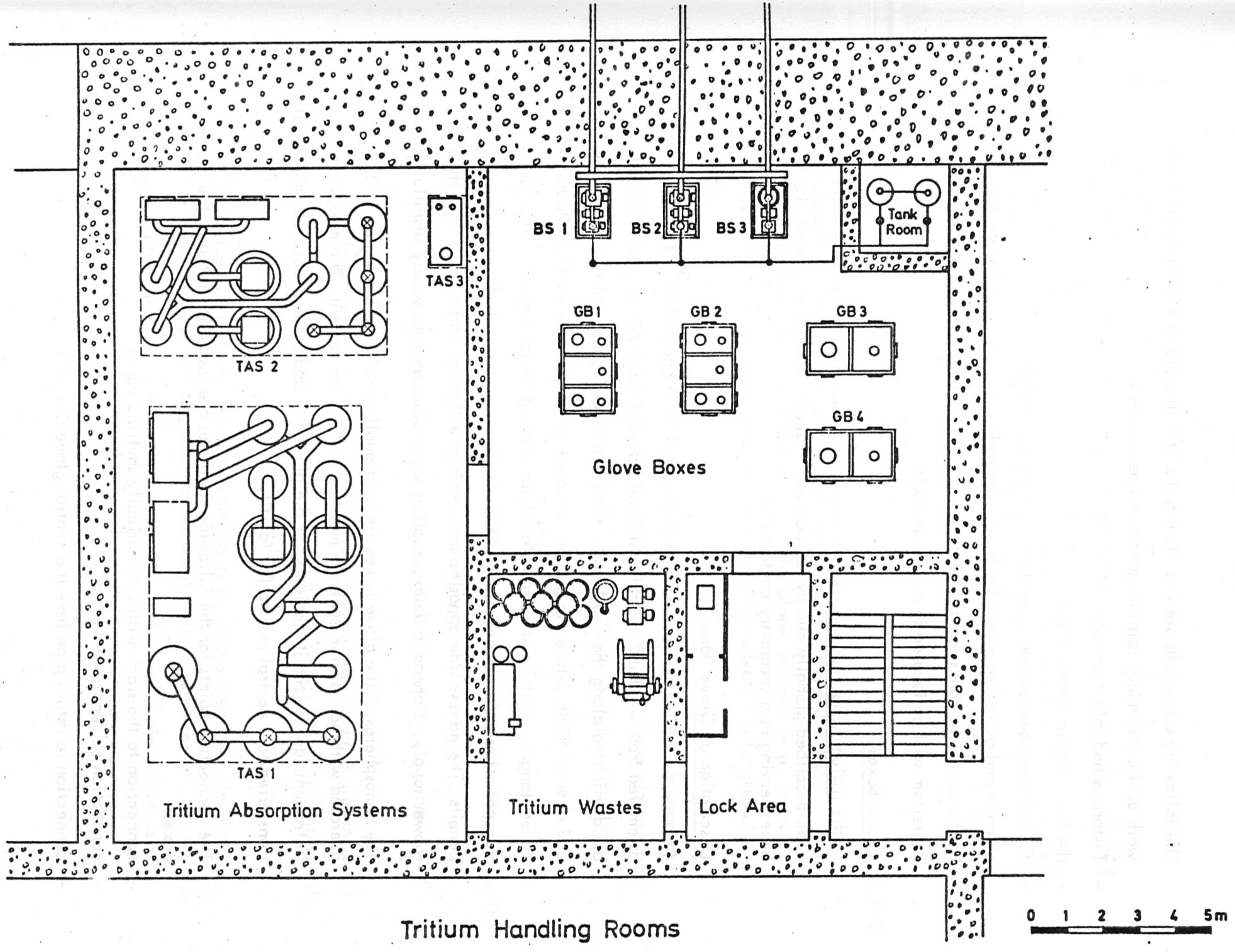
The dimensions can be taken from the preliminary drawing (see Fig. 16).

The entrance by an air lock system is closed for the public.

The room atmosphere is continuously monitored and an efficient ventilation system (~ 10 changes per hour) prevents T-accumulation due to permeation through gloves and so on. Uncontrolled T-releases from the components installed in this room are processed by a specially designed TAS (see B 3).

2.2 Components of the THR

The THR serves as a tertiary containment for all installations with a high T-inventory (for example uranium containers).



Tritium Handling Rooms

Fig. 16

The following subsystems are installed in the THR in separated glove boxes which work as the secondary containment for these systems

- T-storage and injection-system (TSI-S)
- the fore-vacuum system (FVS)
- fuel cleanup and isotope separation system (FCU and ISS)
- cleanup and oxidation system for the recirculation-deuterium of the NB-lines.

Furthermore, the tanks for intermediate storage both of the torus exhaust and the NB-deuterium will be located in a special vault.

2.2.1 Glove Boxes

In the tritium handling room the tritium storage and injection system, which has been described globally and by component, is accommodated in several glove boxes serving as a secondary containment.

Description of Glove Boxes

At present, the volume of the boxes is expected to be about 10 m^3. The boxes are assembled from welded 2 mm thick stainless-steel sheets. Viewing ports and gloves are distributed along the two long surfaces. The viewing ports are fitted with gaskets and screwed tight, while the gloves, when not in use, are secured by (flushable) cover flanges. At the one narrow side there is a tightly screwed door allowing transportation of larger components if the tritium content of the box atmosphere permits. The narrow side opposite contains a pass through port and all feed throughs (power supply, diagnostic leads, cooling water pipes and gas supply installations).

The atmospheres of the glove boxes are continually monitored for O_2 content (if not operated with normal atmosphere), moisture and tritium content. The measuring instruments are placed immediately at the glove box and the test data are additionally transferred to a central monitoring facility.

The connection points for the following facilities are installed on top of the glove boxes:

- connection to the stack with automatically shutting valve
- connection to central glove box TAS
- connection to return pipe from the central glove box TAS

- connection to the TVS-TAS
  with which the exhaust pipes of the vacuum pumps are connected to the TVS-TAS.

  In general, the boxes have to be designed for operation at reduced pressure (Δ P of about a few mm of water) to restrict leakage losses.
  Pressure and temperature regulating or control facilities also have to be provided.

A total of seven glove boxes is required:
It is anticipated that about 7 glove boxes will be required in the THR. Since some of the processes have not yet been selected, let alone designed (e.g. isotope separation), it is not yet possible to define the sizes of the boxes. The functional assignments are as follows:

a) The tritium storage and delivery system will require a box with many gloves, much viewing area, and many feedthroughs for instrumentation, power, water, liquid nitrogen, etc.

b) A second group of three special glove boxes contains the redundant backing system (BS) both for the tritium vacuum system and for the NBVS. If a set of gas-cooled Roots pumps is used (see tritium vacuum system for details), these three glove boxes will have a different shape:
In particular, much fewer gloves are then required and the number of viewing ports can be reduced. Steps also have to be taken to suppress noise since the continuously running Roots pumps have a very high noise level.

To summarize, it can be stated that, when Roots pumps are used, this glove box will be regarded more as a secondary containment with noise protection. If, however, cryopumps are used for collecting the torus burn-up (for details see tritium vacuum system), the second glove box will be similar to the type already described.

c) The 5th glove box will accommodate the facilities for burn-up purification and isotope separation. The dimensions of this box cannot be determined at present.

d) Within the 6th box, the cleanup system for the NB-deuterium.

e) The 7th box, finally, is intended as a spare or universal glove box. In particular, it should be possible to use it for repairs and maintenance work on facilities and components of the tritium system.

As a special feature of this box it is possible to incorporate several pass through ports or one large port and to install simple manipulators. Consideration may also be given to providing light hoists for handling heavy components (e.g. turbopumps).

2.2.2 FV-Manifold

The vacuum lines on the one hand connecting the high vacuum pumps and on the other hand connecting the NB-HV with the redundant fore vacuum pumps enter a manifold which is shown in Fig.9 .
This manifold consists of a SS pipe with larger diameter than the connecting pipes. Diagnostic systems will be fitted to this tube.
If discharge cleaning processes will be applied especially during normal discharges much higher amounts of gases ($D_2 + T_2$) will occur so that it will be of advantage not to pass these gases through the FVS and to store them in the intermediate storage tanks. It is intended to collect these gases in a cryotrap which is flanged onto the mentioned manifold. Heating this cryotrap will permit the recycling of these gases through a special line into the torus directly.

This manifold and cryotrap must be located in the THR too due to the high tritium inventory.

2.2.3 Diagnostic Equipment

2.2.3.1 T-monitors

The glove boxes and other installations will be monitored by proportional counters or, in some cases by ionization chambers. These monitors will be mounted directly at the components to be monitored. By this procedure the measured data can be read by the tritium operators directly while working in the THR. In addition, these data are transferred by electrical means to the central diagnostic room which will not be located within the controlled areas.

2.2.3.2 Liquid scintillation counter

Liquid scintillation counting of smear tests, decontamination liquids and urine samples of the controlled workers will also be done in the THR.

2.2.3.3 Gas chromatography

2.2.3.4 Mass spectroscopy

2.2.4 Additional Equipment of the THR

For some purposes, for example purging connecting lines gases like N_2, Ar and He will be used. At present direct storage of steel cylinders looks to be the practicable way to do this. Pressurized inert gas will be used to operate valves. This gas should be distributed by a fixed line. Furthermore, a waste collecting container for intermediate storage of used gloves and so on will be located in the THR.

3. Room in which the T-Absorptions Systems are located

As described in section B 3 several absorption systems are designed to process the atmospheres of the different ZEPHYR tritium systems. This room must not be within the shielded areas but within the controlled rooms. Normally operators must not work continuously in this room.

Small quantities of tritium may escape from the complex installations, so that an efficient ventilation system will serve this room.
Lines with significant diameters must be foreseen to connect the TAS with the containments to be processed. Maintenance and repair of the TAS should be done in the room itself to prevent T-release during transportation of big components. Therefore sufficient free space must be foreseen and some installations like hook and crane should be available.

To minimize the quantity of tritiated wastes, the molecular sieve dryers will be regenerated periodically.
For a regeneration cycle a compressor must move preheated air (or Ar) through a regeneration loop (∼ 480° K regeneration temperature, this means about 700° K for the air). The regenerating air leaving the molecular sieves (∼480° K) will contain the tritiated water and must be cooled near its dew point. Then the air must pass a condenser where most of the water will be condensed and collected in a tritiated water storage tank.

4. Tritium Waste Room

This room is described in the section dealing with tritium waster (see 5.3).

D. Further Activities

The aim of this report is to show the philosophy and the conceptual methods for handling tritium in the ZEPHYR experiment. Further details will be worked out in the design phase. The following scheme lists the topics.

D1 Storage and Injection System

1.1 Design and construction of uranium beds will be continued;

1.2 Use of Pd diffusors will depend on the required purity of the tritium;

1.3 Testing of different types of injection valves will be necessary;

1.4 Selection and testing of transfer pumps;

D2 Testing of all Components of the TVS

Topics of these test will be:

2.1 T-tight facilities (housings, flanges);

2.2 Gaskets and sealings;

2.3 Accumulation of tritium in pump oils, i.e. saturation and equilibrium concentrations;

2.4 Remote maintenance and repair.

2.5 Testing of cryopumps and mechanical pumps.

D3 Tritium Absorption Systems (TAS)

Design of the TAS on the basis of present technology will be contracted out. Numbers, flow capacities, design features will be decided by the IPP. There might be small experimental activities in order to evaluate the possibility of chemical processes other than oxidation and to investigate ways to make TAS`s based on catalysis and drying more efficient.

D4 Tritium in Neutral Injection

To design the devices necessary for cleanup and recycling the NI deuterium, an intimate knowledge of its T-concentration (both the tolerable and the maximum values) is necessary. Trade off studies involving the costs of D_2 and T_2 waste storage facilities, and recycling facilities should be made.

D5 Fuel Cleanup and Isotope Separation

5.1 The fuel cleanup process envisaged for ZEPHYR entails some basic problems which have to be investigated:

- method of heating the uranium;
- material of the uranium container;
  (corrosion, strength, H_2-permeation);
- capacity of the U-bed (absolute capacity, poisoning of the uranium, maximum concentration of U-nitrides, U-oxides and U-carbides);
- safety (reaction of uranium with oxygen);

In addition, some attention should be given to other cleanup processes.

5.2 Isotope separation by preparative gas chromatography.

These investigations are to be continued. Although sample volumes up to 10 ml have been successfully separated, the generation of spent fuel at a rate of ~ 250 ml per shot requires larger sample volumes or the use of columns in parallel.

5.3 Isotope separation by thermal diffusion

If the decision is made to use this proven method, the design and construction will be contracted out. A design study may be undertaken as soon as the fuel isotopic purity and throughput requirements are firmly established.

D6 Interaction with other Tokamak Experiments (e.g. TFTR, ASDEX)

These experiments should provide data in a time frame which could influence the ZEPHYR design.

- Tritium wastes
- Impurities in the plasma
- T-inventories in the plasma
- Recycling of H-isotopes from the walls.

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