High Pressure Boiling Water Reactor

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Abstract. Some four hundred Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR) have been in operation for several decades. The presented concept, the High Pressure Boiling Water Reactor (HP-BWR) makes use of the operating experiences. HP-BWR combines the advantages and leaves out the disadvantages of the traditional BWRs and PWRs by taking in consideration the experiences gained during their operation. The best parts of the two traditional reactor types are used and the troublesome components are left out. HP-BWR major benefits are;

1. Safety is improved; -Gravity operated control rods -Large space for the cross formed control rods between fuel boxes -Bottom of the reactor vessel is smooth and is without penetrations -All the pipe connections to the reactor vessel are well above the top of the reactor core -Core spray is not needed -Internal circulation pumps are used.

2. Environment friendly; -Improved thermal efficiency, feeding the turbine with ~340 °C (15 MPa) steam instead of ~285 °C (7MPa) -Less warm water release to the recipient and less uranium consumption per produced kWh and consequently less waste is produced.
3. Cost effective, simple; -Direct cycle, no need for complicated steam generators -Moisture separators and steam dryers are inside the reactor vessel and additional separators and dryers can be installed inside or outside the containment –Well proved simple dry containment or wet containment can be used.

1. INTRODUCTION

Now the time has come to move a step further and develop an improved type of power reactors. Common sense, public confidence and economic considerations demand that this new design should not be a big leap from the presently functioning devices; however it should be a significant improvement. Therefore it is important to avoid those parts of the older designs which have caused trouble in the past e.g. PWR steam generators, BWR perforated reactor vessel bottoms and instead rely only on a stable construction with proven components which served well in the past. The High Pressure – Boiling Water Reactor, HP-BWR (Figure 1) attains these goals, by partly using the PWR concept, i. e. the pressure vessel, the electro-magnetic control rod operator, and partly the BWR concept, i. e. core internals, internal circulation pumps and steam and moisture separators. All the figures here are made by the combination of CAD models of existing BWRs and PWRs. The subject was introduced by the European Nuclear Society ENS as is given in the References [1] to [4]

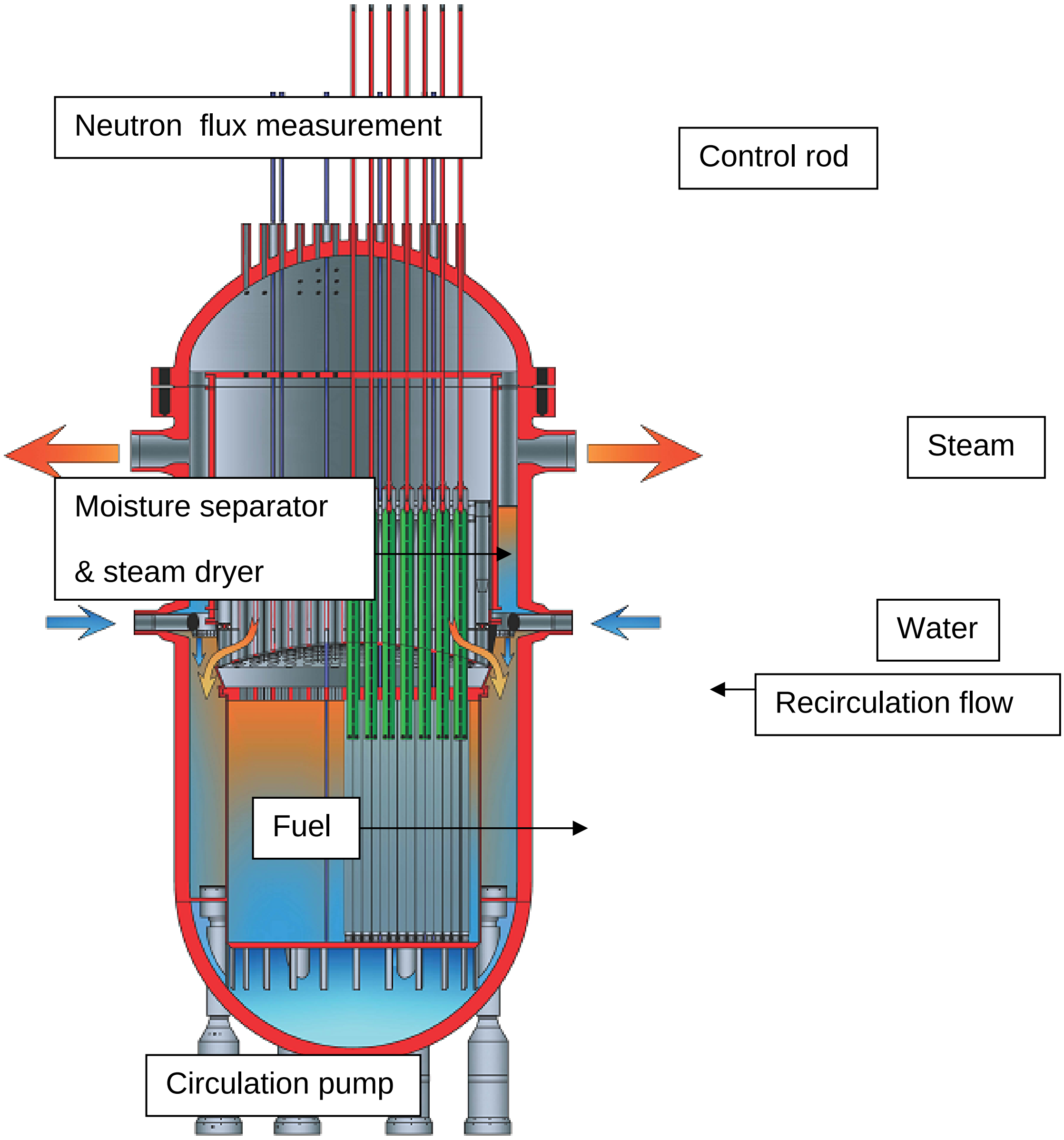

Fig. 1. HP - BWR

2. SAFETY IS APPROVED

The control rods are gravity operated instead of be operated by an intricate hydraulic system. The gravity operated control rod system has served well in PWRs. The stems are introduced into the reactor vessel via the vessel head (Fig. 2.).

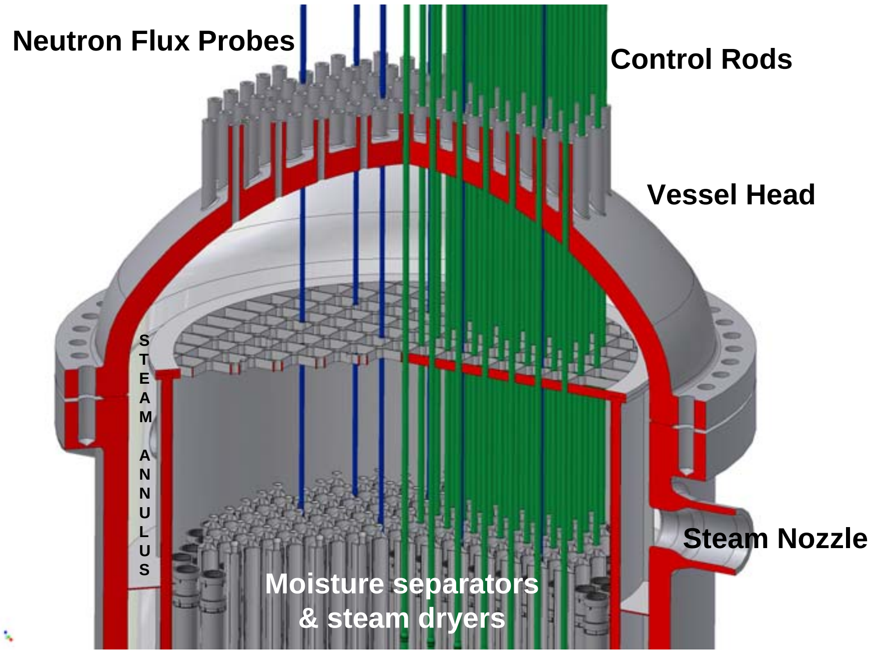

Fig. 2. Vessel head

The control rods (Figure 3) themselves are in the form of a cross, as it is in the BWRs. This assures large space for the cross formed rods between the BWR type fuel boxes. Also the neutron measurement sounds are introduced via the reactor pressure vessel head the way it is used in BWRs.

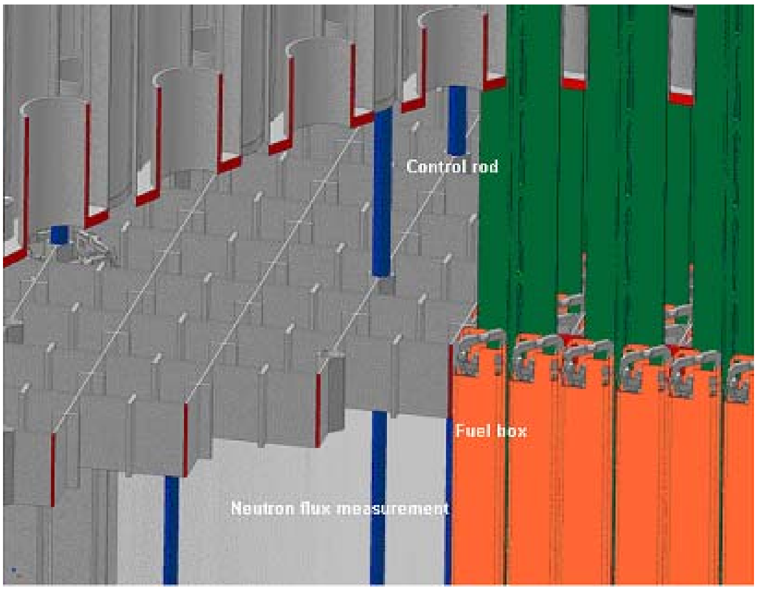

Fig. 3. Control Rods

The bottom of the reactor vessel (Figure 4) is now smooth without numerous control rod penetrations, a great advantage compared with the previous BWR designs.

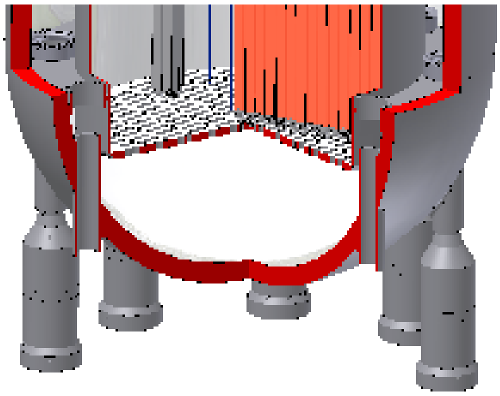

Fig. 4. Bottom of the reactor vessel

All reactor vessel penetrations corresponding to different pipe connections are well above the top of the reactor core. This means that a major pipe break will not uncover the reactor core. Therefore a core spray system is not needed. In Sweden, for example, after the approval of the safety authority, the core spray system has been removed in all internal pump BWRs and has been replaced by high pressure direct water injection in the Downcomer. Detailed studies of this subject are available at the Swedish Radiation Safety Authority.

Internal circulation pumps, located inside the reactor vessel and at the bottom of the Downcomer, are used to assure hydrodynamic stability. In this way the orifices at the fuel channel inlets are chosen so that the one phase pressure drop will dominate over the two phase pressure drop to avoid hydrodynamic oscillations. By utilizing natural circulation one could omit the circulation pumps. However the margin to avoid hydrodynamic oscillations may be reduced. This is an experience gained at several Boiling Water Reactors and a phenomenon studied at thermal hydraulic loops at research institutes, universities and manufacturers

3. THERMOHYDRAULIC CONSIDERATIONS

A thermal design criterion for a PWR reactor core is the limit in the fuel temperature (melting point of UO_2 about 2800 °C), being the design temperatures 2000 °C at rated power and 2350 °C at a maximum linear fuel rating of 54 kW/m (see reference [5]). According to this criterion, recent PWR cores have an average linear fuel rating of 17.9 kW/m and maximum linear fuel rating of 44 kW/m. For a BWR, the maximum allowable temperature at the center of a fuel rod is 2500 °C in an emergency and 1850 °C during normal operation (see referemce [5]).

Following this criterion, a HP-BWR with a thermal power of ~2700 MW, and an electrical power output of ~1000 MW, may have a core with an average linear fuel rating of 13.6 kW/m and a maximum linear fuel rating of 44 kW/m. Without any fuel modifications, the temperature at the center of a fuel rod during normal operation is slightly higher and has been estimated to be 1885 °C. The maximum temperature of the Zircaloy-2 fuel cladding is around 491 °C, which is lower than the allowed maximum temperature of 550 °C.

A detailed comparison of the HP-BWR concept with modern PWRs and BWRs is given in refence [5]

The HP-BWR has further advantages, namely improved thermal efficiency due to higher temperature and further improved inherent stability due to increased negative power reactivity coefficient. Table 1 shows a comparison - calculated with the RELAP5 (Mod3.3 Patch02) and PARCS codes - between a BWR and a HP-BWR. (see Table 1.)
Table 1. Comparison between BWR and HP-BWR, calculated with the RELAP5 (Mod3.3 Patch02) and PARCS codes.

	BWR	HP-BWR
Feed water temperature	486.6 ^{0}K	486.6 ^{0}K
Outlet void temperature	559^{0}K	617.8 ^{0}K
Pressure in the steam dome	7 MPa	15.5 MPa
Inlet temperature to the core	550.29 ^{0}K	582.3 ^{0}K
Inlet core quality	-3.909E-02	-0.254
Outlet quality from the core	0.128	0.323
Total Mass Flow Rate from the core	13634 [kg/s]	5955 [kg/s]
Total Mass Flow Rate in the steam lines	1795 [kg/s]	2026 [kg/s]
Total Mass Flow Rate through the pumps	13634 [kg/s]	5955 [kg/s]
Total Power Coefficient	-1.64e-4[Δk/%]	-4.4e-4Δk/%

The axial power distribution calculated with the RELAP5 (Mod3.3 Patch02) and PARCS codes, is similar in both types. See figure 5

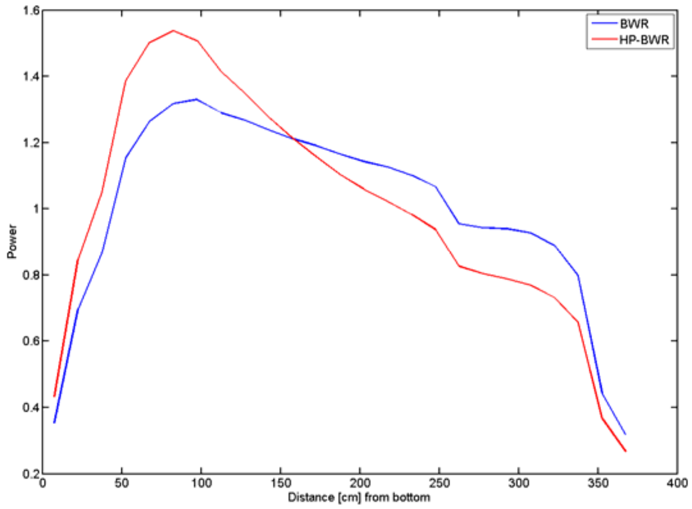

Fig. 5. Axial power distribution in HP-BWR and BWR, calculated with the RELAP5 (Mod3.3 Patch02) and PARCS codes

Ever since the onset of the nuclear power era, negative power coefficient is seen as a virtue, because it means that the reactor will close itself at a perturbation even without the use of the control system. This gives assurance both for the nuclear engineer and the public that the security of using the reactor is satisfactory. After the run away Chernobyl accident the value of the negative power coefficient is even more accentuated. The HP-BWR has a more negative power coefficient (pcm/%) then the traditional BWR and PWR..

At 150 bar the gradient on the saturated water density vs. saturation temperature curve ($kg\cdot m^{-3}/^0C$) is steeper than at 70 bar (the derivative is more negative), resulting in a more negative moderator temperature coefficient ($pcm/^0C$). Se Figure 6.

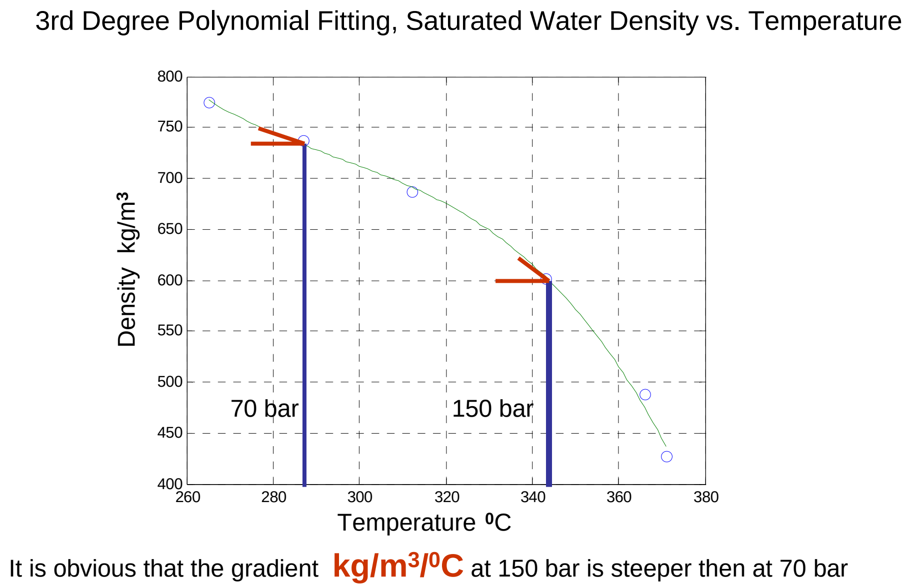

Fig. 6. Saturated water density curve, the derivative is more negative at 150 bar than at 70 bar

The value of the negative void coefficient (pcm/%) is about the same for both types of reactors. However the control algorithm for the pumps' speed and for the control rods' movement might be necessary to be modified compared with the traditional BWR.

Thermalisation of the fission neutrons is successfully accomplished at 150 bars in the traditional Pressurized Water Reactors. PWRs contain not only water, at about a mere ~20 ^{0}C below saturation temperature, but also a lot of bubbles, due to sub cooled boiling.

"Simple is beautiful". As 150 bar is far away from the critical pressure (~214 bar) the design is simple and thereby safer and more economic.

In Figure 7 the results of transient calculations made with the MATLAB code shows the HP-BWR long term stability without the use of any control system. BWRs are operated in the under moderated condition and have, therefore, a strongly negative void coefficient of reactivity. This coefficient is a function of the core design, void location and void volume that can be adjusted to an appropriate magnitude when the operation pressure is increased from 7 MPa to 15 MPa.

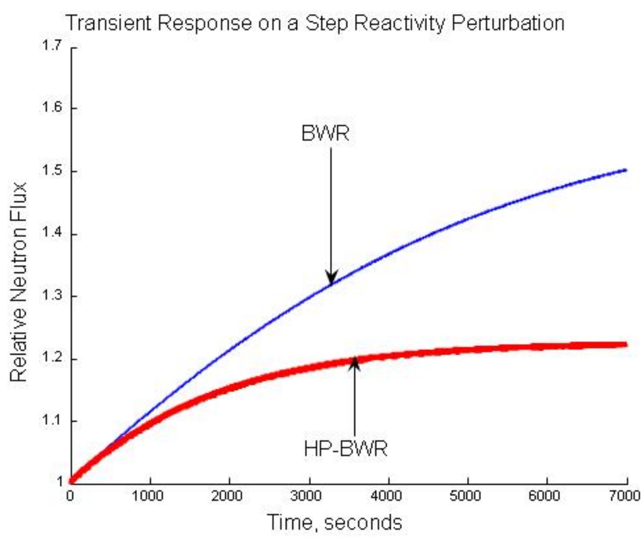

Fig. 7. Long term stability without the use of any control system calculated with the MATLAB code (inherently stable reactor)

4. ENVIRONMENT FRIENDLY

Improved thermal efficiency is attained by feeding the turbine with steam at 343°C (~15MPa) instead of 286 °C (~7MPa). A rough estimate of the efficiency may be obtained through a calculation of the Carnot cycle theoretical efficiency (T_{Hot} - T_{Cold})/ T_{Hot}. This gives for a BWR ~ 46 % and for the HP-BWR ~ 51 % at T_{Cold} = 300 K, i.e. an increase by a factor of 1.109. Assuming the same improvement ratio, today's efficiency of ~ 33 % would increase to ~ 37 %, which is supported by the analysis that follows of the Rankine cycle efficiency (see Reference [5]).
The same results are obtainde with a separate Rankine cycle calculation which is given in Reference [5]. This underlines the advantage of the HP-BWR which utilizes the fuel more efficiently and releases less warm cooling water to the environment per produced kWh and consequently produces less waste. There are several conventional thermal power plants with 15 MPa turbines.

5. COST EFFECTIVE, SIMPLE

The HP-BWR operates in direct cycle mode, with no need for complicated and expensive PWR steam generators and also instead of the rather complicated BWR reactor pressure vessel bottom, a simplified one is used. The main steam separators are inside the pressure vessel and secondary separators and dryers can be installed outside the reactor vessel, inside or outside the containment. The containment can be a simple dry containment (Figure 8) which allows easy entrance and inspections and also minor repairs during operation.

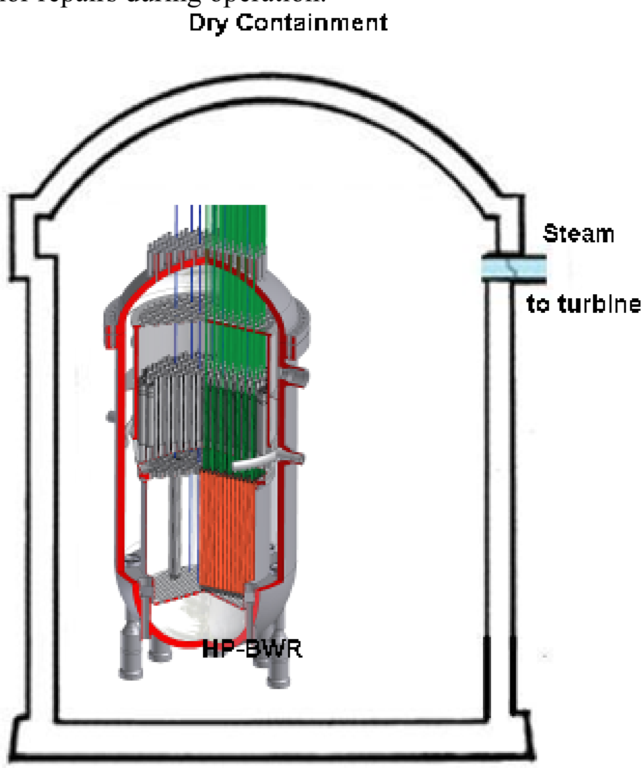

Fig. 8. HP-BWR in a dry containment

Naturally the HP-BWR fits into a usual wet containment too. Also when considering the refurbishment of an old BWR the HP-BWR fits into the picture. Se Figures 9 and 10.

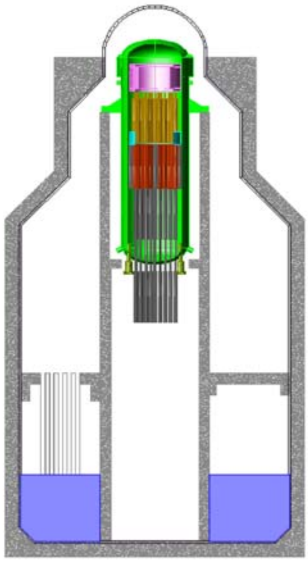

Fig. 9. The closed Barsebäck BWR

There is a suggestion to refurbish Barsebäck with a HP-BWR, granted the aproval of the Swedish and Danish people.

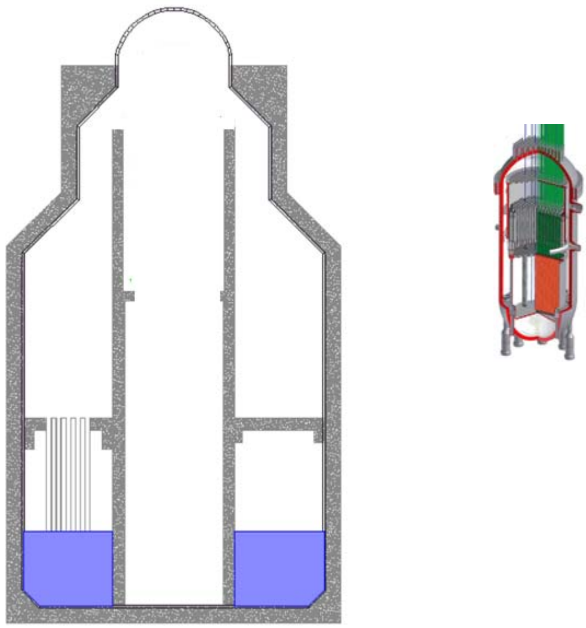

Fig. 10. Proposal to refurbish Barsebäck with a HP-BWR

6. CONCLUSION S AND DISCUSSION

In the present work, a concept of a High Pressure BWR, which combines several advantages and avoids some weaknesses of conventional BWRs and PWRs, has been discussed and analyzed. However, some clarifying remarks should be added to complete this analysis.

The author is convinced that the experience gained during so many years of operation of conventional light water reactors constitutes an unprecedented source of knowledge that new reactor concepts lack to a large extent. Conventional light water reactors may still be redesigned and optimized based on this knowledge, and the present concept represents a clear example of these possibilities. Knowing how the different materials behave under the prevailing reactor conditions and how to design the different components (the reactor vessel, the control rods etc.) from a structural mechanics point of view are examples of the advantages of using a reliable technology.

The HP-BWR concept also implies higher pressure and temperature for the turbine-generator plant then for the traditional BWRs and PWRs. Modern conventional thermal power plants with supercritical steam/water conditions (25 MPa and 560 °C) are generally employed, This indicates the possibility of developing a steam cycle that could fit the steam conditions delivered by the HP-BWR. Finally the question arises of why the present concept of increasing the pressure and temperature of a BWR has not been considered before by the industry. The interest of the industry in lowering the costs by increasing the total power of the reactor, not by increasing its efficiency, may have played a part in this issue. Probably it was estimated in the past that an efficiency increase do not justify the necessary design and licensing efforts. Now, with arising environmental requirements, the industry may be willing to consider this alternative.

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IAEA

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