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A CONCEPT OF PWR USING PLATE AND SHELL HEAT EXCHANGERS

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ABSTRACT

In previous work it was verified the physical possibility of using plate and shell heat exchangers for steam generation in a PWR for merchant ships. This work studies the possibility of using GESMEX commercial of the shelf plate and shell heat exchanger of series XPS. It was found it is feasible for this type of heat exchanger to meet operational and accidental requirements for steam generation in PWR. Additionally, it is proposed an arrangement of such heat exchangers inside the reactor pressure vessel. Such arrangement may avoid ANSI/ANS51.1 nuclear class I requirements on those heat exchangers because they are contained in the reactor coolant pressure barrier and play no role in accidental scenarios. Additionally, those plates work under compression, preventing the risk of rupture. Being considered non-nuclear safety, having a modular architecture and working under compression may turn such architectural choice a must to meet safety objectives with improved economics.

1. INTRODUCTION

Previous work [1] studied the possibility of using plate and shell heat exchangers for steam generation in PWR, improving economics, compactness and weight, contributing to the economic feasibility of nuclear merchant ships.

Shipping was responsible for 2.7% of global CO2 emissions in 2007 [2], and it is responsible for 4 to 9% of global emissions of SOx and for 15% of global emissions of NOx [3].

Some advantages of nuclear power for merchant ships are: to reduce CO2 emissions; to reduce SOx emissions; to reduce frequency of oil spill at sea; to provide more stable prices for fuel. Taking into account that shipping is responsible by 95% of global commerce [4], it substantially impacts on economy and prosperity.

Some of major disadvantages of nuclear power for merchant ships are: high capital costs; uncertainties about nuclear safety regulation; need of specialized competencies [4].

A possible turnaround for some difficulties is to adopt PWR integral designs with generation IV passive safety. A great advantage of naval reactors over land nuclear power plants is the presence of a reliable heat sink - the sea.

In this context, the use of the more compact plate and shell heat exchangers (Figure 1) may help size and costs reduction, mainly at steam generation function. Previous work [1] had the limitation of being a theoretical study without consulting any supplier. In order to overcome this limitation, this work presents a PWR design using a commercial of the shelf heat exchanger assembly, taking into account one supplier. GESMEX's plate packs are fully laser welded and seem to be a good choice for present harsh environment.

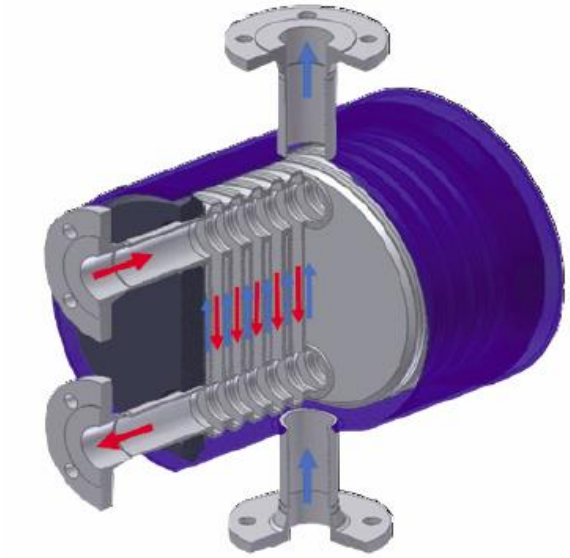

Figure 1 - Plate and shell heat exchanger

2. ASSUMPTIONS

This section lists a series of assumptions made in order to make this work applicable from the point of view of nuclear power plant vendors and merchant ships builders and operators:

- It is required a thermal power of 240MW from the reactor [1];
- The reactor should be integral type;
- It must be possible to realize periodic in service inspections;
- Only proven technologies may be employed;
- The overall cycle efficiency is 25%;
- The same core and core calculation assumptions from previous work [1];
- The base heat exchanger is the XPS 50 from GESMEX;
- The plate material is the steel alloy AISI 316L with 1,25mm thickness;
- The secondary pressure is 62,4 bar;
- The primary mean pressure is 148 bar and the mean temperature is 304ºC;
- Margin of 25% on the required heat transfer area is adopted;
- The heat exchangers adopt multiple passes in secondary side and single pass in the primary side;
- The heat exchangers are positioned in the vertical direction;
- In normal operation, the pressure difference between primary and secondary sides does not surpass 100 bar;
- The steam speed in pipes must not surpass 50 m/s and the water must not surpass 3 m/s;
- The feed water is near saturation;
- Functional segregation between power conversion function and emergency secondary heat removal function;
- A distance of 24 inches from the core is enough to prevent major fast neutrons damage to the plate packs;
- An array of heat exchangers may have problems of water carry over in case of trim conditions; and

•	In order to prevent water carry over it is necessary to assure the heat necessary to vaporize the entire mass flow is inferior to the heat exchange capability of the heat exchanger, even when the mass flow is enhanced by the hydrostatic force due inclination.

It was found steel alloy AISI 316L is the best option for this application, given the temperatures and pressure involved. However, it was necessary to reduce pressure and temperatures to be able to resist to primary pressure after a steam line break accident. The upper limit pressure for plate and shell heat exchanger is 150 bar [5].

3. METHOD

This work uses the same core analysis models as in previous work [1]. Reference heat exchangers were sized by GESMEX. Extrapolations were done where necessary. The pressure losses in primary and secondary sides are estimated by extrapolation from the reference heat exchanger. The extrapolation law adopted is:

$$\Delta p_1 = \Delta p_0 \left(\frac{N_1}{N_0}\right)^3 \left(\frac{\dot{m}_1}{\dot{m}_0}\right)^2 \left(\frac{D_0}{D_1}\right) \left(\frac{L_0}{L_1}\right)^2 \tag{1}$$

Where:
Δp = pressure loss
N = number of passes
$\dot{m}$ = mass flow
D = plate diameter
L = Heat exchanger length
Subscripts: 0 refers to reference heat exchanger and 1 to estimated heat exchanger.
The pressure losses are calculated to know if they are sufficiently low in the primary side and sufficiently high in the secondary side to prevent water carry over in case of inclined conditions.

4. DEVELOPMENT

4.1. Core Sizing

The first step is to estimate a core able to provide the power needed. This was done by reusing the same core of previous work [1].
As temperature and pressure needed to be reduced to allow the heat exchangers resist a steam line break accident, minimum core flow and temperature difference between cold and hot legs were recalculated to respect the minimum departure from critical heat flux ratio.
With the core size and assumptions on spacer grids, it was estimated the core charge losses.

4.2. Steam Generator Sizing

From reactor thermal power and water latent heat, it is estimated the steam mass flow. With the mass flow and maximum flow speed in pipes, it is estimated a minimum pipe diameter and it is chosen a commercial diameter along its schedule (wall thickness). From the core diameter and pipes chosen diameter, it is estimated the annulus internal diameter.
From a reference GESMEX heat exchanger calculated for a similar application, with close pressures and temperatures, it was calculated the power density. With total power and power density, it is calculated the total volume of heat exchangers.
Adopting three rows of XPS 50 heat exchangers, as shown at Figure 2, it was obtained the required number of heat exchangers with a margin of 9 heat exchangers. Dividing the total flow by the number of heat exchangers, it was obtained primary and secondary flows for each

heat exchanger. From total volume of heat exchangers, XPS diameter and number of heat exchangers it is calculated the heat exchangers length. For arrangement reasons, it was adopted cells of 42 centimeters diameter (the plate pack has 36 centimeters diameter) in order to include space for flow directors and structures.

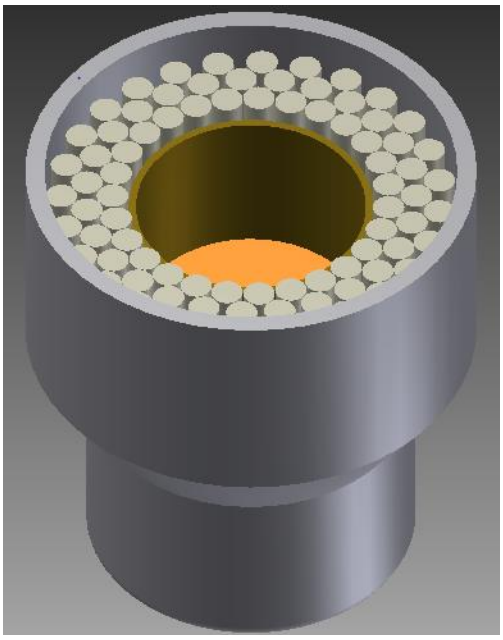

Figure 2 - Reactor configuration and steam generation heat exchangers arrangement

It is adopted a configuration with both inlet and outlet at upper part in order to ease maintenance activities, as shown at Figure 3.
In order to prevent water carry over during startup or small power operation, it were adopted 3 passes in the secondary side (Figure 3), so liquid water is kept far from outlet nozzle and needs to travel through a entire pass, provided liquid level is lower than two thirds of heat exchanger height.
The plate packs are placed in cells which act as flow directors for the primary coolant fluid. The shell is the reactor pressure vessel itself. Both steam and feed water flanges are linked to pipes which lead to headers located right above the plate packs.

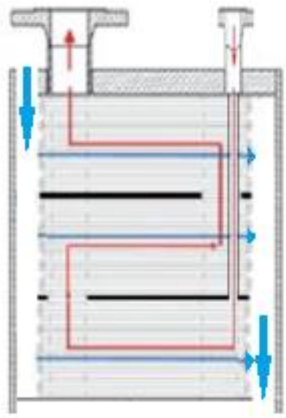

Figure 3 - Heat exchanger arrangement

It was also verified if, in case of inclination of the reactor, it is possible to have water carry over in any heat exchanger because of the added head due gravity, which would cause a greater flow in the lowest heat exchanger. It was found that this may really happen, but by taking appropriate measures it is possible to prevent this problem. Those measures include:

- Increasing pressure loss in secondary side of heat exchangers;
- Imposing a margin in steam superheating (or heat transfer surface); and
- Limiting ship inclination angles.

It was found that for a 45º angle from vertical, heat exchangers with 3 passes and a margin of 21% in heat transfer area, there should be not water carry over problems.

4.3. Steam Generator Safety Function

Typically in stationary PWR, the steam generators play a dual role: they generate steam to be used on power conversion system and in case of design basis accidents, they play the emergency secondary heat removal function, according with ANSI/ANS 51.1 (1988).
This solution imposes constraints in design and operation of steam generators, like the number of two or more steam generators, periodic inspections, material classification, segregation, redundancy and independency requirements.
If the safety function of emergency secondary heat removal is played by other equipment, not used during normal operation (adoption of functional segregation), the steam generator used for power conversion does not need to be redundant nor classified, provided its failure do not impair the safety functions.
The typical steam generators tubes are a part of the reactor coolant pressure barrier, so they need to be classified as class 1, as defined by ANSI/ANS 51.1 (1988). It means their failure cause loss of coolant accidents, so there is not great advantage in functional segregation because they need to be class 1 anyway. It has to be noted the constant operation has wear and tear effects on the tubes, regardless of the class.
But, if the plate packs of the heat exchangers are place inside of the reactor pressure vessel (Figure 4), their failure does not impair the capability of the reactor coolant pressure barrier of containing the coolant, provided the steam and feed water lines are parts of the reactor coolant pressure barrier. So, their failure potentially causes only limited coolant leakages affecting the plant availability, but not the plant nuclear safety.
The safety steam generators could be a non-pressurized tank with a heat exchanger inside. The drive for the coolant flow inside the heat exchanger must be gravity according with ANSI/ANS 51.1 (1988). This circuit should only be pressurized for tests and accidental situations. Figure 4 presents a diagram of this solution, which is quite similar to IRIS [6].

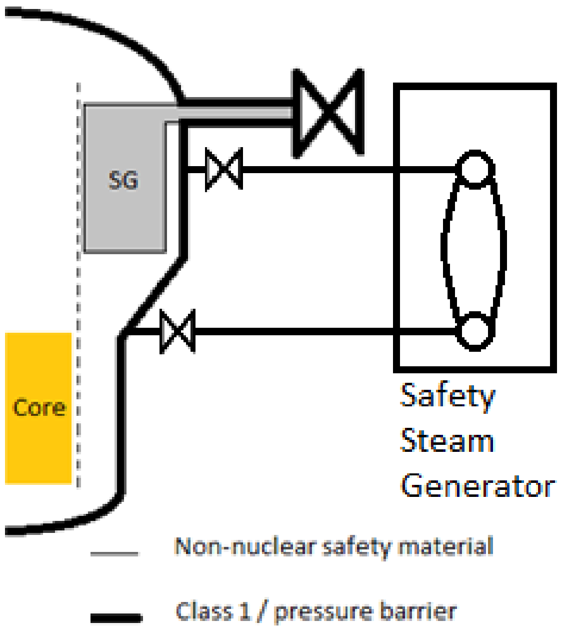

Figure 4 - Steam generators inside reactor coolant pressure barrier

If the plates work in compression by primary fluid, which precludes cracking propagation, the catastrophic failure becomes virtually impossible and only small leakages may happen with a frequency above that allowed for design basis accidents by ANSI/ANS 51.1 (1988). In this case, the association of a steam generator for power conversion and other two small steam generators used only for design basis accidents scenarios may be safer than current practice, once those safety steam generators will not suffer corrosion wear during service life.

5. RESULTS

The core for the required power has the following characteristics (Table 1):

Table 1 – Values obtained for the 240MW core

Nuclear reactor characteristics	Value	Unit
Number of fuel elements	137	
Number of tubes per fuel element	289	
Percentage of fuel rods	90,25%	
tubes external diameter	0,0098	m
Fuel rods length	2,11	m
Element width	0,2207	m
Core diameter	3,04	m
Minimum Departure from Nucleate Boiling Ratio at hot channel	2,17	
Output temperature	318,6	ºC
Delta T	28,6	ºC
Hot leg Subcooling margin	22,4	ºC
Coolant mass flow	1710	kg/s
Pressure loss at Reactor	4073	Pa

The final values obtained for the characteristics of the heat exchangers are presented at Table 2.

Table 2 - Description of heat exchangers adopted

Steam generator array	Value	Unit
Reference power density	1,27E+07	W/m^3
Inner diameter	3,64	m
Assumed number of heat exchangers	67,00	
Heat exchanger margin	25%	
Total volume of heat exchangers	16,08	m^3
Volume for each heat exchanger	0,24	m^3
Plate diameter	0,36	m
Heat exchanger length	2,36	m
Number of secondary passes	3	
Number of primary passes	1	
Power for each heat exchanger	4,48E+06	W
Primary flow for each heat exchanger	25,52	kg/s
Secondary flow for each heat exchanger	2,83	kg/s
Secondary pressure loss	33539	Pa
Primary pressure loss	4444	Pa

The secondary water chemical treatment should take EPRI guidelines [7] for once through steam generators, summarized in Table 3. According with the supplier, any water chemistry that does not harm the steel alloy 316L is good enough. However, EPRI guidelines indicate that the steam from once through steam generators tend to carry over solid corrosion products, causing turbine erosion. Therefore, chemistry is not limited by the plates, but by the turbine.

Table 3 – Chemical parameters for the secondary water

Parameter	Maximum Value	Unit
Sodium	1	ppb
Chloride	3	ppb
Sulfate	1	ppb
Silica	10	ppb
Total Iron	5	ppb
Oxygen	5	ppb

6. DISCUSSION

Those results are not best estimate calculations. They are conservative calculations to allow demonstration of feasibility. This work included other aspects, like chemistry, fabrication, and inspection in service. Fabrication is assured by the fact this heat exchanger is a commercial of the shelf solution. Chemistry in primary and secondary water is not limited by the plates but by turbine blades. The secondary water chemistry has limitations because the solid particles cause corrosion on turbine blades. According with EPRI once through steam generator plants should be operated with the lowest practicable impurity levels consistent with their secondary system design.

It is certainly possible to inspect the state of the plates using proper tools and the modular architecture eases the identification of the position of leakages. For instance, if there is a leakage, it is possible to identify the leaky heat exchanger by pressurizing the steam line with nitrogen while the vessel is open to atmosphere and filled with coolant. The heat exchanger with the leak should release bubbles which are easily noted by operators. Then it is simple to replace an entire heat exchanger.

7. CONCLUSIONS

The use of plate and shell heat exchangers for steam generation a reactor vessel is demonstrated feasible and more compact than other solutions. With functional segregation between the power conversion function and emergency secondary heat removal function, which allows employing industrial standards in the power conversion function, it is possible to make the emergency secondary heat removal function more reliable by avoiding corrosion wear during the service life.

However, as the power conversion function is a part of the first level of defense in depth, it shall be able to assure it does not cause accidents frequently. This is achieved by keeping the steam generators plates under compression, so there are not crack propagation and pipe ruptures. Only leakages and collapses may occur, which, if frequent, does not cause safety problems, but only plant availability problems.

Another aspect for future work is the sizing and modeling of the safety steam generators, along its application in the design basis accidents.

ACKNOWLEDGMENTS

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