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ABSTRACT

A double-walled steam generator is used in the fusion power cycle to replace the intermediate loop. This will save the cost associated with a complicated system and the associated temperature degradation. The mechanical design of the steam generator is similar to that proposed for LMFBR application. The heat transfer and tritium diffusion calculations are performed. The double-walled steam generator provides a tritium diffusion barrier factor > 10^5 while increasing the surface area by 25% compared to a single-walled steam generator.

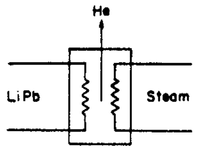
INTRODUCTION

$Li_{17}Pb_{83}$ is an attractive material for D-T fusion applications. It has excellent neutronic properties, is relatively inert toward water and has very low tritium solubility. One of the most difficult problems associated with using $Li_{17}Pb_{83}$ is tritium confinement. The low tritium solubility results in a very high tritium partial pressure, which causes large tritium leakage toward the steam side. If a tritium partial pressure of 10^{-4} torr faces a steam generator at 450°C with a single wall and no additional diffusion barrier, the tritium leakage rate will be 3.5×10^5 curies/day for a 3360 MW-t reactor. Therefore, a reduction of 10^5 on tritium leakage will be needed. However, the tritium permeation path is identical to the heat transfer path. In order to best use the primary coolant temperature, the resistance to heat transfer should be minimized. The problem is, therefore, to design a system which will have minimum impact on heat transfer, while providing a diffusion barrier of 10^5 to mass transfer.

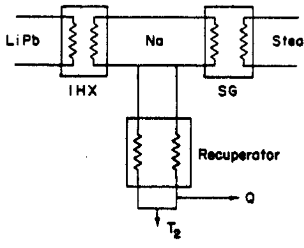
A sodium intermediate loop(1) is usually suggested to provide the required tritium diffusion barrier. A cold trap system is used for tritium cleanup from sodium. Since 3.5×10^5 curies/day of tritium has to be recovered from sodium from a very low sodium tritium concentration, the total sodium coolant flow will have to pass through the cold trap, as shown in Fig. 1. This requires three full-sized heat exchangers and the corresponding temperature degradation from three heat exchange processes. Therefore, a sodium intermediate loop is an expensive form to provide the required tritium diffusion barrier.

A double-walled steam generator has been proposed to provide the tritium diffusion barrier.(2) The double wall is actually two tubes in contact. The irregularities on the surface of the contacting metal provide passages for mutual diffusion of tritium and the purge gas. The purge gas is He with small oxygen partial pressure so that the tritium molecules diffusing across the first wall will be oxidized in between the two walls.

Although the concept of double-walled steam generators has been around for both fusion and fission applications,(3) no detailed analysis



DOUBLE-WALLED SYSTEM



Na INTERMEDIATE LOOP

Fig. 1. Comparison of a double walled steam generator with a Na intermediate loop.

has ever been performed for fusion applications, and significant different requirements exist from fission applications. The work reported here is for the MARS interim report. The feasibility of a double-walled steam generator in fusion applications is studied. The final power cycle design for MARS, however, may be significantly different from this.

MECHANICAL DESIGN

Heat exchange equipment for the MARS power cycle must fulfill exacting requirements while at the same time retain design features acceptable to the utility industry. The design requirements of liquid metal to water heat exchangers are complicated by:

- The component must provide a tritium diffusion barrier between blanket coolant and steam cycle.
- The component design must permit practical inspection and maintenance procedures in spite of radiation levels produced by activated corrosion products present in the blanket coolant.

The design described in Figs. 2 through 5 was created to meet the above requirements. It provides the following features:

1. Provision of an adequate tritium diffusion barrier.
2. Avoidance of size limitation problems typical of double-walled heat exchangers.
3. Detection, location and repair of leaks by conventional methods (eddy current).
4. More conventional, less difficult component assembly.

The space between inner and outer shells and between inner and outer walls of each tube assembly is filled with helium containing oxygen at a partial pressure of one torr. A pumping system (not shown) is used to circulate this gas longitudinally through each tube wall gap as a sweep (or monitor) gas to detect water vapor.

The hemispherical heads shown in Fig. 2 are similar in configuration to those used for "once through" PWR steam generators. Thus the tube inspection and repair equipment developed for this equipment is applicable to the design shown in the above figure. This equipment has been used satisfactorily to perform inspection and maintenance work in radiation levels up to about 15 rem at the hemispherical head tube face.

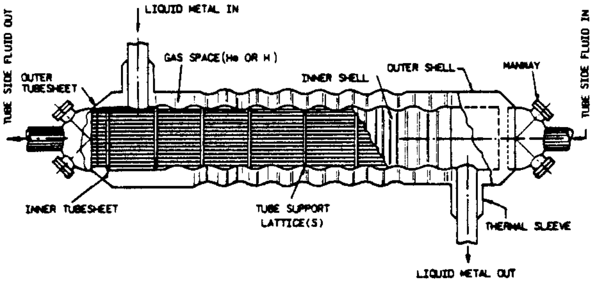


Fig. 2. General arrangement of the design.

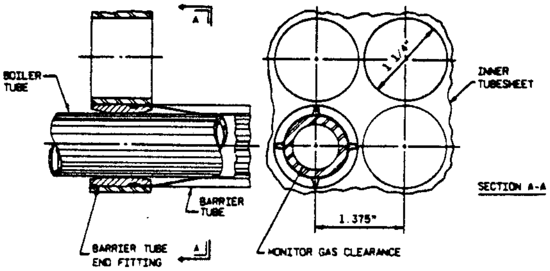
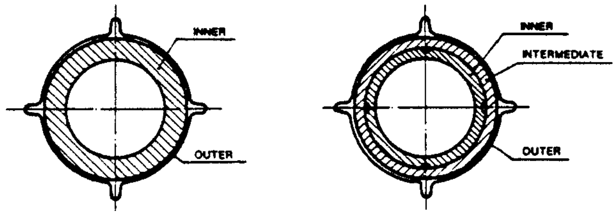


Fig. 3. Barrier tube to inner tubesheet detail.

To cope with higher radiation levels, the manways can be replaced by full opening closures, which in turn will permit use of rotating plugs and other equipment developed in the past for hot maintenance. The effect of activated corrosion product radiation on inspection and maintenance tends to be minimized by the following:

1. Vertical (instead of horizontal) tube sheet faces which reduce collection of corrosion particles on the surfaces.
2. Inner and outer tube sheets with a space between which attenuates streaming of gamma rays through tube ID's.
3. Corrosion products will tend to collect at the top of the inner shell. Radiation from this location will not be in line with tube sheet holes.



2 WALL TUBE (BASE DESIGN)

3 WALL TUBE (OPTIONAL)

Fig. 4. Two walled tube design and optional three walled tube design.

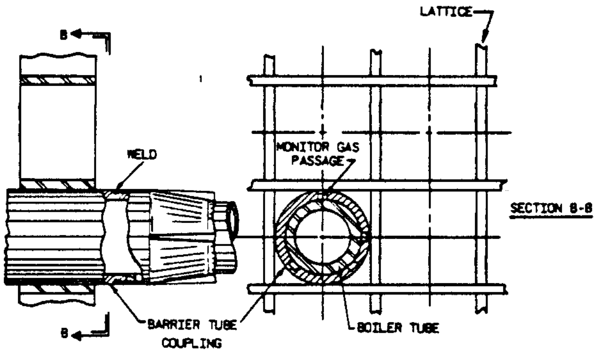


Fig. 5. Tube support detail.

HEAT TRANSFER

The double-wall design is actually two metal walls in contact in helium. The contact resistance between stainless steel in air has been measured(4) and is shown in Fig. 6. The conductance at near zero normal pressure is 0.28 watt/cm^2-°C. At such low normal pressure, the heat conduction is mainly across the gas gap and the conductance is, therefore, proportional to the thermal conductivity of the gas. Since helium gas is now in the gap, a conductance of 1.4 watt/cm^2-°C is used for the gap in the heat transfer calculation. Table 1 summarizes the heat transfer calculations for the double-walled steam generator. The total heat transfer area required is 3.5 x 10^4 m^2 for 3360 MW thermal power. If regular steam generator tubing is used, the heat transfer area is 2.7 x 10^4 m^2. The difference in the steam generator surface area between a single-walled and double-walled steam generator is about 25%. The relatively small difference is because the superheater has the largest surface area, where the heat transfer is dominated by the vapor phase side.

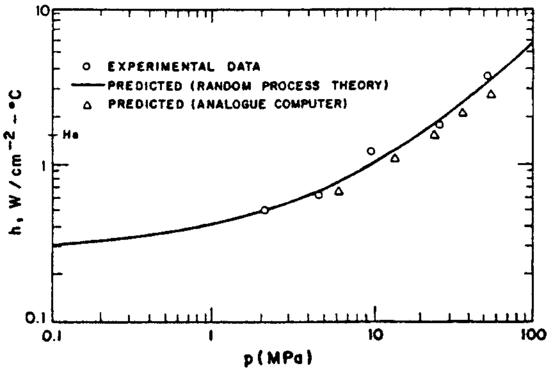


Fig. 6. Experimental values for contact resistance between stainless steel in air.

TRITIUM DIFFUSION CALCULATIONS

Hydrogen permeability through different ferritic steels has been summarized.(5) The best estimation of tritium permeability through HT-9 is

$$P_e = \frac{1.8 \times 10^3}{\sqrt{3}} \exp\left(-\frac{11100}{RT}\right) \frac{\text{mol } T_2 \cdot \text{mm}}{\text{d} \cdot \text{m}^2 \cdot \text{atm}^{1/2}} .$$

With this permeability and a steam generator area of 3.5 x 10^4 m^2, the tritium leakage rate is 3.5 x 10^5 Ci/day. Therefore, a tritium diffusion reduction of 10^5 is needed.

In the MARS design, a double-walled heat exchanger is used to provide the required tritium diffusion barrier. The construction, with two tubes in close contact, was shown in Fig. 4. A helium purge with 1 torr of oxygen pressure passes through the channels to provide an oxidizing atmosphere between the two tubes. The oxide films formed between the two tubes, as well as the oxide film on the water side, provide an effective diffusion barrier.

Figure 7 shows two tritium diffusion paths through the double-walled steam generator. This is an enlarged figure around one contact point between the tubes.

Path 1: Through wall 1, across the gap and through wall 2.

Path 2: Through the contact point.

TABLE 1. MARS Double-Walled
Steam Generator for 1 MW

	Preboiler	Boiler	Superheater
Q, MW	0.245	0.429	0.326
ΔT_1, °C	64	22	95
ΔT_2, °C	22	95	18
$\Delta T/m$, °C	39	50	46
h H_2O side, W/cm^2-°C	1.7	2.3	.17
h tube wall, W/cm^2-°C	1.7	1.7	1.7
h gap, W/cm^2-°C	1.4	1.4	1.4
h second wall, W/cm^2-°C	1.7	1.7	1.7
h LiPb, W/cm^2-°C	1.7	1.7	1.7
U, W/cm^2-°C	0.33	0.34	0.12
A, m^2	1.9	2.5	5.9
q", W/cm^2	12.9	17.2	5.5

<u>For MARS Q = 3360 MW</u>

A, m^2	6.4×10^3	8.4×10^3	1.98×10^4

Total area = 3.46×10^4 m^2

Average heat flux = 9.7 W/cm^2

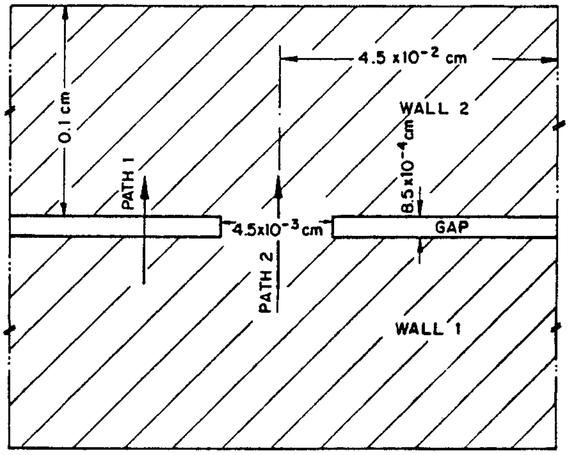
<u>Comparing to a single-walled steam generator</u>

U, W/cm^2-°C	0.48	0.52	0.14
Area, m^2	4.4×10^3	5.6×10^3	1.70×10^4

Total Area = $3.46 \times 10^4 m^2$

Average heat flux = 12.4 W/cm^2

To evaluate the effect of gap thickness δ on the permeation, a calculation is performed for a two zone diffusion problem in a plane geometry. The equations and boundary conditions are



TRITIUM DIFFUSION PATH

Fig. 7. Two tritium diffusion paths through the double-walled steam generator.

$$D_1 \frac{d^2C_1}{dx^2} - \frac{v}{\lambda} C_1 = 0$$

$$D_2 \frac{d^2C_2}{dx_2} = 0$$

at

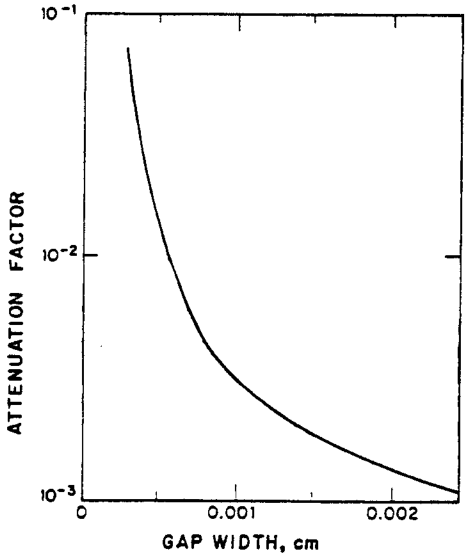
$$x = 0 \qquad -D_1 \frac{dC_1}{dx} = J_o$$

$$x = \delta \qquad -D_1 \frac{dC_1}{dx} = -D_2 \frac{dC_2}{dx} ,$$

$$K_s (C_1 RT)^{1/2} = C_2$$

$$x = L \qquad C_2 = 0$$

where indices 1 and 2 refer to the gap and tube wall zones, respectively; D - diffusion coefficient; K_s - solubility of T_2 in steel; λ - mean free path of T_2 and O_2 reaction; v - velocity of T_2; δ - gap width; R - gas constant; and T - temperature. With calculated parameters, the solution of the equations is easy to find, and we get the attenuation factor $P = J_o/J$, where J is the tritium current at x = L. Figure 8 shows the attenuation factor P as a function of the gap thickness δ with the thickness of wall tube being 0.1 cm.



ATTENUATION FACTOR DUE TO GAP

Fig. 8. Attenuation factor as a function of the gap thickness for a wall tube thickness of 0.1 cm.

The tritium permeation can further be reduced by oxidized layers attached to the tube wall surfaces. Suppose one oxidized layer can reduce the permeation through a steel wall by a factor of 1/f; this effect can be incorporated into the above calculation. The first oxidized layer at $x = 0$ reduces the current J_o to J_o/f, the next two layers at $x = \delta$ and L act as if the thickness of the tube wall is increased by a factor of $(2f - 1)$. Examining the solution of this problem, we get an approximate additional attenuation factor by these 3 oxidized layers in the form

$$F = \frac{1}{\sqrt{f}\,(2f - 1)} \quad .$$

The combined attenuation of the gap filled with oxygen and the oxidized layers is the product of the two. From this calculation an attenuation of 10^{-5} is possible with $\delta = 0.0025$ cm and $f = 14$. A single layer of oxide coating has an attenuation factor of a few hundred. Therefore, a combined attenuation factor of 10^{-5} is clearly available for diffusion across the gap.

A two-dimensional, finite difference tritium diffusion calculation was calculated for tritium leakage along path 2. The results depend strongly on the oxide condition around the contact point. If assuming an oxide layer exists in between the contact point, an attenuation factor of 10^{-6} is available. The total diffusion is the sum of the diffusion along these two paths. Therefore, a diffusion barrier factor $> 10^5$ is achievable.

CONCLUSION

A thermal, mechanical design of a double-walled steam generator is discussed. Double-walled design can be used to provide a required tritium diffusion barrier instead of a sodium intermediate loop, thus significantly simplifying the power cycle design. The preliminary tritium diffusion calculation shows that a diffusion barrier of $> 10^5$ is available. The diffusion barrier, however, strongly depends on the tube surface conditions and, therefore, has to be experimentally verified.

ACKNOWLEDGMENT

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