Tritium and Impurity Removal from a Liquid Pb-Li Blanket

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Abstract

Tritium and radioactive impurities result in fusion reactors having a Pb-Li liquid blanket via interactions of neutrons with the lithium and lead. The tritium and impurities are to be extracted for use as fuel and to maintain blanket performance as well as provide a safe operating environment. The proposed design for tritium removal consists of a vacuum permeation method whereby niobium is used as the principle permeating window. A laser isotope separation method is also proposed for removal of the impurities. The tritium concentrations, partial pressures, and removal rates have been investigated as part of the design of the removal system and the results are presented.

1. Introduction

Maintaining a sustainable supply of clean, renewable, and cost effective energy in the face of global energy consumption (e.g., 5% increase in 2010 [1]) is a considerable challenge. One potential solution to meet these requirements and the growing world demand is energy from a nuclear fusion reactor. Mainly due to the relatively low temperature demands, the fusion of tritium and deuterium atoms is the reaction of choice for many reactor designs.

While deuterium is a comparatively abundant isotope of hydrogen that can be extracted from seawater, the main issue that is faced by fusion reactors is the supply of tritium. Tritium's natural abundance is much less than 1% of naturally occurring hydrogen [1] and, therefore, natural sources are not a viable source of this fuel. Tritium can be bred in a reactor from lithium irradiated by the neutrons produced during the fusion-reaction process. This breeding process can be done in a blanket of material composed of liquid lithium (^{6}Li), liquid Pb-Li eutectic, lithium ceramics, or liquid molten salts. Each blanket composition has its own advantages and disadvantages. The liquid Pb-Li eutectic, which has been studied extensively [3-5], utilizes the neutron multiplication capability of the lead to improve the tritium breeding ratio (TBR). A primary issue is the extraction and safe storage of the tritium from the breeder blanket. This paper investigates methods by which tritium and impurities bred in a fusion reactor might be removed. The method proposed in this paper is applicable to all fusion reactor designs that use a liquid Pb-Li eutectic.

2. Literature Review

The extraction of tritium from fusion reactor blankets has been studied extensively and various methods and designs have been proposed. Some of the methods that have been studied in previous years include molten salt extraction by Maroni *et al.* [6] and Calaway [7], gettering recovery by Clinton and Watson [8], and Buxbaum [9], permeation windows by Buxbaum [10-11], a combination of gettering and molten salts by Sze [12] and Ihle [13], and finally vacuum distillation by Vortmeyer and Michael [14]. The International Thermonuclear Experimental Reactor (ITER) which is by far the largest project related to Fusion Engineering has also opted for the use of a liquid blanket of pure lithium. The methods being considered for ITER are the use of equilibrium vacuum distillation, cold traps, and non-equilibrium molecular reflux distillation [13]. For reactors using a Pb-Li eutectic, the extraction methods proposed for ITER would also be applicable, however differences arise in the method parameters, e.g., a higher tritium partial pressure in Pb-Li as compared to pure lithium.

2.1 Tritium Removal Selection

A review of existing designs was conducted in which the designs were qualitatively and quantitatively assessed. The gettering recovery, NaK cold trap, liquid gas contractor, vacuum distillation, and vacuum permeation window methods were studied and it was found that the vacuum permeation window is potentially the best method for tritium extraction from the Pb-Li eutectic as it has the highest reported efficiencies [15] compared to the other methods.

2.2 Laser Isotope Separation

The method of laser isotope separation was investigated for the removal of impurities produced from the activation of the lead in the eutectic, such as polonium and bismuth. The method of laser isotope separation works on the principle that different elements have different ionization energies. The ionization energy is the energy that needs to be imparted to an atom to excite the outermost electrons so that they can escape the electron shells of the atom. This input of energy places the atom into an excited or charged state allowing it to be separated from the other neutral atoms via electric fields. The laser can be tuned to emit photons of a specific wavelength that only ionize atoms of a particular isotope, leaving the atoms of other isotopes and elements unaffected.

The Atomic Vapour Laser Isotope Separation (AVLIS method) [16] was investigated. In order to ionize the atoms of a desired isotope, the material must first be vaporized, which can be achieved by using electron-bombardment heating or induction heating. Once vaporized, a scanning laser ionizes the preferred atoms, which can then be drawn to an electrostatically charged plate where they are collected. The atoms condense on the plates and run down to a catcher. This method has been proven for uranium, tantalum, and rhenium, all of which have considerably high boiling points.

3. Proposed Method

The proposed tritium and impurity removal system consists of a vacuum permeation loop and a laser isotope separation loop. For the vacuum permeation loop, the liquid Pb-Li will be irradiated and heated in the reactor blanket region of the fusion reactor and then be sent via electromagnetic pumps from the reactor blanket system shown in Figure 1 to the vacuum permeation vessel. The tritium will permeate through U-tubes made of vanadium, niobium, or tantalum [13]. Once the tritium has permeated through the tubes, a vacuum pump on the secondary side will pump the tritium to storage. The liquid Pb-Li will then proceed from the outlet of the vacuum permeation vessel to the main heat sink (HS).

For the laser isotope separation loop, some of the liquid Pb-Li will be sent to a heating vessel which will vaporize the liquid and send the gases to a laser isotope separation vessel to remove the polonium and bismuth impurities. The eutectic will then be sent to the heat sink from where it will be pumped back into the reactor blanket system via an electromagnetic pump for the next cycle. Parameters calculated for this system are shown in Table 1 for a spherical 150 MW(th) fusion reactor in which a 1 m thick blanket surrounds a fusing compact toroid.

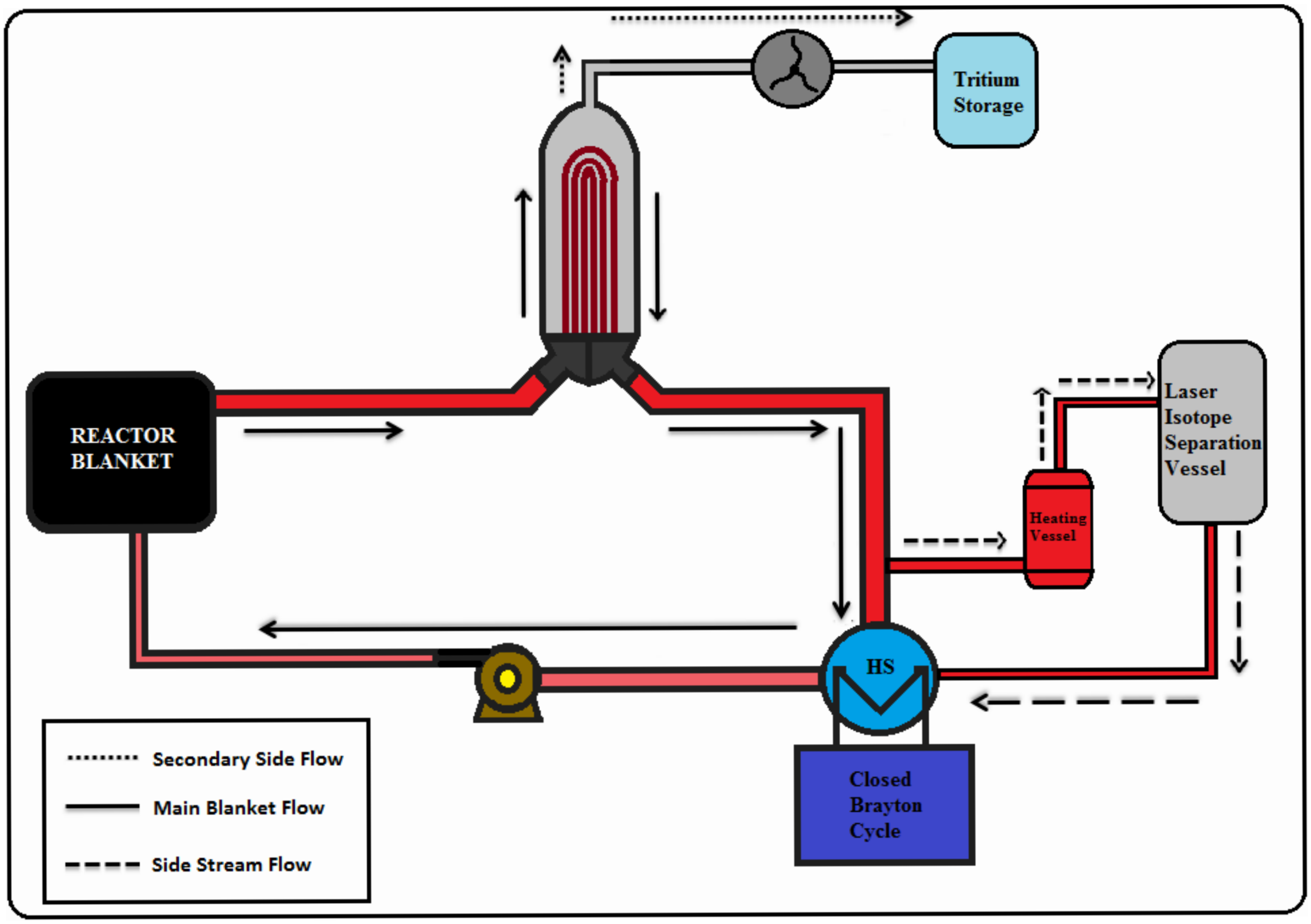

Figure 1. Tritium and impurity removal flow diagram.

Parameter	Calculated Value
Fusion Reaction Rate	2.66×10^{19} reactions/s
$<\sigma v>$	4.58×10^{-16} cm^3/s
TBR	1.016
Pb-Li Temperature$_{reactor\text{-}inlet}$	773 K
Pb-Li Temperature$_{reactor\text{-}outlet}$	923 K
Tritium Concentration$_{reactor\text{-}outlet}$	1.87×10^{-11} moles/cm^3
Tritium Partial Pressure$_{inlet}$ (into permeation vessel)	422.10 mPa
Tritium Partial Pressure$_{outlet}$ (out of permeation vessel)	40 mPa

Table 1. Calculated Parameters.

4. Safety Considerations

Because tritium is a volatile and dangerous radionuclide, there are many safety aspects of a tritium removal system that must be considered to prevent ingestion or inhalation. For example, permeation of tritium through the primary Pb-Li piping from the reactor vessel to the vacuum permeator, and to the heat exchangers must be kept to an absolute minimum to remain within the airborne operational release limits which are set by a regulatory body.

The method proposed involves very high temperatures to achieve the high partial pressures needed for effective permeation of the tritium; therefore, the Brayton cycle is the suggested thermodynamic cycle for improved efficiency. The Brayton cycle would use helium as the secondary-side coolant and thus any tritium permeation from the heat exchanger piping to the helium environment must be kept to an absolute minimum since this would provide the tritium a direct pathway to the environment via helium leakage from the Brayton cycle. The ARIES-CS project extrapolated data from the measured leakage rate of helium from a 10 MW(th) Chinese, high-temperature fission-reactor and determined an annual release of 7 mg of tritium for a dual coolant Pb-Li blanket surrounding a 2000 MW Stellarator reactor [17].

One method by which these releases could be lowered is by using an alloy of aluminum for the inter-coolant pipe walls. The aluminum alloy would slow down the permeation by a factor of 10 to 1000 depending on the alloy [17].

5. Conclusion

A literature review was conducted and it was found that vacuum permeation windows and laser isotope separation would be most suitable candidates for removing tritium and impurities, respectively, from a liquid Pb-Li eutectic blanket. Tritium removal would be performed on the bulk of the fluid during normal operation of the facility. Given the proposed method for tritium removal, high efficiencies would be required. Impurity removal would be performed on a smaller portion of the fluid to remove the polonium and bismuth resulting from the irradiated lead. Future work will involve the determination of the laser requirements for the isotope separation loop.

6. References

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