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Assessment of Process Options and Identification of Critical R&D Issues

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Abstract

The Tritium Extraction System (TES) is a gas loop with a helium / hydrogen mixture as carrier gas which is used to extract the tritium generated in the blanket by a nuclear breeding process. In addition to a description of the operational requirements of a TES for an ITER test blanket, ten process options are discussed. Then an additional procedure is proposed which includes several process steps of the approaches mentioned above. This method uses a cold trap operated at ≥ -100°C to extract HTO and a molecular sieve bed (MSB) operated at -195°C to extract HT / H_2. Both process steps will be tested and optimized in the pilot plant PILATUS at the Tritium Laboratory of Karlsruhe, TLK. The most important objectives of the corresponding tests are:

- To prevent the formation of ice aerosol in the cold trap which could lead to a decreasing removal efficiency for H_2O / HTO,
- To investigate the adsorption / desorption of H_2, HT, O_2, and N_2 in the MSB under realistic conditions with respect to gas flow rate and gas composition,
- To select and test reliable analytical techniques, which are needed to demonstrate the feasibility of the extraction method as well as to supply appropriate methods for process control.

Zusammenfassung : Tritium Extraktion aus einem ITER Testblanket – Verfahrensoptionen und wichtige Fragen für weitere Entwicklungsarbeiten

Das Tritium-Extraktionssystem (TES) ist ein Gaskreislauf mit einem Helium / Wasserstoff Gemisch als Trägergas, mit dem das im Blanket erbrütete Tritium extrahiert wird. Nach der Darstellung der Anforderungen an ein solches System für ein ITER Testblanket werden zehn verschiedene Verfahren diskutiert und dann ein weiteres Verfahren vorgeschlagen, in das verschiedene Prozeßschritte der anderen Optionen übernommen wurden. Das als HTO vorliegende Tritium wird darin in einer Kaltfalle bei ≥ -100 °C abgetrennt und das als HT vorliegende Tritium zusammen mit H_2 in einem Molekularsieb Bett (MSB). Beide Verfahrensschritte sollen in der Pilotanlage PILATUS im Karlsruher Tritiumlabor (TLK) erprobt und optimiert werden. Die wichtigsten Ziele dieser Versuche sind:

- Vermeidung der Bildung von Eisaerosolen in der Kaltfalle, die zur Verringerung des Abscheidegrades führen können,
- Untersuchung der Adsorption und Desorption von H_2, HT, O_2 und N_2 im MSB unter realistischen Betriebsbedingungen bzgl. Gasdurchsatz und Gaszusammensetzung,
- Auswahl und Test geeigneter analytischer Methoden, die sowohl für die Demonstration des Verfahrens als auch für die spätere Prozeßkontrolle benötigt werden.

Table of Contents

Abstract / Zusammenfassung
1. Introduction 3
2. Requirements for Tritium Recovery from the ITER TBM 4
3. Discussion of Process Options 7
4. Description of the FZK Concept 8
5. Critical R&D Issues for the Proposed Procedure 10
6. Evaluation of Cryogenic Cold Trap Experiments for Humidity Removal 11
   a) Test series performed at CEA 12
   b) Tests performed at JRC-Ispra 15
   c) Tests performed at JAERI 18
   d) General conclusions 20
7. References 21

1. Introduction

It is one of the main goals of the Helium Cooled Pebble Bed (HPBC) Test Blanket of ITER to demonstrate a tritium breeding ratio sufficiently high to perform quantitative measurements of the generated tritium and to allow reliable extrapolation of the breeding ratio to a full size blanket. For this purpose, the Test Blanket Module (TBM) will be equiped with a Tritium Extraction System (TES) in which a helium purge gas stream containing up to 0.1 % of H_2 is used to facilitate the tritium release by isotopic exchange.

It is then the task of the TES to

- separate tritium from the helium purge gas,
- to remove any solid or gaseous impurities, and
- to recondition the purified gas for further use as purge gas.

As tritium is expected to occur not only as HT but also as HTO, it is necessary to include a chemical decomposition step before it can be sent to the Isotope Separation System (ISS) for T_2 recovery.

In principle, the extraction of tritium from the purge gas can be achieved in two ways:

I By removal of HT and HTO in two separate steps with subsequent chemical reduction of HTO to HT, or

II By oxidation of all HT to HTO, followed by its removal from the purge gas and chemical reduction.

The first way appears to be more straightforward and economically effective because any additional production of HTO is avoided. The second way is relevant if it is intended to minimize the permeation of tritium into the blanket coolant by adding oxygen and water to the purge gas instead of hydrogen. In this case, however, the amount of tritiated water to be processed will be more than 100 times larger than in the first case.

Following to a description of the technical requirements for the TES loop foreseen for the ITER TBM, the present paper briefly discusses several process options which have been evaluated in a preceeding paper. As a conclusion of this evaluation, a process is described which is expected to have the best potential for applicability and will incorporate the smallest development risk. Nevertheless, this process has to be tested and to be optimized with respect to component design and to procedures for process control. In addition, the availability of reliable methods for quantitative measurement of very small concentrations of tritium, hydrogen, water vapor, and impurities has to be demonstrated. The corresponding R&D issues are discussed. In the last part of the report, some cryogenic cold trap experiments performed at CEA, Ispra, and JAERI are described; the conclusions drawn from these tests are the basis for the design of a new cold trap, which is a main component of a test facility to be set up and operated with the aim to demonstrate the feasibility of the proposed tritium extraction method.

2. Requirements for Tritium Recovery from the ITER TBM

The main design data of the tritium extraction system for ITER TBM /1/ are given in Table 1.

Table 1 : Main Design Data for the Tritium Extraction System

He Mass Flow		0.85 g/s = 17 Nm^3/h
Swamping Ratio		He : H_2 = 1000
Tritium Production Rate		0.2 g / day
Partial Pressures[a]	p (H_2)	110 Pa
	p (HT+HTO)	0.4 Pa[b]
	p (H_2O)	≈ 0.3 Pa[b)c]
Extraction Rates	H_2	18.4 mole /day
	HT	0.05 mole /day
	H_2O / HTO	≈ 1 g / day
Temperature of Purge Gas		
at Test Module Outlet		450 °C
at Test Module Inlet		20 °C
Pressure of Purge Gas		
at Test Module Outlet		0.106 MPa
at Test Module Inlet		0.120 MPa
Pressure Drop in Test Module		0.014 MPa

[a] Average values at Test Module outlet (accounting for plasma pulse dwell time)
[b] about 80 % of HTO is assumed to be converted to HT + H_2O by isotopic exchange, no HTO / H_2O is considered to be reduced by the steel walls
[c] additional water can leak into the purge gas from the blanket coolant system

The average tritium activity in the purge gas is about 5 Ci/Nm^3 at the TBM outlet. This average value will vary due to the plasma pulses, and it will generally increase if the tritium removal efficiency of the TES is less than 100%. The increase corresponds to a factor of

- 1.05 at a tritium removal efficiency of 95 %,
- 1.1 90 %,
- 1.25 80 %,
- 2.0 50 %, etc.

There is no strong requirement, therefore, for a very high tritium removal efficiency like 99%. On the other hand, the presence of two different chemical forms of tritium has to be considered. Depending on the nature of the extraction process, it may be necessary to have a high removal efficiency for Q_2O (Q = H,D,T) while a smaller one could be sufficient for Q_2.

Additional requirements result from the following aspects:

- As the purge gas is recirculated into the TBM after tritium removal, the extraction steps have to be carried out in a once-through mode through the TES components at the relatively large gas flow rate of 17 Nm^3/h.

- Due to the much higher concentration of Q_2 in comparison to Q_2O, it appears to be not recomendable to oxidize Q_2 to Q_2O with the intention to use only one extration step for all tritium species. This would mean that the amount of tritiated water to be processed in the Chemical Decomposition System would be about 330 g per day and thus 360 times larger than in the case in which only the primary Q_2O is extracted. In the case of a large blanket of a power reactor like DEMO, the corresponding amount of water would even be of the order of 200 kg/day.
  Thus, separate removal steps must be provided for Q_2O and Q_2.

- As operation phases of $\leq$ 6 days are envisaged for the ITER TBM, it is necessarry to supply corresponding storage capacity for the separated Q_2/Q_2O. If regeneration operations are required for single components during the time span of 6 days, these components must be available at least twice, with one of them in the extracting mode and the other in the deloading and / or regeneration mode.

- A circulation pump is needed not only to carry the purge gas into the TES but also to compensate the pressure drop in the TBM (0.014 MPa) and in the TES loop; the latter is expected to be of similar size. Thus, the circulation pump has to act as a compressor with the following requirements:

Pressure rise	Δp = 0.03 MPa
Inlet pressure	p = 0.09 MPa
Flow rate	f = 17 Nm^3 helium / h

  The compressor should be installed between TES outlet and TBM inlet, where the purge gas is depleted from tritium and where the gas temperature will be close to room temperature (rf. component No. 8 in Figure 1).

- For process control, the following devices will be needed:

  Flow controller,
  Pressure indicator (manometer),
  Tritium detectors at TES inlet and after each purification step,
  Analytical instruments for quantitative measurement of H_2O, H_2, and O_2;

  The required sensitivities of these instruments are given in Table 2.

Table 2 : Required Sensitivities for Analytical Process Control

Location	Constituent	Sensitvity Range (vpm)
TES Inlet	H_2	10 - 2000
	O_2	1 - 100
	H_2O	1 - 50
	HT	0.2 - 2
After Q_2O Removal Step	H_2O	0.1 - 50
	HTO	0.01 - 2
TES Outlet	H_2	0.1 - 100
	O_2	0.1 - 10
	HT	≤ 2
TBM Inlet	H_2	10 - 2000

The control of O_2 can be simultaneously used as a sensitive method of leak detection.

- For radiological safety reasons, the complete TES has to be installed in a glove box as secondary containment.

3. Discussion of Process Options

Ten different methods for tritium extraction have been described and evaluated with respect to their applicability for ceramic breeder blankets in /2/.The main process steps of these methods are summarized in Table 3.

Table 3: Summary of Process Options described in /2/

No.	Method / Origin	Main Components
1	Pressure Swing Adsorption (PSA) AECL, Canada	Compressor (0.1→1 MPa) MSB (-195°C) Vacuum Pump / Compressor Pd/Ag Permeator
2	Thermally Coupled Pressure Swing Adsorption (TCPSA), Canada	Cold Trap (-195°C) Several Compressor Units in parallel Several Adsorber Units in parallel Several MSBs (-195°C) Pd/Ag Permeator
3	ANL Tritium Recovery System, USA	Cold Trap (-100°C) Several MSBs (-195°C, +25°C) Small / large Electrolytic Cell Pd/Ag Permeator
4	JAERI - Option A / Japan	MSB (20°C) Pd/Ag Permeator MSB (-195°C), Electrolytic Cell
5	JAERI - Option B / Japan	Oxidizer MSB, WGSR, Pd/Ag Permeator
6	ENEA - Option A / Italy	Oxidizer (2) Cold Trap or Cryosorber WGSR, Pd/Ag Permeator, MSB (2)
7	ENEA - Option B / Italy	Oxidizer Cold Trap or Cryosorber WGSR, MSB CO_2 Adsorber, Pd/Ag Permeator
8	ENEA - Option C / Italy	Oxidizer, Cryotrap WGSR, Pd/Ag Permeator
9	Sulzer - Option A / Switzerland	Compressor (→10 bar) Cold Trap (-100°C), MSB (-195°C) Cryogenic Freezer (-263°C)
10	Sulzer - Option B / Switzerland	Oxidizer, Compressor (→6 bar) MSB, Condenser, Water Processor

MSB = Molecular Sieve Bed
WGSR = Water Gas Shift Reactor

Up to now, none of the methods mentioned above has been demonstrated to be reliably applicable for the purge gas conditions foreseen for the operation of an ITER blanket test module (or larger ceramic blanket designs such as for DEMO). These conditions are characterized by high / very high gas flow rates and extremely low concentrations of HT and HTO.

As a consequence of the evaluation, a proposal has been made (FZK concept) which is expected to have the best potential for applicability to ITER and DEMO and to incorporate the smallest development risk. In the FZK concept, which is similar to the ANL proposal (No. 3), the extraction of tritium and excess hydrogen is accomplished by using a cold trap for freezing out HTO/H_2O and a 5A molecular sieve bed for the adsorption of HT/H_2.

4. Description of the FZK Concept

A flow diagram of a tritium extraction system designed according to the FZK concept is shown in Figure 1. The instrumentation for process control like sensors for temperature, pressure, flow rate, etc. are not included in the figure. The mode of operation shown is the extraction mode where the cold trap and the first molecular sieve bed are in operation.

At the beginning of the loop, there are 5 valves (V1...V5) which are used to enable a safe isolation of the loop from the TBM. This is especially important in the case of a pressure increase in the TBM caused by a leakage in the TBM Coolant System. Valve V4 is part of a bypass line which allows functional tests of the loop without sending gas through the TBM.

Front-end components of the loop are a cooler (No.1) to reduce the temperature of the incoming gas to room temperature and a filter cartridge (No.2) to remove particulate material which might be carried out from the blanket zone. Downstream of the filter, there is a bypass line leading to the compressor (No.8) which is foreseen for initial scavenging of the TBM.

The next component is an ionization chamber (No.3a) mounted in a bypass to the main gas stream; an orifice or a throttle valve is needed to provide the required small gas flow through the ionization chamber.

The Q_2O content of the gas is frozen out in the cold trap (No.4) at $\leq$ -100°C. The residual Q_2O concentration at the outlet is < 0.015 vpm. The amount of ice accumulated within 6 days is of the order of a few grams (max. 6 g). It will not be necessary, therefore, to exchange the water collector (Volume $\leq$ 200 ml, No.10) after each test run.

The purge gas is further cooled down by a recuperative heat exchanger (No.5) and then passed through an adsorber bed (No.6a) operated at liquid nitrogen (LN_2) temperature (-196°C). The bed is filled with 5A zeolite pellets which adsorb molecular hydrogen as well as gaseous impurities and residual moisture. The bed contains filters on the down-stream and upstream side to prevent particulate material from being transferred during loading/ unloading operations.

In addition, the bed is equipped with a LN_2 chiller and an electrical heater. The second bed provides additional adsorption capacity; it can be also used when the first bed is being unloaded or regenerated.

The clean gas leaving the adsorber bed is utilized in the heat exchanger mentioned above to precool the gas coming from the cold trap. It is then further warmed up by an electrical heater (No.7). The next components are the purge gas blower (No.8) coming in contact only with clean gas at room temperature, and the helium make-up unit (No.9) where hydrogen is added to provide a He : H_2 swamping ratio of 1000 for the gas reentering the test blanket module. In addition, this component is used for the first fill-up of the loop with helium.

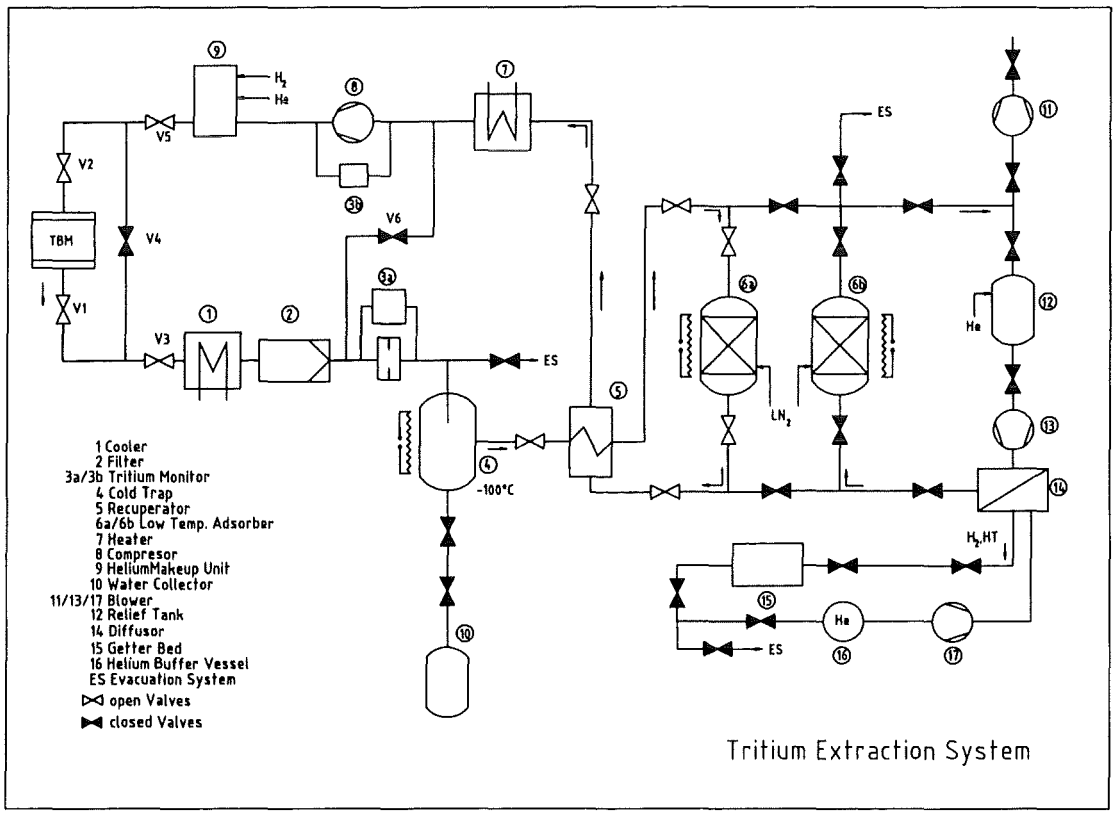

Figure 1: Flowsheet of the Tritium Extraction System proposed for the ITER TBM

5. Critical R&D Issues for the Proposed Procedure

Prior to the application of the procedure decribed above at a fusion reactor test blanket, it will be necessary to demonstrate the feasibility of the proposed process steps under realistic conditions with respect to gas flow rates and gas composition. It is planned to carry out corresponding tests with the small pilot plant PILATUS (*Pilot*anlage für *Tritium* Extraktions*s*ysteme) in the Tritium Laboratory of Karlsruhe, TLK.

The critical issues of the test program are:

a) Design of a Cold Trap for Q_2O inlet concentrations < 50 vpm at gas flow rates ≤ 3 Nm^3/h. It is the aim to obtain outlet concentrations below 0.1 vpm, because it is desirable to keep the amount of adsorbed water on the molecular sieve bed as small as possible.
A literature study on cryogenic cold trap experiments has shown that a high Q_2O removal efficiency can be obtained only if the formation of ice aerosols is prevented. Therefore, a variable temperature profile will be needed to avoid a critical supersaturation of the gas (see also Chapt. 6).

b) Design and test of a 5 A Molecular Sieve Bed; the tests will have
- to confirm or to improve the few existing data on the adsorption of H_2/HT for concentrations in the range of 1 - 1000 vpm,
- to give results on the cosorption of O_2 and N_2 with Q_2 at -195 °C,
- to show if it is possible to separate Q_2 from O_2/N_2 during unloading by moderate temperature increase from -195 °C to about -150 °C,
- to answer the question if an advantage can be drawn from the fact that HT is more strongly bound on the MSB than H_2; if the incoming HT is able to replace e.g. 1-3 % of the previously adsorbed H_2, the MSB can be operated until complete break through; it would not be necessary, in this case, to add further H_2 to the purge gas on its way back to the TBM, and the amount of gas to be sent to the ISS later on would be much smaller.

c) Selection and test of reliable analytical techniques to control the removal efficiency of each process step. Due to the extremely low residual concentrations, this challenging task must be accomplished
- to demonstrate the process feasibility, and
- to supply appropriate methods for process control.

d) An additional R&D issue is to design and test an oxidizer for small concentrations of Q_2 (≤ 10 vpm). Concentrations of this order of magnitude have to be extracted from the TBM coolant system. The following results are expected from these tests
- the oxidation efficiency as a function of temperature,
- the minimum amount of required excess oxygen,
- the most appropriate oxidizer material (e.g. Pt or Pd on aluminia) with respect to its hygroscopic behavior which could lead to a relatively high retention of the generated Q_2O in the oxidizer unit.

6. Evaluation of Cryogenic Cold Trap Experiments for Humidity Removal

The first component to be designed and tested is the cold trap. We have carried out an evaluation of cryogenic cold trap experiments the results of which are described in the following.

a) Test series performed at CEA /3/

In the frame of the European Fusion Technology Program for NET (Next European Torus), an experimental task has been carried out at CEN Fontenay-aux-Roses to determine the efficiency of a cold trap for removing water from Helium / Argon / Air streams. In addition, it was intended to obtain data for a scale-up of the tested cold trap for the NET Tritium Systems. Design and construction of the trap was carried out by SNIA TECHNIT Group (Italy). The main design data were

Max. gas flow rate	1.1 Nm^3/h
Water content at inlet	$\leq$ 1000 vpm
Water content at outlet	$\leq$ 1 vpm
Inlet gas pressure	$\leq$ 1100 mbar
Pressure drop	$\leq$ 50 mbar
Inlet temperature	$\approx$ 20°C
Capacity	$\leq$ 12 g water
Refrigerant	LN_2 with constant level control
Tightness	$\leq 6 \cdot 10^{-9}$ mbarl/s
Temperature control	by removable thermocouples located in the gas flow and on the walls
Dimensions	1200 mm Hight x 250 mm Diameter

The principle of the cold trap employed in the first test series is shown in Fig. 2. 16 cooling fins are welded on a cylindrical vessel enclosed in a Dewar flask filled with LN_2. In order to collect microcrystals of ice entrained by the gas stream, the gas is sent through a sintered stainless steel filter before leaving the trap. An automatic refilling device regulating the level in the Dewar allows an adjustment of the gas temperature in the trap. The gas introduced at the top is progressively cooled down by heat exchange either with the liquid nitrogen or with the cold vapour above the liquid phase. When the trap is completely immersed in LN_2, the residual water vapour pressure is expected to be below 10^{-9} mbar due to a gas temperature of -190°C.

Results of the first test series:

- The pressure drop measured for pure N_2 and He (without water vapor) was $\leq$ 80 mb for gas flow rates $\leq$ 1100 Nl/h. In particular, Δp was 3 mb for 100 Nl/h.
- When the gas contained moisture (25 / 1000 vpm), a rapid plugging occured due to ice deposition in the small diameter inlet pipe.

Δp = 500 mb for He + 25 vpm water

Δp > 1000 mb for N_2 or He + 1000 vpm water

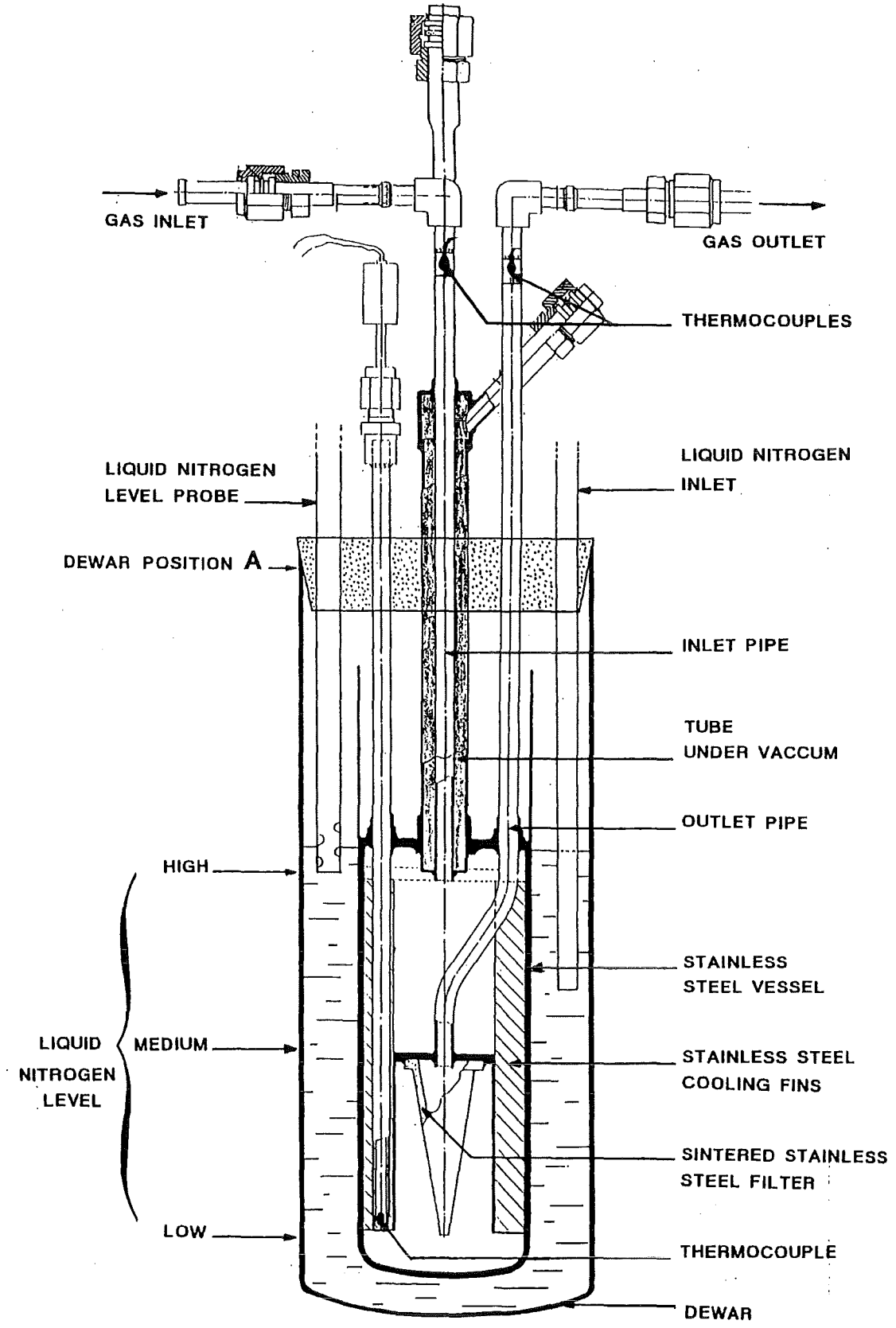

Figure 2: Principle of the Cold Trap

As a consequence of these results, the cold trap was modified: The part of the trap located above the fin zone was lengthened by 20 cm in order to avoid temperatures below 0°C in the narrow inlet pipe and thus to prevent the formation of ice. The modified trap is shown in Figure 3.

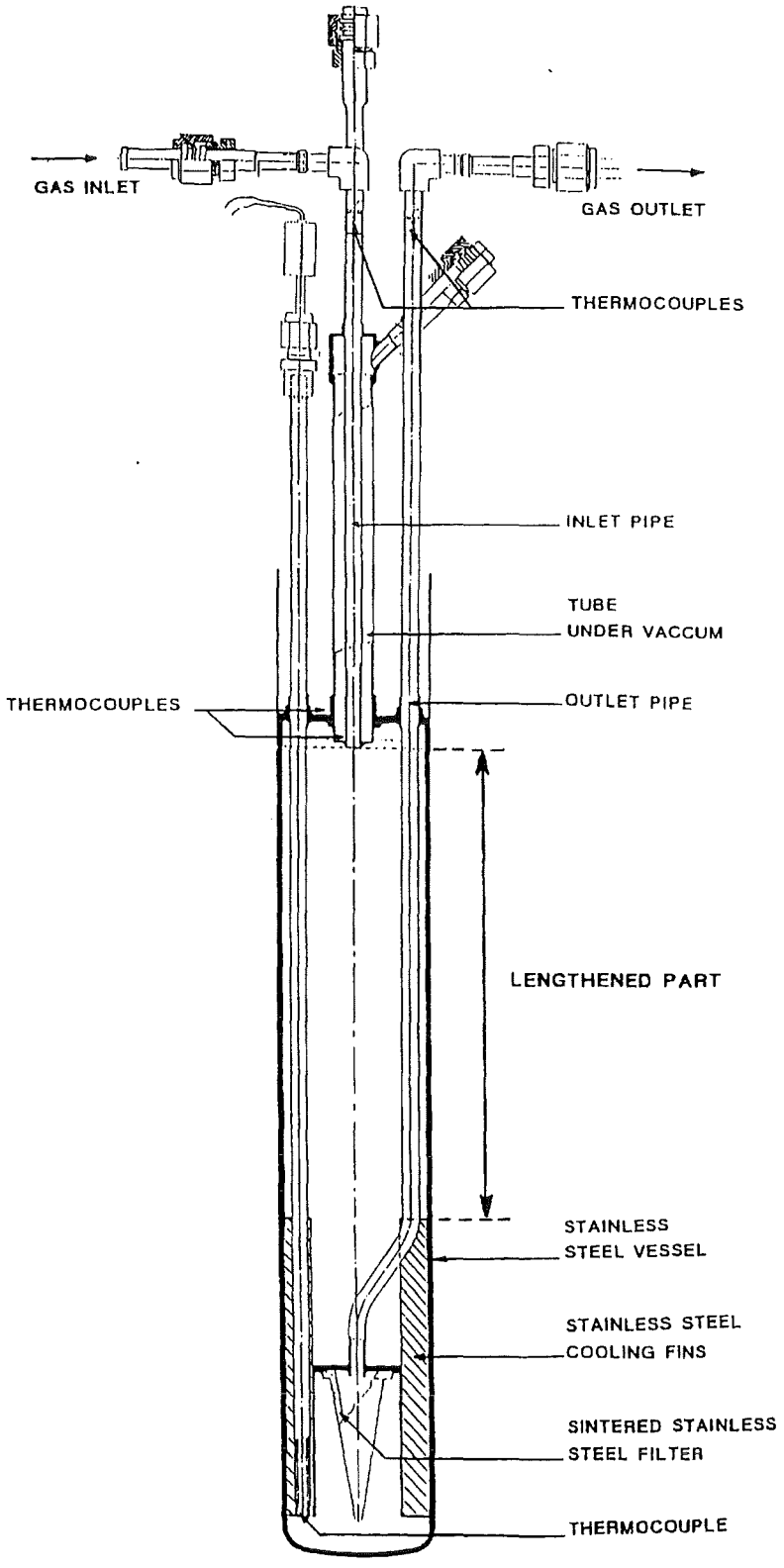

Figure 3: Principle of the Modified Cold Trap

Results of a test series with the modified cold trap

a) With a temperature of 10°C in the gas inlet zone, no plugging occured, and the pressure drop Δp between trap inlet and outlet remained

$\leq$ 5 mb for 80 hours at 100 Nl/h and with 1000 vpm H_2O in N_2, and

$\leq$ 40 mb for 110 h at 500 Nl/h and 1000 vpm H_2O in He.

The H_2O outlet concentration was $\leq$ 0.5 vpm (detection limit) in all cases.

b) It is supposed that partial clogging of the filter occurs due to ice deposition when the flow rate is increased to 200 Nl/h or 500 Nl/h.

c) In tests with 5 vpm H_2O in He at 500 Nl/h, however, the pressure drop was markedly higher than in the tests with 1000 vpm H_2O at 500 Nl/h (see Figure 3). This phenomenon does not occur at a flow rate of 100 Nl/h.

d) When a counter-current flow of dry gas is sent through the trap at the end of the test, the pressure drop can be almost entirely reduced to the initial value at the start of the test (see Figure 4).

Results of additional tests with no stainless steel filter at the trap exit

a) For inlet concentrations of 1000 vpm H_2O up to 250 vpm (70 vpm) water was detected at the outlet for flow rates of 500 Nl/h (100 Nl/h), respectively. In both cases, the humidity level at the outlet decreased to $\leq$ 1 vpm within 15 hours.

b) When the cold trap contained a certain amount of previously deposited ice, no water was detected at the trap outlet. The minimum amount of ice was found to be 5 g (1.5 g) for flow rates of 500 (100) Nl/h, respectively.

Conclusions of the CEA Tests

1. At flow rates of 100 Nl/h and water vapour inlet concentrations of 5 - 1000 vpm, the modified cold trap was fully efficient to remove the water down to $\leq$ 0.5 vpm. The pressure drop Δp remained negligible ($\leq$ 5 mb), even for tests up to 100 h.

2. At flow rates $\geq$ 200 Nl/h, the trap was still efficient to reduce the water concentration down to $\leq$ 0.5 vpm; however, the pressure drop increased due to partial clogging of the stainless steel filter caused by ice deposition; this effect primarily occured at very low water concentrations, i.e. in the range < 50 vpm;

3. It is obviously an essential condition that the humidity of the gas is fully precipitated as ice on the inner surfaces of the cold trap before it comes into contact with the stainless steel filter. The precipitation is facilitated by a high humidity level in the gas, by small flow rates, and by ab-initio-presence of ice on the inner surfaces.

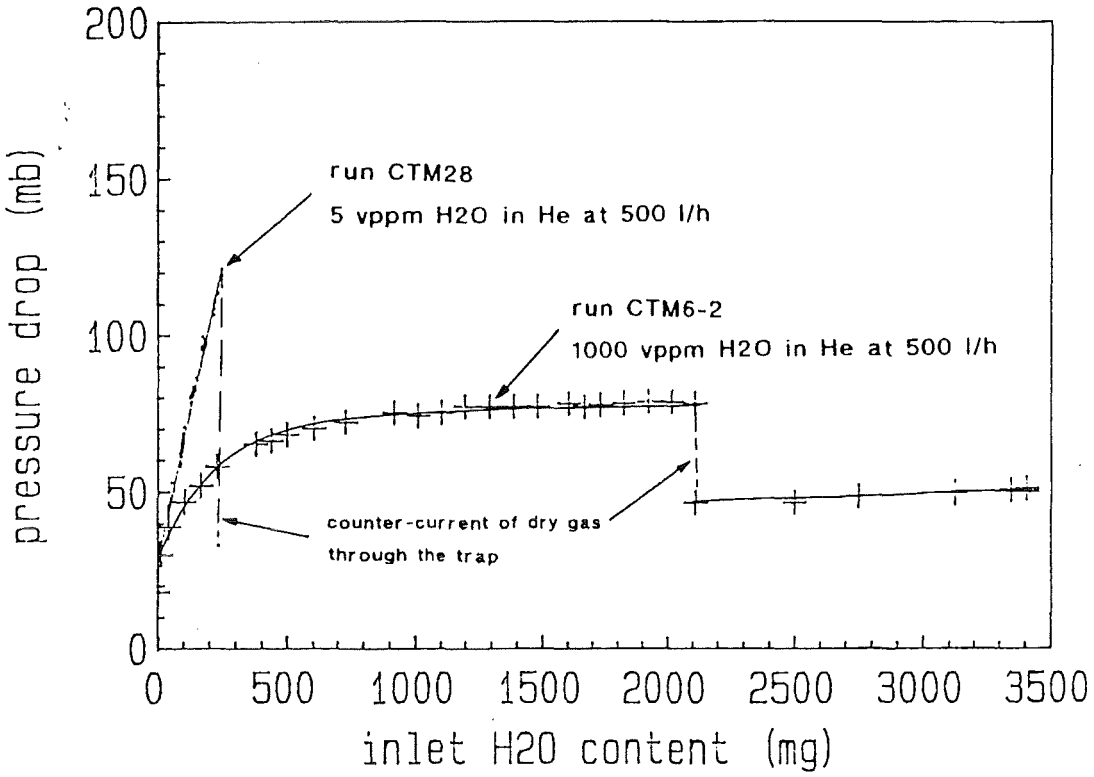

Figure 4: Pressure drop of the modified cold trap as a function of accumulated water for two different inlet concentrations; also shown is the effect of counter-current dry gas on the pressure drop

b) Tests performed at JRC-Ispra /4/

For atmospheric air detritiation requirements, a water vapour cold trap was developed in the form of a shell-and-tube heat exchanger. The emphasis of the study was placed on the influence of the cryogenic cooling on the efficiency of the process. In comparison to the classical molecular sieve dryer approach, cold trapping is considered as a more attractive technique, because it produces small amounts of liquid water rather than large volumes of regenerating gases which eventually require further detritiation.

Main design data of the cold trap (see also Figure 5)

- Tube bundle of 57 vertical tubes (11 mm diameter, 183 mm in length); gas flow downward through the tube bundle, then upward through a single tube
- Cooling by introducing LN_2 into the shell; use of a special CRYO valve of SIO
- A vacuum tight chamber, providing thermal insulation surrounds the shell

- Temperature sensors (Pt 100) in the upper and lower region (Points A and
- Bottom of the trap is sloped for draining the melted ice after removal of the cryogenic fluid (the trap does not contain an electrical heater)

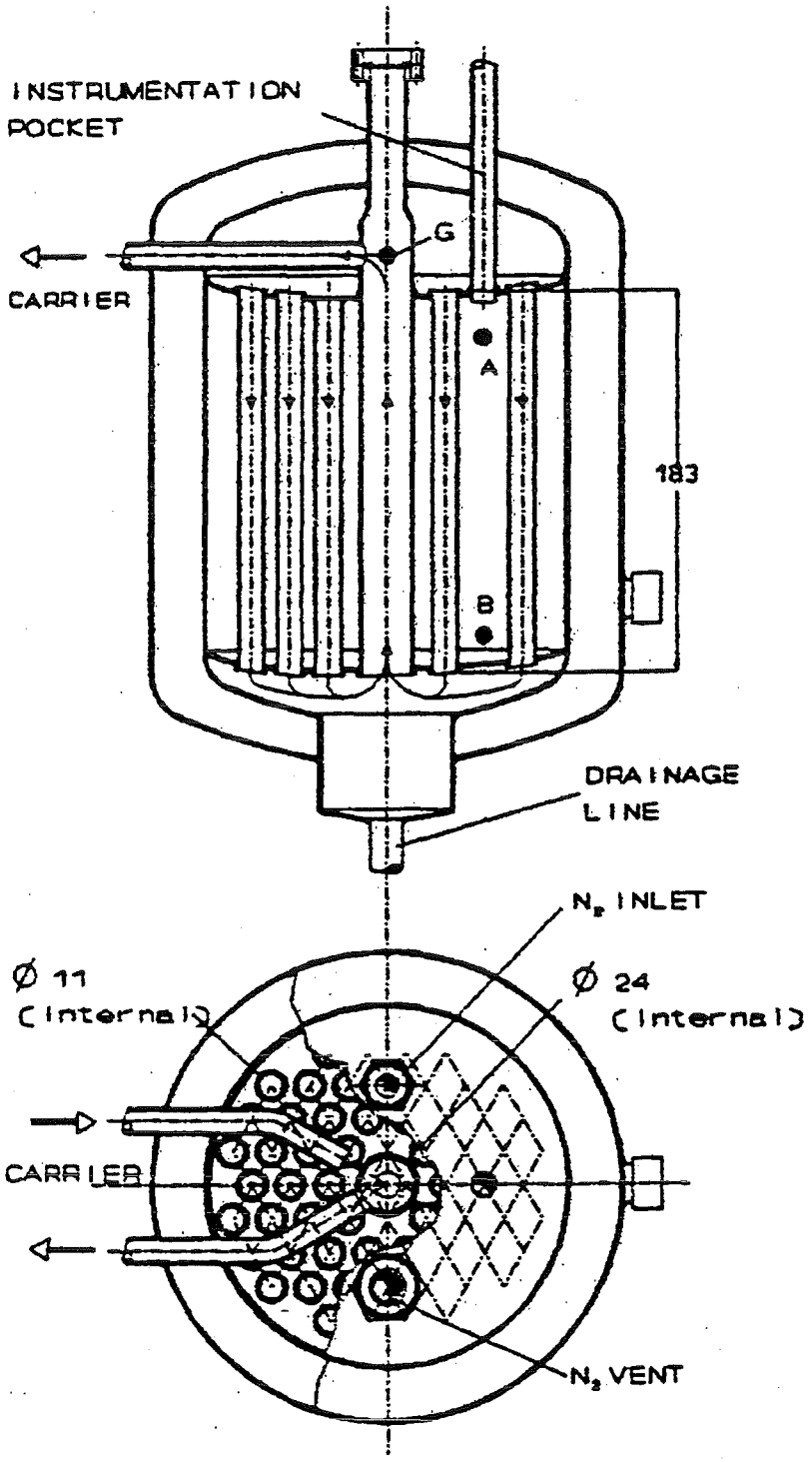

Figure 5: Principle of the JRC Cold Trap

Operational Data / Experimental Techniques

Flow rate 1 Nm^3/h (air, 20°C, 1 bar)

Water vapour content 1250 vpm

On-line hygrometer for dew points +20°C .... - 80°C

Prior to each test, the entire loop is dried with dry air to obtain the same initial moisture loading of all parts in the loop.

Results

- Down to a temperature of 225 K (- 48 °C), the trapping efficiency was good, i.e. most of the humidity was frozen out;
  The best humidity removal obtained was 98.89 %; it was associated with a water vapour content at the exit of about 14 vpm;
  The outlet concentration c_{out} was even less than the saturatian concentration c_{sat} which is apparently paradox;
  Assumed reason : Cold spots in the trap with improved precipitation.
- At lower temperatures, the efficiency became worse, and the gas left the trap supersaturated; further temperature reduction did not improve the situation; the effect is explained with massive entrainment of ice aerosol particles.

Conclusions of the JRC Tests

As soon as ice nucleates in the gas flow, water vapour is exclusively depleted in favor of particle growth, i.e. condensation on the walls becomes negligible.

When the gas temperature is moderately reduced, no nucleation occurs in the gas flow, and a good efficiency is obtained.

To achieve ultra-dry exit conditions, appropriate means must be taken to trap the out-flowing aerosol particles. Application of filters does not seem to be an effective approach. Calculations have shown that the mass-mean radius of the particles is of the order of 1 µm. Possible alternatives to enhance particle deposition could be:

- Creation of high turbulence in the flow to improve impaction deposition, or
- Use of electrostatic fields to get particle precipitation by electrophoresis.

c) Tests performed at JAERI /5/

The cold trap developed at JAERI and tested at TSTA was intended to be used as a process component of the Plasma Fuel Cleanup System. In this system, three cold traps of the same type and size have been alternately operated in a trapping, regenerating, and precooling cycle with approximately 60 minutes periods. The operating specifications were as follows:

Gas flow	40 mol He /h = 0.9 Nm^3/h
Pressure	1 bar
Inlet gas temperature	40°C
Cold trap temperature	- 110°C (Freon cooling)
Inlet humidity	0.8 mol /h = 2% (!)
Outlet humidity	$4 \cdot 10^{-6}$ mol /h
Removal factor	99.9995 %
Dimensions	1200 mm (Length) x 220 mm (Diameteter)

At the bottom of the trap, there was a 20 µ filter, the interior was filled with copper balls (8 and 5 mm in diameter)

Figure 6 gives a rough idea about the construction; unfortunately, the inscription numbers of the figure are not explained in English.

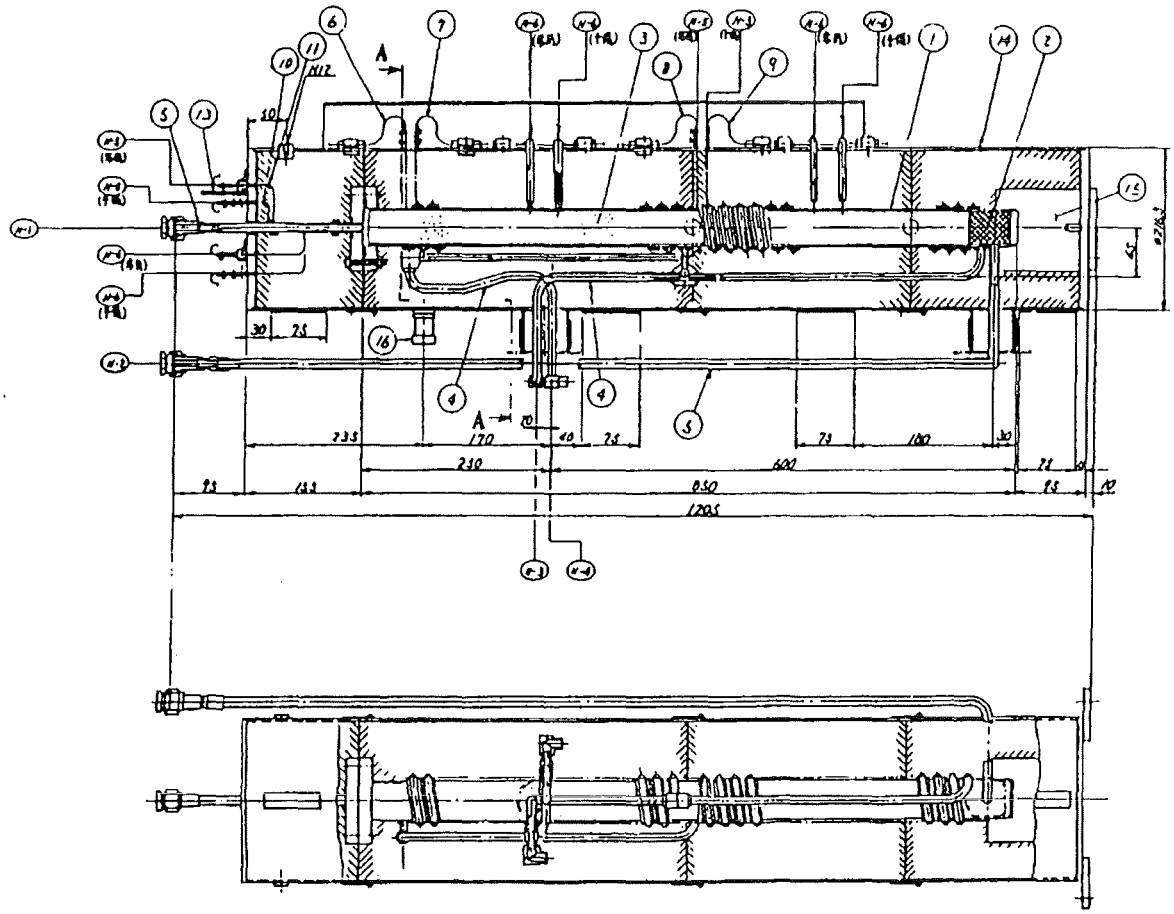

Figure 6: Principle of the JAERI Cold Trap

Test results

Shortly after start of operation, a humidity spike of almost 400 ppm was observed at the outlet; however, this humidity level decreased slowly (i.e. within 20 min) to about 1 ppm. It was believed that the spike was caused by water going through the trap in unknown form as supercooled water vapour or as submicron frost which passed through the filter. Several modifications were investigated to reduce the humidity spike:

- Decrease of linear gas velocity,
- Increase of internal surface area,
- Prevention of rapid pressure changes due to fast valve operations.

Since these modifications did not lead to significant improvements, a small molecular sieve bed (filled with 15 g of 5A granules) was installed at the cold trap exit, see Figure 6. A heater was wound around the MS bed to enable regeneration. This method turned out to be very effective in reducing the humidity spike. In later tests, the MS bed contained only 10 g of 4A molecular sieve material.

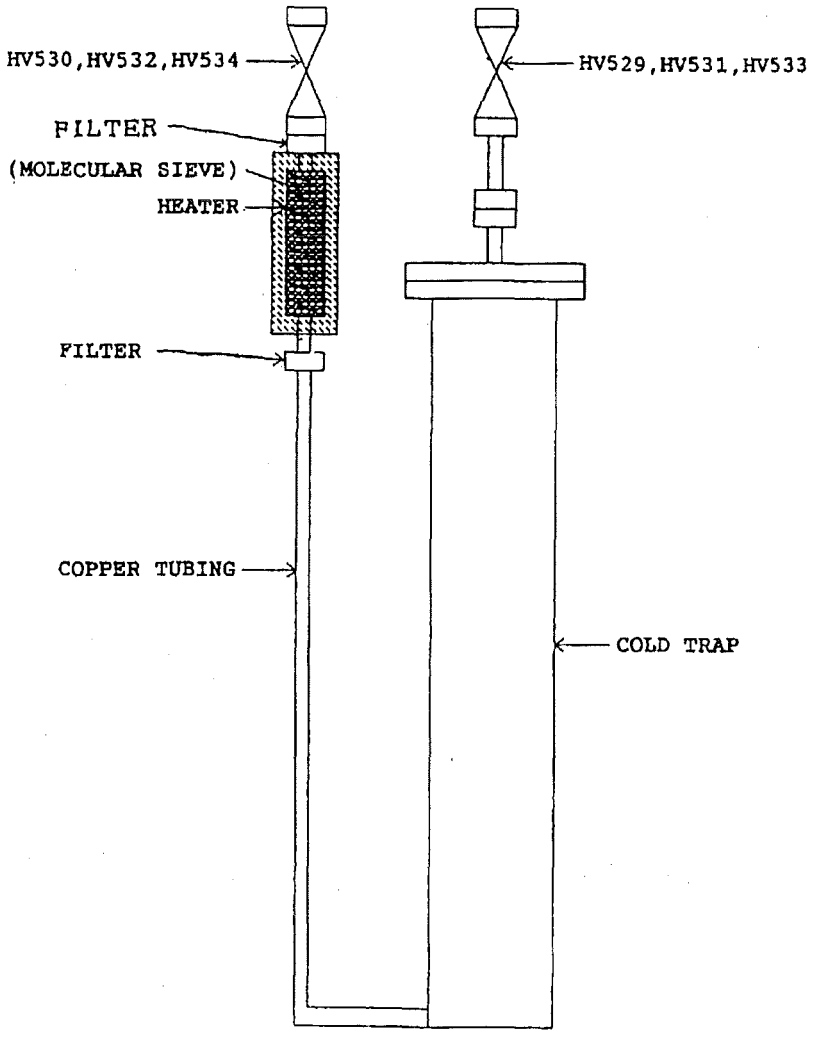

Figure 7: Configuration of the Cold Trap with a Molecular Sieve Bed

Conclusions of the JAERI Tests

It was not possible to detect the reason for the occurence of the high humidity spike after start of operation, and no reason was given for the considerably improved trap efficiency after 20 minutes.

The only way to improve the overall behavior of the trap was an additional installation of a small molecular sieve bed at the trap exit.

In addition, it should be mentioned that the trap was designed and tested for quite high humidity levels at the inlet; it cannot be concluded, therefore, that similar effects would have happened for small humidity levels such as 10 vpm.

d) General Conclusions

The following general conclusions can be drawn from the experiments described above:

1. During cool down of the gas in the cold trap, water vapour removal can be achieved by condensation on the inner walls of the trap as well as by trapping of ice aerosol particles on a filter.

2. Ice aerosol formation is connected with two main disadvantages:
   Very small particles ($\leq$ 1 μm) can pass through the filter and leave the trap without being removed; larger particles will be retained on the filter but will cause clogging and an increasing drop of pressure.

3. To obtain a good removal efficiency, it should be tried to avoid the formation of ice particles; this can be done by cautious cool down, i.e. by avoiding fast under-cooling / critical supersaturation /6/ which is the reason for spontaneous aerosol formation. The presence of particulate impurities in the gas should be prevented because these impurities will act as condensation nuclei for aerosol formation. The most appropriate temperature gradient in the trap depends on the gas flow rate and on the humidity of the gas. In any case, it will be necessary to test the cold trap with different temperature gradients to optimize its behavior for a specific gas flow.

4. In addition, it should be tried to enhance the process of wall condensation. For this reason, the gas flow should be rather turbulent than laminar. A coiled tube geometry will probably be more adequate than a linear tube geometry. It may be also advantageous to expose the gas to a rough surface rather than to a very smooth surface at the inner side of the cold trap.

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