CORE DESIGN CONCEPTS FOR HIGH PERFORMANCE LIGHT WATER REACTORS

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Light water reactors operated under supercritical pressure conditions have been selected as one of the promising future reactor concepts to be studied by the Generation IV International Forum. Whereas the steam cycle of such reactors can be derived from modern fossil fired power plants, the reactor itself, and in particular the reactor core, still need to be developed. Different core design concepts shall be described here to outline the strategy. A first option for near future applications is a pressurized water reactor with 380°C core exit temperature, having a closed primary loop and achieving 2% pts. higher net efficiency and 24% higher specific turbine power than latest pressurized water reactors. More efficiency and turbine power can be gained from core exit temperatures around 500°C, which require a multi step heat up process in the core with intermediate coolant mixing, achieving up to 44% net efficiency. The paper summarizes different core and assembly design approaches which have been studied recently for such High Performance Light Water Reactors.

KEYWORDS : Supercritical Water Cooled Reactor, Core Design, Generation IV

1. INTRODUCTION

Pressurized water reactors (PWR) and boiling water reactors (BWR) have been among the most successful nuclear reactors during the last 40 years. More than 270 PWR have been built up to now, of which the latest ones reach a net electric power output of 1600MWe and a net efficiency of 36%. With 93 units built, the BWR had almost been as successful, even though power and efficiency levels were somewhat lower. Both reactor types are using a saturated steam cycle of around 7MPa live steam pressure, corresponding with a boiling temperature of 286°C. These live steam conditions, however, are still almost the same as those used in the 1960ies. Little improvements in cycle efficiency had primarily been due to better steam turbine blades only. On the other hand, fossil fired power plants have increased their efficiencies significantly since then. Steam has been superheated, and live steam temperatures and pressures have been increased stepwise to 600°C and 30MPa, respectively. Since around 1990, all new coal fired power plants have been using supercritical steam conditions, reaching more than 46% net efficiency today. As a consequence, the application of such steam cycle technologies to light water reactors could offer a huge potential for further improvements.

The general advantages of such High Performance Light Water Reactors (HPLWR) are first of all a higher steam enthalpy at the turbine inlet, which does not only increase efficiency and thus reduces fuel costs, but also reduces the steam mass flow rate needed for a target turbine power. This lower steam mass flow rate reduces the turbine size as well as the size of condensers, pumps, pre-heaters, tanks and pipes, and thus the costs of the overall steam cycle. As the capital costs of nuclear power plants are usually higher than their fuel costs, this latter advantage has even a higher impact on electricity production costs than efficiency. Even more cost advantages are expected from plant simplifications such as missing steam separators or primary pumps in case of a direct steam cycle at supercritical pressures. Another advantage of using supercritical water in a nuclear reactor is that a boiling crisis will physically be excluded, which adds a new safety feature to this design.

On the other hand, supercritical water introduces some new challenges compared with a conventional PWR or BWR. Aiming at steam temperatures similar to those achieved in fossil fired power plants, density differences of the coolant in the core will exceed those of a BWR, resulting in a lack of moderator at steam temperatures beyond the pseudo-critical point of water (e.g. 384°C at 25MPa). Additional moderator needs to be added to obtain a thermal neutron spectrum, or the core design may even be designed for a fast neutron spectrum instead. The hotter coolant will result in hotter cladding temperatures of fuel pins, such that stainless steel or even high temperature alloys will be needed instead of Zircalloy. Finally, the enthalpy rise in a boiler of a fossil fired power plant is more than ten times higher than the enthalpy rise in a PWR or BWR. A more sophisticated core design will be needed to avoid hot spots caused by a non-uniform power profile or by uncertainties and allowances for operation.

The following chapters will summarize different design concepts which have been developed up to now to meet these challenges. The primary focus will be on thermal reactor concepts, but the additional challenges of a fast neutron spectrum shall also be discussed.

2. FUEL ASSEMBLY DESIGN CONCEPTS

First design studies had concentrated on a suitable assembly design to optimize the axial power profile under the constraint of larger coolant density differences in the core. Based on some early core design concepts studied since the 1960ies, significant new design work has been performed in the 1990ies at the University of Tokyo, initiated by Oka and Koshizuka [1]. A first fuel assembly design for a thermal neutron spectrum, with additional water rods flattening the axial power profile, has been presented by Dobashi et al. [2]. They used a hexagonal arrangement of fuel pins cooled by rising coolant which were housed in an assembly box like in a BWR. Additional moderator needed near the top of the core was provided by water tubes inside this assembly through which feed water was flowing preferably downwards to be mixed with additional feed water at the core bottom. These water tubes were thermally insulated to minimize heat up of the moderator water by the hotter coolant. Control rods could be inserted from the top into these water tubes. Squarer et al. [3] used this assembly design concept as a reference for their first HPLWR concept, but concluded that the radial power distribution was still rather non-uniform, requiring different enrichments in several fuel pins to homogenize the coolant heat up. A square fuel pin arrangement with up to 36 additional square water tubes, providing the moderator for the upper part of the core, could solve this issue. It has been presented by Yamaji et al. [4]. A similar design, but with 25 square water tubes, as well as an improved hexagonal assembly, served as an option for HPLWR core design studies by Cheng et al. [5]. Buongiorno [6] tried to avoid the additional complexity of water rods inside the assembly by selecting smaller, hexagonal assemblies with 19 fuel pins each, which were moderated by water in gaps between the assembly boxes. The inner fuel pin, however, turned out to be under-moderated again so that a higher enrichment became necessary. Larger assemblies with quite uniform power distribution were proposed by Joo et al. [7] who compensated the missing moderation of the coolant by adding cross shaped zirconium hydride rods to the assemblies. Control rods were assumed to run inside these ZrH rods. Hofmeister et al. [8] tried to combine and optimize these concepts in a design study performed under the constraints that each fuel pin should be next to any moderator water, the moderator to fuel ratio should be close to a PWR to optimize the power density, and the ratio of structural material to fuel should be minimum to minimize fuel enrichment. Their result was a square arrangement with 40 fuel pins and with a single water tube in each assembly, similar to a BWR assembly. Different from BWR design, however, cross shaped control rods were assumed to be inserted from the core top into the water tubes. As such small assemblies would require a large number of individual control rod drives, 9 of these assemblies have been combined to an assembly cluster with a common head and foot piece, shown in Fig. 1, which will also ease handling during revisions.

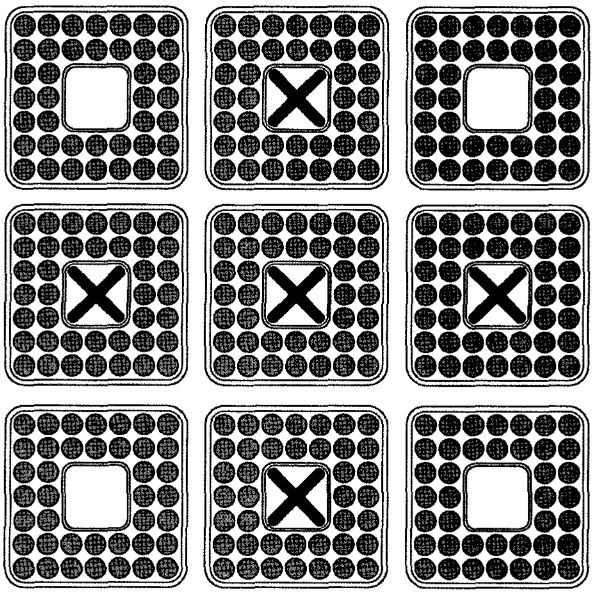

Fig. 1. Cross Section of the HPLWR Fuel Assembly Cluster with Water Tubes and Control Rods, Hofmeister et al. [8]

The fuel considered for each of these thermal assembly design studies is UO_2 with an enrichment ranging from 5%, e.g. in the analyses of Waata et al. [9] for the assembly design of Hofmeister et al. [8], up to 7% like in the assembly design of Buongiorno et al. [6]. Fuel pin diameters being proposed up to now range between 8 mm outer cladding diameter as proposed by Squarer et al. [3] and 10.2 mm like in the assembly design by Yamaji et al. [4]. Whereas these data are still close to a conventional PWR design, the pitch of the fuel pins needs to be significantly smaller to provide sufficient coolant mass flux for the envisaged heat transfer, despite the significantly smaller coolant mass flow. In a parametric study by Cheng et al. [5], the pitch to diameter ratio has been varied systematically to yield a minimum of cladding temperatures at a ratio of 1.15 for square arrangements and at 1.3 for hexagonal arrangements. Yamaji et al. [4] were using even a smaller ratio of less than 1.1 for their square fuel pin arrangement to minimize the peak cladding temperatures. Heat transfer studies by Behnke et al. [10] indicate, however, that such small distances between fuel pins could be risky with respect to thermal-elastic instabilities caused by any non-uniformities of the cladding temperatures and by the fuel pin bending resulting from them.

An alternative to a smaller pitch of the fuel pins could be an artificial surface roughness of claddings, such as used for gas cooled reactor studies in the past, or even a cross flow or swirl flow trough the assemblies. Bastron et al. [11] propose some innovative ideas with this respect. They show that the heat transfer coefficient can be doubled compared with an axial flow along smooth claddings, resulting in around 50°C smaller cladding surface temperatures at the same mass flow. Moreover, improvements of the coolant mixing inside the assemblies can be expected. A disadvantage of these proposals, however, is an increase of pressure drop of the coolant by about a factor of 8.

The maximum cladding surface temperature to be allowed for operation will depend on the cladding material selected. First tests with Zircalloy indicated that rather other alloys with higher creep strength and with better corrosion resistance will be required to reach coolant temperatures beyond 500°C. Stainless steels such as SS316 or 1.4970 which were used for sodium cooled reactors in the past would be suitable candidates with sufficient creep strength up to 620°C and acceptable neutron embrittlement, as summarized by Ehrlich et al. [12]. Stainless steels and ferritic-martensitic steels were successfully tested with respect to their corrosion resistance under supercritical water conditions, as summarized by Was and Allen [13]. Recent stress corrosion crack (SCC) data by Was et al. [14], however, still left some concern at 550°C which will require further test beyond 600°C. Inconel such as IN690 or IN625 showed a smaller crack depth, but irradiated IN690 showed recently even larger SCC cracks than SS316 as reported by Teysseyre et al. [15]. This fact and the higher neutron absorption cross sections are making Inconel less favourable than stainless steels. There is some hope that oxide dispersed strengthened (ODS) materials might enable to design for cladding temperatures beyond 620°C, but further material tests will be necessary to verify this assumption.

As boron acid cannot be used for burn-up compensation in a direct steam cycle, a higher neutron absorption than in a PWR needs to be foreseen in control rods. They were assumed to be made of natural boron-carbide (B_4C) in the study of Yamaji et al. [4]. In addition, burnable poisons can be used for compensation of the initial excess reactivity. Joo et al. [7] as well as Yamaji et al. [4] propose to use Gadolinia (Gd_2O_3) in some of the fuel rods for this purpose.

The complexity of additional moderator needed at lower coolant densities can be overcome if a fast or epithermal neutron spectrum is assumed. Addition of plutonium to the UO_2 fuel, with a concentration up to 25%, would be required to reach criticality but, on the other hand, more plutonium would be produced during burn-up, which leads to a sustainable fuel cycle if this plutonium will be recycled in a reprocessing plant. Early design studies have been published already in 1995 by Oka et al. [16] showing indeed advantages compared with the thermal option. This initially fascinating concept, however, has been restricted by the risk of negative reactivity coefficients of the coolant density. Recently, Mori [17] published a comprehensive core design study for such a supercritical water fast reactor. Several different arrangements of seed zones, breeding zones and ZrH moderator pins in a hexagonal arrangement have been tried, but the risks of negative density coefficients could not yet be excluded for sure.

3. CORE DESIGN CONCEPTS

The higher enthalpy rise of the coolant would not matter if it were uniform in the entire core. This, however, can never be fully achieved. Fuel composition and distribution, water density distribution, size and distribution of sub-channels, neutron leakage and reflector effects, burn-up effects, effects of control rod positioning or effects due to the use of burnable poisons will influence the radial power profile of the core. Material uncertainties, fluid properties, uncertainties of the neutron physical modelling, heat transfer uncertainties, uncertainties of the thermal-hydraulic modelling, scattering of the inlet temperature distribution, manufacturing tolerances, deformations during operation, or measurement uncertainties will cause a statistical scatter of the enthalpy rise. Finally, some small but allowable transients might be caused by control of power, coolant mass flow, core exit temperature and pressure. Schulenberg et al. [18] estimate that a total hot channel factor of 2 should be multiplied with the average enthalpy rise, as a first guess, to yield the maximum, local enthalpy rise under worst case conditions. An analogue problem is also known from boiler design of fossil fired power plants. It has been solved there by splitting the total enthalpy rise into an evaporator and two successive superheaters, and by mixing the coolant homogeneously between each of these components. Next, we will show some examples of how the HPLWR design can accomplish this issue.

Core design concepts, which are under discussion today, can be classified basically by their flow path. We differ between a single, two, or three pass core concept, depending on the change of flow direction during heat up of the coolant. The systematic is sketched in Fig. 2.

The single pass core concept assumes a feed water supply at the core bottom and a hot coolant release at the top like in a PWR. If the coolant is pre-heated by downward flow in some assemblies of a two pass core concept, the mixing plenum below the core can be used to mix coolant non-uniformities before the second heat-up step with upward flow, which serves as a superheater then. We will be closer to boiler design if we heat up the coolant in three steps, starting with an evaporator with upward flow, a first mixing in a steam plenum above the core, a second heat up in a superheater with downward flow, and a third step with upward flow again after mixing in a second mixing plenum below the core. The following chapters shall illustrate some design studies taken up to now using these different concepts.

3.1 Single Pass Core Concept

Starting from a conventional PWR design with 15MPa pressure and 325°C core exit temperature, the system pressure could be increased to 25 MPa and, in a first step, the core exit temperature to 380°C. Now, the coolant pressure will be higher than the critical pressure so that a boiling crisis will be avoided. The particular selection of the core exit temperature can better be understood when we look at the specific heat. It has a pronounced peak at 384°C, which we call the pseudo-critical temperature at this pressure. Similar to the sub-cooled boiling phenomenon in a PWR, this peak enables to run a sub-channel of the coolant at a significantly higher exit enthalpy, while reaching only slightly higher

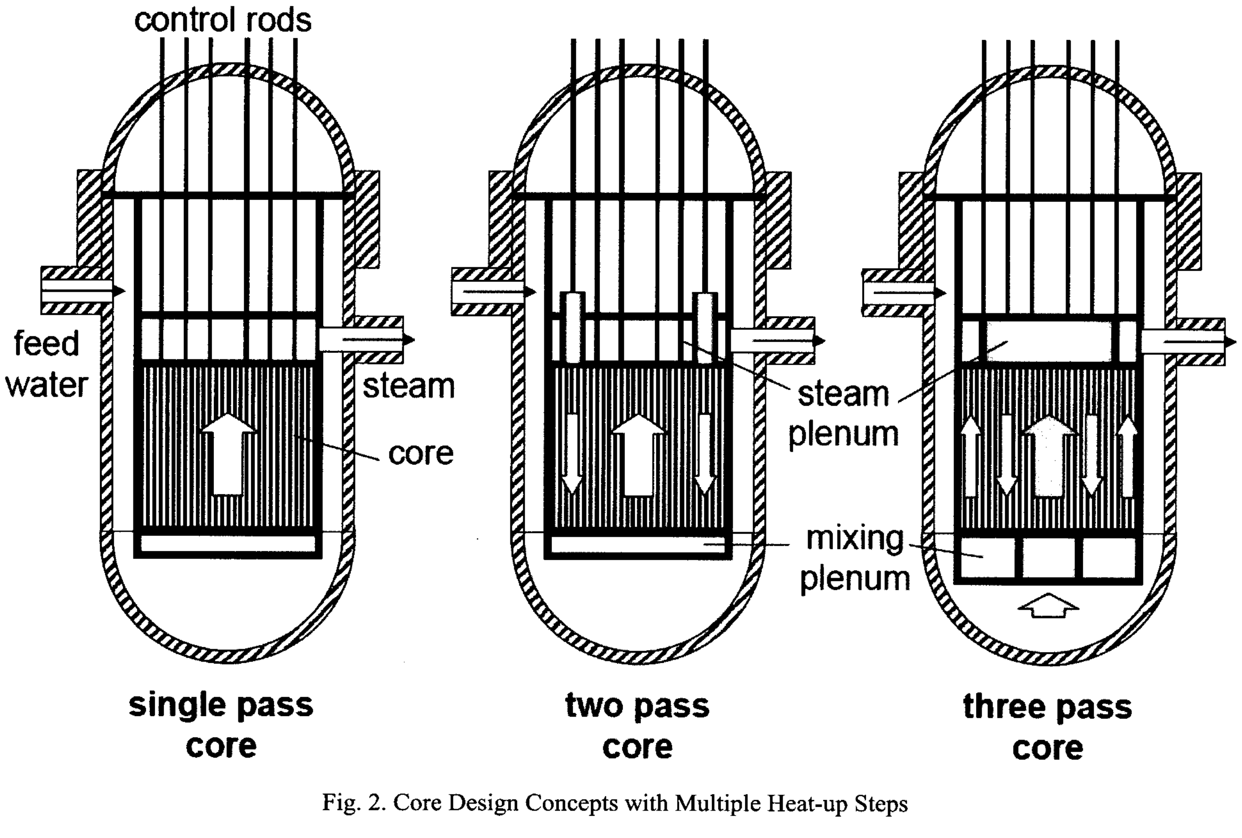

Fig. 2. Core Design Concepts with Multiple Heat-up Steps

exit temperatures, if the average exit temperature is chosen slightly below the peak. This phenomenon is sometimes called "pseudo-boiling" of supercritical water.

Vogt et al. [19] worked out such a core design as a near term application for supercritical water technologies, called PWR-SC. They used the assembly design of Hofmeister et al. [8], Fig. 1. Moderator water is flowing downwards through water rods inside the assemblies and through the gaps between the assembly boxes, whereas the coolant rises upwards. The core has been designed exemplarily for a thermal power of 2000MW using 88 clusters. A coolant mass flow of 2772.7 kg/s is heated up from 280°C to 380°C in average, resulting in a power density of 100MW/m^3, which is comparable with a PWR. The initial fuel enrichment varied between 3.75% and 5.5% as shown in Fig. 3. Burn-up optimization studies still need to be done. Each cluster has been equipped with an inlet orifice in the core support plate to adjust the coolant mass flow through each cluster to the average power therein. A residual temperature spread at the cluster outlet is caused by a non-uniform power profile inside the cluster. This method reduces the coolant temperature distribution at the core outlet to a small range of 355°C to 385°C only, as shown in Fig. 4. Vogt et al. [19] show that the maximum core exit temperature, even using a total hot channel factor of 2.14 for the hottest sub-channel under worst case conditions, reaches 416°C only. As supercritical water at a core exit temperature of 380°C is still liquid, steam generators need to be foreseen with superheaters instead of separators, which produce superheated steam at 370°C and 7.5MPa. As a consequence of the higher enthalpy rise in the core, the primary pumps will require only 24% power compared with a PWR and cross sections of the primary loop may be reduced by a factor of 4. The higher live steam temperature of the secondary side reduces the mass flow rate there to 82% but increases the gross electric power by 3% at the same thermal power of the core. The net efficiency is predicted to be 2% points higher than the latest PWR design.

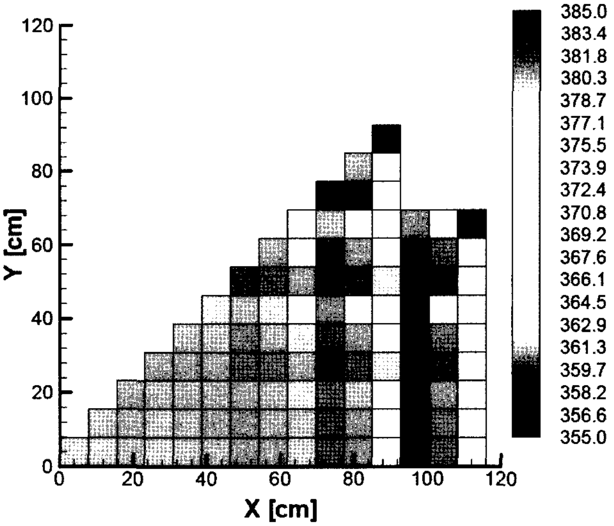

Fig. 4. Core Outlet Temperature Distribution of 1/8 of the Single Pass Core Design Concept by Vogt et al. [19]

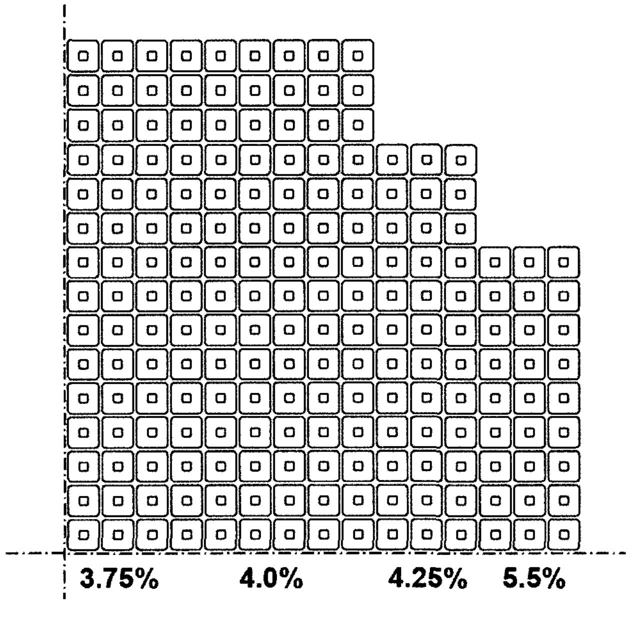

Fig. 3. Cross Section of 1/4 of the Single Pass Core Design Concept and Initial Fuel Enrichment, Vogt et al. [19]

3.2 Two Pass Core Concept

If the core exit temperature will be further increased beyond the pseudo-critical temperature, steam will be generated in the core and steam generators can be omitted. Like in a BWR, the outlet lines of the reactor may be connected directly with the inlet of the high pressure turbine which reduces the plant erection costs. The advantage of pseudo boiling, however, which keeps the core exit temperature limited, will be given up. Like in a fossil fired power plant, the coolant must now be heated up in steps with intermediate mixing to avoid overheated fuel pins in hot channels. A core design with a two-step heat up has been proposed by Kamei et al. [20], called Super LWR. They used 42% of the total reactor inlet mass flow rate (1418 kg/s at 280°C) as coolant running downwards in peripheral fuel assemblies, 50% as moderator water flowing downwards in moderator rods, and the remaining 8% are supplied through the downcomer to the lower plenum where all mass flows are added and mixed.

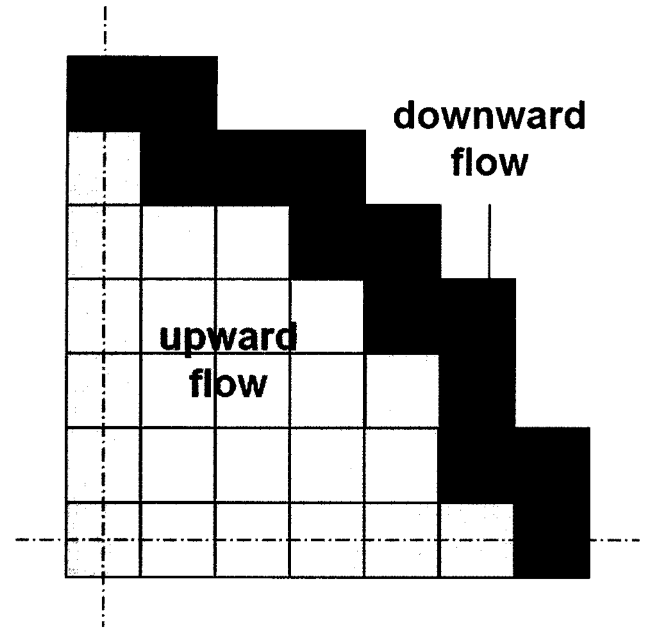

Fig. 5. Cross Section of $^1/_4$ of the Two Pass Core Design Concept by Kamei et al. [20]

The core cross section is sketched in Fig. 5 for $^1/_4$ core. It has been built with 121 square fuel assemblies with 300 fuel rods and 36 water rods each. In the first heat up step, the coolant shall be preheated in 48 peripheral fuel assemblies to obtain around 380°C in the lower plenum. From there, the coolant rises in the inner 73 fuel assemblies of the core where it is further heated up to 500°C average core exit temperature according to their proposal. Now, the inner fuel assemblies serve as a superheater of the core described above. The total thermal power of this core was designed to be 2744MW, giving an average power density of 60MW/m^3. Use of Gadolinia as a burnable poison in 40 fuel pins of each assembly enabled to reach an average discharge burn up of 45GWd/t_{HM}. The peak cladding surface temperature of the inner assemblies of a similar, further optimized core reaching 530°C average coolant exit temperature, has been predicted by Yamaji et al. [4] at 732°C, not yet including uncertainties and allowances for operation. While these peak temperatures will exceed the limits of available cladding materials, a less ambitious core exit temperature could certainly match the creep and corrosion limits of stainless steel.

3.3 Three Pass Core Concept

Higher core exit temperatures, and thus a higher specific turbine power and a higher net efficiency, can be achieved if we strictly follow the concept of supercritical fossil fired power plants and include even a second superheater. The resulting three pass core concept, sketched in Fig. 2, has been assessed by Schulenberg et al. [18] for a thermal power of 2188 MW and a total coolant mass flow of 1160kg/s. An evaporator (or rather "pseudo evaporator" in case of supercritical water), made of 52 fuel assembly clusters as sketched in Fig. 1, is situated in the centre of the core as shown in Fig. 6 for $^1/_4$ core. Underneath its inlet at the core bottom, all moderator mass flows from moderator tubes and from gaps between assemblies are mixed with feedwater from the downcomer to an inlet temperature of around 310°C. The evaporator heats the coolant up to 390°C. An inner steam plenum above the core shall eliminate hot streaks. A first superheater with downward flow, again with 52 clusters surrounding the evaporator, heats the coolant up to 433°C. After a second mixing in an outer mixing plenum below the core, the coolant will finally be heated up to 500°C with upward flow in a second superheater built of 52 clusters at the core periphery. Wire wraps have been proposed as grid spacers to improve coolant mixing in both flow directions. Schulenberg et al. [18] could show with a simplified single channel analysis that peak cladding temperatures of around 620 – 630°C can be expected in all heat up steps, even if a hot channel

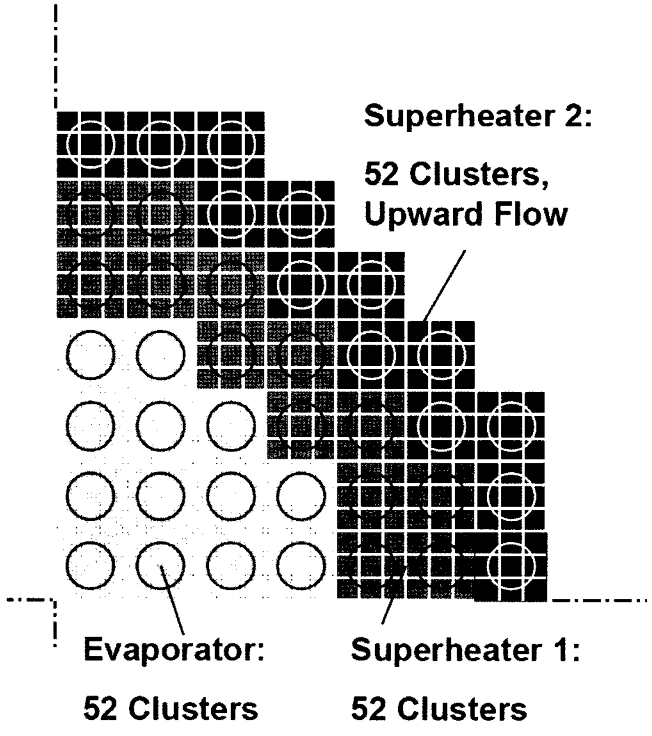

Fig. 6. Cross Section of $^1/_4$ of the Three Pass Core Design Concept by Schulenberg et al. [18]

factor of 2 is assumed to scale a hot coolant sub-channel from an average sub-channel. The total coolant pressure drop of this core is almost 500 kPa, which is not a major issue for the feedwater pumps, but requires stronger assembly box walls than the single pass concept by Vogt et al. [19].

The European consortium of the project "HPLWR Phase 2", which started recently in September 2006, agreed to work on this concept with the objective to access its feasibility, its safety features and its economic potential. Schulenberg and Starflinger [21] report about more details of this project.

4. CONCLUSIONS

The High Performance Light Water Reactor is intended to be a continuous development from well proven pressurized and boiling water reactors, using technologies of latest fossil fired power plants. Whereas most of the steam cycle components outside the reactor pressure vessel can easily be derived from these conventional power plants, the reactor core itself will be basically new. Three examples of core concepts, described above, illustrate that the complexity of the core design will increase with increasing core exit temperature. Up to now, only conceptual design studies have been performed and still a lot needs to be done. These first concepts show, however, that light water reactors still have a huge potential for further improvement of plant efficiency and specific turbine power and thus encourage to work out further details.

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