A VACUUM DISENGAGER FOR TRITIUM REMOVAL
FROM HYLIFE-II REACTOR FLIBE

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ABSTRACT

We have designed a vacuum disengager system to remove tritium from the Flibe (Li_2BeF_4) molten salt coolant of the HYLIFE-II fusion reactor. There is a two-stage vacuum disengager in each of three intermediate heat exchanger (IHx) loops. Each stage consists of a vacuum chamber 4 m in diameter and 7 m tall. As 0.2 mm diameter molten salt droplets fall vertically downward into the vacuum, most of the tritium diffuses out of the droplets and is pumped away. A fraction $\Phi = 10^{-5}$ of the 8.6 MCi/day tritium source (from breeding in the Flibe and from unburned fuel) remains in the Flibe as it leaves the vacuum disengagers, and about 21 % of that permeates into the intermediate coolant loop, so about 20 Ci/day leak into the steam system. With Flibe primary coolant and a vacuum disengager, it appears that an intermediate coolant loop is not needed to prevent tritium from leaking into the steam system. An experiment is needed to demonstrate Flibe vacuum disengager operation.

INTRODUCTION

The HYLIFE-II inertial confinement fusion reactor uses 5 MJ of heavy ion beams to compress and ignite fuel pellets yielding 350 MJ per pulse at a repetition rate of about 8 Hz. Falling jets of Flibe (Li_2BeF_4) molten salt protect the blast chamber wall.^{1,2}

For tritium removal we have chosen a vacuum disengager spraying tiny Flibe droplets into a vacuum chamber. As the droplets fall, tritium diffuses out and is pumped away by the vacuum system.^{3,4}

Although a flowing inert gas would prolong droplet residence in the spray chamber and enhance mass transfer rates, we decided not to use gas, because dissolved gas would interfere with Flibe condensation in the blast chamber.⁵

With all tritium removal done in the primary loop, the tritium leak rate is

$$L = \epsilon nQ f_x (1-f_s) \quad (1)$$

where

ϵ = fraction of Flibe flowing through the IHxs = 0.19,

nQ = tritium flow rate leaving blast chamber
= 1.08×10^{22} atoms/s = 45 MCi/day,

f_x = fraction of tritium in Flibe permeating through IHx tubes

≈ 0.21 (A previous value of 0.07 was based on lower diffusivity)⁶ and

$(1-f_s)$ = fraction of tritium not removed by vacuum disengagers.

With $(1-f_s) \approx 10^{-5}$ the resulting leak rate $L \approx 20$ Ci/day, which meets the 40 Ci/day goal.⁷

The concentration ratio of T_2/TF has not been computed, but it can be controlled by addition of Be or CeF_3 buffers to the Flibe. To be conservative, we assume all the tritium to be in the T_2 form, which has the highest permeation rate.

TRITIUM RELEASE FROM FLIBE DROPLETS

There are two diffusion problems to be solved: the tritium diffuses out of Flibe droplets, and then the released tritium gas diffuses out of the spray region to the vacuum pumps. The fraction of tritium remaining in a liquid droplet after a fall

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time t is given by the equation⁸

$$\Phi = p_{\infty}/p_0 + 6(1 - p_{\infty}/p_0) \sum_{m=1}^{\infty} \exp(-\lambda_m^2 Fo) (\sin \lambda_m - \lambda_m \cos \lambda_m)^2 / \lambda_m^3 (\lambda_m - \sin \lambda_m \cos \lambda_m) \quad (2)$$

where $Fo = D_F t / a^2$ = Fourier number, D_F = diffusion coefficient of tritium in the liquid droplet (m^2/s), a = droplet radius, p_{∞} = tritium pressure in the surrounding gas, p_0 = initial tritium pressure in the droplet, the λ_m are eigenvalues found from the equation

$$\lambda_m \cot \lambda_m = 1 - Bi, \quad (3)$$

$$Bi = ah_m / D_F = \text{Biot number}$$

and h_m = mass transport coefficient at the droplet surface into the surrounding gas or vacuum (m/s). As the droplets fall they move into a region of lower external tritium pressure p_{∞} , and the ultimate limiting pressure is that at the bottom of the spray ($z=h$). We approximate this time-varying boundary condition by using a constant external pressure $p_{\infty} \approx p(r=0, z=0.67h)$. The fraction Φ of tritium remaining in the droplet is shown in Figure 1 as a function of Bi and Fo .

Figure 1. Tritium fraction remaining in a Flibe droplet as a function of Biot and Fourier numbers.

For the case of TF in Flibe at $T = 923K$, the experimentally measured diffusion coefficient is $D_F = 6.3 \times 10^{-9} m^2/s$.⁹ According to H. Moriyama (Kyoto University), the HT or T_2 form has a diffusivity 10 times higher than the TF form, as expected by analogy from the measured mass transport coefficients, so we have assumed $D_F \approx 6.3 \times 10^{-8} m^2/s$. Based on crude estimates we have assumed $h_m \approx 100 m/s$,⁵ at which $Bi = 3 \times 10^5$. As can be seen from Fig.1, Φ is insensitive to Bi when $Bi > 100$.

ORIFICE PLATES

We use orifice plates to produce parallel jet sprays, in order to avoid spray overlap and droplet coalescence. Individual $0.1 \times 0.1 \times 0.001m$ orifice plates will be suspended from a stainless steel lattice like suspended ceiling panels. The orifice plate assembly will have excess panels to compensate for holes that may become clogged or enlarged. For flow into a vacuum, the droplet size will typically be about twice the orifice hole size.¹⁰ The fraction of surface area occupied by holes in a triangular array is

$$f_h = \pi d_o^2 / 2(3)^{1/2} P^2. \quad (4)$$

where d_o = hole diameter and P = distance between hole centers. An orifice plate containing 300 $50\text{-}\mu m$ diameter holes has demonstrated production of multiple parallel streams of droplets.¹¹ The minimum ratio of P/d_o for the holes is about 3, in order to prevent droplet coalescence. The corresponding value of $f_h = 0.10$.

Let $\epsilon_v(z)$ = fraction of the spray volume occupied by Flibe droplets at position z . At the orifice plate exit $\epsilon_v(0) = f_h$. As the droplets are accelerated by gravity, they spread apart. The volume fraction at any position z is given by

$$\epsilon_v(z) = f_h / \beta \quad (5)$$

$$\beta \equiv (1 + 2gz/v_o^2)^{1/2},$$

where g = acceleration of gravity, and

v_0 = initial velocity through the orifice.
Values of $\epsilon_v(z)$ are illustrated in Figure 2.

TRITIUM DIFFUSION OUT OF SPRAY REGION

If the Flibe droplets in the spray are close together, then a substantial tritium backpressure can build up, which limits the tritium release rate from the droplets via the p_∞ terms in Eq.(2). In the coordinate system of Figure 3, the droplets are falling in the z direction, and the tritium gas diffuses through the spray in the radial direction to reach the vacuum pumps. The tritium gas diffusion coefficient out of the spray region is estimated from

$$D_s = v_t a / 9\epsilon_v \quad (6)$$

where v_t = tritium molecular speed.⁵ For our design $a = 0.2$ mm, $v_t = 1800$ m/s, $v_0 = 5$ m/s, $\epsilon_v(z)$ is given in Fig. 2, and D_s varies from 0.4 m²/s (at $z = 0$) to 0.9 m²/s (at $z = h$).

If n_{T_0} = concentration of tritium in the Flibe at the spray chamber inlet, then the source term of tritium gas released from the droplets is found to be

$$S = -\epsilon_v n_{T_0} \partial \Phi / \partial t$$

$$= (6n_{T_0} D_F f_h / a^2 \beta) (1 - p_\infty / p_0) \sum_{m=0}^{\infty} \frac{\exp(-\lambda_m^2 F_0) (\sin \lambda_m - \lambda_m \cos \lambda_m)^2}{\lambda_m (\lambda_m - \sin \lambda_m \cos \lambda_m)} \quad (7)$$

$$* \exp [-\lambda_m^2 D_F v_0 (\beta - 1) / a^2 g]$$

The tritium gas diffusion equation is

$$D_s [\partial^2 n / \partial r^2 + (1/r) (\partial n / \partial r) + \partial^2 n / \partial z^2] + (\partial D_s / \partial z) (\partial n / \partial z) + S = 0. \quad (8)$$

with boundary conditions

$$\partial n / \partial r = 0 \text{ at } r = 0$$

$$\partial n / \partial z = 0 \text{ at } z = 0 \text{ and at } z = h$$

$$n(R, z) = p_w / kT,$$

where p_w = tritium pressure at wall (controlled by vacuum pumping system).

The diffusion coefficient and source term are both nonlinear. We have solved the diffusion equation using a simultaneous

Figure 2. Variation of ϵ_v with distance z the droplets have fallen.

Figure 3. Coordinate system for tritium gas diffusion out of Flibe spray region. (Droplet size is exaggerated.)

overrelaxation technique with a finite difference approximation.¹² For a chamber with $R = 2$ m, $h = 5$ m, the resulting profiles of tritium gas pressure are shown in Figure 4. For this case we would take $p_{\infty} \approx 0.25$ Pa in solving Eq.(2).

Figure 4. Two-dimensional distribution of tritium gas pressure in Flibe spray region, assuming initial tritium pressure in Flibe droplets $p_0 = 294$ Pa and pressure at the chamber walls $p_w = 0.09$ Pa.

The tritium back pressure inside the spray region and attainable values of Φ can be further reduced by including flow channels free of spray droplets,⁵ but we have not taken credit for this effect here.

VACUUM DISENGAGER PARAMETERS

The volumetric flow rate of Flibe in the IHX loops $\dot{Q} = 12.5$ m³/s. For redundancy, each of the three IHX vacuum disengagers can handle half this amount, $\dot{Q}_s = 6.3$ m³/s.

Although upward sprays would have much lower chamber height and pumping power, the jets would overlap and coalesce, unless the velocities were carefully tailored, so we use a downward spray. With an initial velocity v_0 , the time to fall a distance $z = h$ is

$$t = (\beta - 1)v_0/g. \quad (9)$$

For our design $v_0 = 5$ m/s, $h = 5$ m, and $t = 0.62$ s.

The required spray volume V_s is estimated from the equation

$$V_s = Q_s t / \langle \epsilon_v \rangle \quad (10)$$

where $\langle \epsilon_v \rangle$ = the average fraction of chamber volume occupied by the Flibe droplets ≈ 0.06 . Thus, $V_s \approx 65$ m³. The total orifice plate area

$$A = 1.1 Q_s / f_h v_0 \quad (11)$$

where the factor 1.1 provides additional area for extra plates and for structure supporting the plates. For our design $v_0 = 5$ m/s, $A = 14$ m², and the spray radius $R = 2.1$ m. To allow for inlet and outlet pipes at the top and bottom, the total spray chamber height

$$H = h + 2D_t, \quad (12)$$

where h = spray height and D_t = Flibe tube diameter = 1 m.

At each spray height h there is an optimum droplet size, as shown in Figure 5. If the droplet is smaller than optimum, then

Figure 5. Tritium fraction remaining in droplet as a function of droplet radius for various spray heights. The operating point is denoted by an asterisk.

D_s is low, the tritium gas diffusion out of the spray region is slow, and backpressure inhibits tritium release from the droplets. If the droplet is larger than optimum, then diffusion within the droplet becomes the limiting process. For the present design we choose $a = 0.2$ mm and $h = 5$ m per stage, which yields a theoretical separation factor $\Phi = 1.33 \times 10^{-3}$, or $\Phi = 1.8 \times 10^{-6}$ for two stages. Assuming some performance degradation in each stage due to non-uniform vacuum pumping and other causes, we estimate that $\Phi \approx 10^{-5}$ is attainable for the two-stage disengager. Spray chamber parameters are summarized in Table 1.

Table 1. Spray chamber parameters.

Maximum Flibe flow rate per vacuum disengager
$Q_s = 6.3 \text{ m}^3/\text{s}$
Maximum tritium flow rate per vacuum disengager
$= 5.2 \times 10^{20} \text{ molecules/s}$
$= 4.3 \text{ MCi/day,}$
Spray radius $R = 2.1 \text{ m}$
Spray height $h = 5 \text{ m.}$
Droplet radius $a = 0.2 \text{ mm}$
Theoretical separation factor, 2 stages
$\Phi = 1.8 \times 10^{-6}$
Droplet velocity through orifice plate
$v_0 = 5 \text{ m/s}$
Hole fraction of orifice plate $f_h = 0.10$
Flibe temperature $T = 923 \text{ K}$
Tritium diffusion coefficient in Flibe
$D_F = 6.3 \times 10^{-8} \text{ m}^2/\text{s}$
Tritium gas diffusion coefficient among spray droplets
$D_s = 0.4 - 0.9 \text{ m}^2/\text{s}$
Henry's Law Tritium solubility in Flibe ¹³
$S = 5.4 \times 10^{17} \text{ atoms/m}^3\text{Pa}$

Each spray chamber is surrounded by eight vacuum pumping ports, as illustrated in Figure 6. Flibe pumping and vacuum pumping calculations are described in Ref. 5.

ELIMINATION OF INTERMEDIATE LOOP

The primary loop will have a double-wall containment of tritium, with an inert purge gas at 95 kPa pressure flowing between the

Figure 6. Layout of the vacuum disengager.

walls. The inner wall will be the vacuum boundary, and the outer wall will be a thin shell. Tritium may be removed from the purge gas by use of palladium windows or by catalyst bed oxidation and trapping.

If the vacuum disengager works as planned, it may be feasible to eliminate the intermediate coolant loop. A double-wall steam generator could isolate the Flibe primary coolant loop from the steam system. An inert gas or liquid could be used to enhance thermal coupling between the inner and outer tubes. In the event of a steam tube rupture, the steam could be vented to a condensation chamber through a rupture disk connected to the space between the inner and outer tubes. A double-wall steam generator would have a higher capital cost than an ordinary steam generator, but the additional cost might be less than that of an intermediate coolant loop.

SUMMARY

Tritium will be removed from the HYLIFE-II Flibe coolant by a two-stage vacuum disengager in each of the three IHX loops. The theoretical separation factor of the two-stage vacuum disengager is 2×10^{-6} . Taking

non-ideal effects into account, a separation factor of 10^{-5} could probably be attained. The design does not take credit for reduced tritium backpressure in the spray region from the use of flow channels. The optimum Flibe droplet diameter is 0.4 mm. Larger droplets release tritium more slowly, and smaller droplets impede tritium gas flow out of the spray region. Effective tritium removal in the primary loop obviates the need for double wall tubing in the intermediate loop, and it may be possible to eliminate the intermediate loop by using a double-wall steam generator. Experimental confirmation of the molten salt vacuum disengager concept is needed.

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