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Hydrogen isotope separation for fusion power applications

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ABSTRACT

The invited talk given at MH2014 in Salford ranged over many issues associated with hydrogen isotope separation, fusion machines and the hydrogen/metal systems found in the Joint European Torus (JET) machine located near Oxford. As this sort of talk does not lend itself well to a paper below I have attempted to highlight some of the more pertinent information. After a description of the Active Gas Handling System (AGHS) a brief summary of isotope separation systems is described followed by descriptions of three major projects currently being undertaken by the Tritium Engineering and Science Group (TESG), the upgrade to the Analytical Systems (AN-GC) at the AGH, the construction of a Water Detritiation System (WDS) and a Material Detritiation Facility (MDF). Finally, a review of some of the challenges facing fusion with respect to metal/hydrogen systems is presented.

1. Introduction

The Joint European Torus (JET) tokomak and the connected Active Gas Handling System (AGHS), operated by the Tritium Engineering and Science Group (TESG), were built for the study of a fusion reactor with operating conditions relevant to a potential power plant. This required the use of deuterium–tritium gas mixtures for plasma fuelling. This meant that the design of the JET tokomak and its associated support systems had to make provision for processing of radioactive tritium gas mixtures and tritium contaminated materials.

JET is the only tritium compatible magnetic confinement fusion device currently active. Tritium was injected into a large tokomak for the first time during the Preliminary Tritium Experiment (PTE) in 1991 and since then 2 follow up T_2 experiments in 1997 and 2003. The next tritium campaign, DTE2 (Deuterium Tritium Experiment 2), is being planned for 2017 and lessons learned during this campaign will provide further valuable information to ITER and DEMO.

The main motivational factors for DTE2 focus on risk mitigation for ITER (the next generation tokomak being constructed in Cadarache, France, by an international consortium. The operation with various hydrogen isotopes and helium could have unforeseen influences on the 'ITER scenarios' and an integration of DT H-mode plasma operations with a Be/W first wall is required. Tritium inventory control is an area which requires improvement, as does a validation of wall conditioning techniques for tritium, and methods for tritium removal. Possibly the most valuable area is that of operational experience. The training of staff in DT operations, and the development of organisational competence, is an area that is vital. The final details of DTE2 are to finalised but the planned throughput of tritium is to rise from 100 g in DTE1 to 1000 g in DTE2 and the total inventory in the AGHS will increase from 20 g in DTE1 to 60 g in DTE2.

As the operators of the world's only fusion related tritium plant the members of the TESG are uniquely placed to understand the issues associated with tritium/fusion operations. As part of the new EuroFusion consortia the TESG has become involved in the design of DEMO, the European Fusion device currently in the conceptual design stage which is planned to provide >300 MW (electric) to a national grid by 2050.

2. Overview of the AGHS PLANT

The Joint European Torus (JET) Active Gas Handling System (AGHS) was designed and built for the purpose of safely storing, supplying and recycling the hydrogen isotopes of deuterium (D_2) and tritium (T_2) used in fusion experiments at JET [1]. The AGHS consists of an interconnected series of subsystems (Fig. 1). The Torus contains the deuterium–tritium plasma during short (of

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[1] See appendix of Romanelli F. at al Proc. 24th IAEA Fusion Energy Conf. (San Diego, CA, 2012).

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the order of 10 s) pulsed fusion experiments. The adjacent Neutral Injection Boxes (NIBs) are used for heating and fuelling the plasma through highly energetic neutral beams of deuterium and tritium. The AGHS provides the tritium used in the plasma and subsequently extracts the gas (a mixture of deuterium, tritium and impurities) after each experiment.

Deuterium and tritium are stored in the Product Storage (PS) subsystem in the form of uranium hydride, using bespoke uranium beds (UBeds). The PS UBeds contain either 1 kg or 4 kg of depleted uranium allowing for storage of 7 or 27 mol of hydrogen, respectively [2,3]. The UBed is heated to a temperature of 873 K to release gaseous D_2 and T_2. The D_2 and T_2, is then expanded into the Gas Introduction and Distribution (GI and GD) transfer lines for supply to the Torus, either directly via a Gas Introduction Module (GIM) or from the NIBs.

Hydrogen isotopes and other impurity gases (predominately helium and traces of nitrogen and hydrocarbons) resulting from the JET plasma experiments are pumped back to the AGHS via ML1 and ML2 using the Mechanical Forevacuum (MF) subsystem or, when tritium is present, the Cryogenic Forevacuum (CF) subsystem, which provides cryogenic pumping at liquid helium temperatures. CF separates the hydrogen isotopes from the other gases (impurities) using a mixture of activated charcoal trapping and rough cryogenic distillation. The impurities are then taken to the Impurity Processing (IP) subsystem. The hydrogen isotopologues (a mixture of H_2, D_2, T_2, HD, HT and DT) are sent to the Intermediate Storage (IS) subsystem, where the gas is temporarily stored on UBeds.

The IP gas processing loop consists of a 2 m^3 reservoir, a cold trap cooled by gaseous nitrogen (to 160 K) for removal of water, a nickel catalyst module for removal of hydrocarbons, a thin palladium permeator membrane for removal of any remaining impurities, four UBeds for hydrogen storage and a 150 m^{-3} h^{-1} pump connected in series. The IP subsystem separates any remaining hydrogen isotopologues from the impurity gases.

The Cryogenic Distillation (CD) subsystem is used to roughly separate the deuterium and tritium isotopes and remove the hydrogen isotope from the gas mixture. The deuterium and tritium can then be separated using the Gas Chromatography (GC) subsystem (note, the interconnections between the CD and GC systems are not shown in Fig. 1). The resulting D_2 and T_2 products are then sent to PS for long term storage ready for supply to the Torus.

Additional AGHS subsystems, which are not part of the main D_2 and T_2 recycling process, are used to aid the gas processing and ensure safety. The Analytical Laboratory (AN) is capable of analysing gas samples from each subsystem, allowing the composition of the gas at every processing stage to be determined. The Exhaust Detritiation (ED) system (EDS) removes the remaining traces of tritium, by converting all free hydrogen and hydrogen containing compounds to water, from any gases destined for discharge to the environment.

3. Hydrogen isotope separation for future fusion applications

The balance of deuterium and tritium in a deuterium–tritium plasma is crucial for fusion applications. Fusion reactions also have a very low burn-up rate for the tritium. Therefore, large quantities of tritium must be separated from deuterium (after removal of other impurities) and re-cycled after extraction from the Torus.

Some of the work currently being undertaken by TESG involves looking into alternative isotope separation techniques that can be utilised by future fusion reactors. At present, the only fusion reactor capable of operating with tritium is the JET and the two methods used are Gas Chromatography (in the GC subsystem) and Cryogenic Distillation (in the CD subsystem)

It is likely that the methods used at the AGHS will not be fully suitable for larger reactors such as ITER and DEMO. This is because these methods are costly, complicated to operate, energy intensive, operator intensive and time consuming. Because of the requirement for more efficient technologies in future reactors, a number of different techniques (both established and new) will be assessed by the TESG, in order to determine their viability.

All isotope separation systems work by exploiting the small differences in physiochemical behaviour deriving from their difference in mass (isotope effects, see e.g. [4]). Examples of these effects include variations in vapour pressure, chemical bond strength, boiling and freezing points, viscosity, surface tension, and variations in optical omission spectra. Chemical equilibrium and reaction rates can also change between isotopes and be exploited. In the case of hydrogen, the large proportional mass difference can prove beneficial for isotope separation as it enhances the isotopic effects.

In order to establish the most promising candidates for an isotope separation system for future reactors, a review of current and promising future technologies will be produced by TESG. The use of metal hydrides as a separation tool will be a key area of investigation, along with the use of nanoporous framework materials and molecular sieves. Other areas of research will include: Atomic vapour laser isotope separation (ALVIS), catalytic exchange, gaseous diffusion, thermal cycling absorption, centrifugation, biological techniques and continuous ion exchange alongside the existing technologies used in the AGHS.

4. Outline of the AN-GC upgrade

The primary instrument for determining the hydrogen isotopologue content of samples (including hydrogen in hydrocarbons) in AN is the Analytical Gas Chromatograph (AN-GC) instrument [5]. GC instruments separate the various molecular components of a mixed gas by passing a sample through a series of separation columns, which separate the gases in space, followed by an appropriate detector which distinguishes the boundaries between the gaseous species (see [5] for a detailed description with diagrams). Hydrogen isotopes are chemically very similar and there are difficulties associated with handling tritium due to its radioactivity. Therefore, there are no commercially available GC solutions for a tritium processing plant.

A new customised GC is being constructed for use during DTE2. In addition to several standard separation columns, a customised hydrogen isotope separation column containing palladium will be included. For safety reasons, the entire assembly is contained within a nitrogen filled glovebox, thus bespoke furnaces and liquid nitrogen dewars are required for temperature control.

The AN-GC assembly includes several detectors; Thermal Conductivity Detectors (TCDs) for the detection of hydrogen isotopes, a Methaniser and Flame Ionisation Detector (FID) combination for hydrocarbons, and Ionisation Chambers (ICs) for tritium. The ICs for this system are custom built low volume units, with 5 cc chambers and flush gold plated outer chambers and zero dead volume micrometering valves to ensure the separation within the AN-GC is not affected. A Quadrupole Mass Spectrometry (QMS) will also be connected to the system, which allows detailed analysis of small samples (pressures $10^{-12} < P < 10^{-5}$ hPa) through a Residual Gas Analyser (RGA) detector. The RGA allows species that the AN-GC cannot separate to be discriminated, as well as determining the isotopic content of overlaying non-radioactive species. The exhaust of the AN-GC will include a bypass containing a custom built, tritium compatible Laser Raman (LARA) gas cell for further analysis of the gasses [6].