A COMPARATIVE OVERVIEW OF THERMAL HYDRAULIC CHARACTERISTICS OF INTEGRATED PRIMARY SYSTEM NUCLEAR REACTORS

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This paper presents a review of small-to-medium-sized, pressurized-water-cooled nuclear power reactors whose major primary coolant systems are integrated into a reactor pressure vessel, the concepts categorized as Integrated Primary System Nuclear Reactors (IPSRs). Typical examples of these proposals of interest in this review are CAREM, SMART, IRIS and IMR, all of which are being aimed at the near term deployment. Emphasis is placed on thermal hydraulic aspects. A brief characterization of the IPSR concepts is made and comparisons of plant key parameters are shown. Discussions will follow for the core cooling under rated power conditions and natural circulation heat removal on the basis of the design data available in the public domain.

KEYWORDS : Integrated Primary System, IPSR, PWR, Thermal Hydraulics, Natural Circulation

1. INTRODUCTION

A number of new designs of nuclear reactors have emerged in the last decade in attempts to achieve very high levels of safety and to enhance the economical competitiveness of nuclear power with alternative ways of electricity generation. For example, a review of development status of advanced light water reactor (LWR) designs is found in IAEA-TECDOC-1391 [1]. It includes small-to-medium size modular nuclear reactors that meet the demands, not only from already industrialized nations but, in particular, from developing countries which have smaller grids and more limited financial investment capabilities. In this context, the medium size reactors refer to those generating electricity in a range of 300 to 700 MWe and the small size reactors less than 300 MWe following the IAEA's definition. A more specific and comprehensive review of the innovative small-to-medium-sized nuclear reactor designs is going to be published in the IAEA TECDOC series [2].

In this article, among the small-to-medium sized advanced pressurized water reactor (PWR) designs, focus is placed on the Integrated Primary System Reactors (IPSRs) or integral type PWRs, all looking at the near term deployment. Many of them are based on well-proven PWR technology; however there are several concepts that require additional R&D efforts depending on how innovative their features are. Innovative approaches are directed toward adopting new compact design for the primary system components and some concepts adopt natural circulation (NC) core cooling for normal operation.

Elimination of primary system piping, modularization, and, in some cases, reliance on NC for core cooling is claimed to result in simplified systems with reduced cost and to provide a very high safety level. With regard to core cooling, however, it must be kept in mind that the NC system is not always as flexible as the forced circulation (FC) system in design optimization and in operation. The use of the NC core cooling requires thorough understanding of the three-dimensional phenomena of local as well as global scales, intricate and meticulous design in optimizing component arrangement and the NC flow path. Also it is noted that the lower driving forces of NC systems might result in larger equipment, thus leading to a contradiction against the cost reduction. In general, the NC core cooling would be practical for the small nuclear power reactors. Therefore it is a challenge to design larger IPSRs with natural circulation core cooling at normal operation.

IPSRs, in general, are variants of the current pressurized water reactor (PWR). Main features of the IPSR are: small to medium power (up to 1000 MWth/module); and a simplified compact design where the primary coolant paths are formed within the reactor pressure vessel (RPV).

In the IPSR designs, the reactor pressure vessel houses the major components of primary system including steam generators (SGs), and main coolant pumps (MCPs) for the concepts that rely on the FC core cooling, control rod drive mechanisms (CRDM) and pressurizer depending on designer's philosophy. There, every effort is made to eliminate as many penetrations as possible through the RPV wall. As a result, major penetrations that still exist in common to all the concepts are the main steam and feed water lines connected to the SGs inside the pressure vessel. Other inevitable penetrations in common may include those for emergency decay heat removal systems, and power and signal transmission cable lines. It is noted that Toshiba is proposing even the use of special E-M couplers for power and signal transmissions to avoid these cable penetrations for BWRs [3]. These are a logical consequence of the efforts of eliminating the causes of accidents and reducing the core damage frequency from the design stage (safety-by-design [4]), where the loss-of-coolant accidents (LOCA) have been always major contributors otherwise. The use of the internal CRDMs has been also motivated for next generation BWRs as well as PWRs to eliminate the vessel penetrations. This elimination would further reduce the occurrence frequency of LOCA as well as rod ejection accidents for IPSR designers to consider. Development of the internal CRDM is an on-going effort in particular in Japan [3, 5].

Typical design concepts in the class of IPSR, aside from many other important concepts from various institutes all over the world, would be represented by CAREM, SMART, IRIS and IMR (in chronological order of their first publication) [1, 2]. Those reactors are also included in a list of the International Near Term Deployment (INTD) reactors by the Generation IV International Forum (GIF), USDOE. In the context that follows, brief characterization of each concept, comparisons of plant key parameters with emphasis on thermal hydraulics aspects, and brief discussions on natural circulation (NC) decay heat removal capabilities are made on the basis of the design data available in the public domain.

2. CHRONOLOGY OF IPSR

CAREM (Central Argentina de Elementos Modulares) is an Argentine project to develop, design and construct an innovative, simple and small nuclear power plant [1, 2, 6]. Argentina started the project after installing a 340 (later 357) MWe nuclear power plant of the PHWR type into the electricity grid in 1974 and a 600 MWe CANDU-PHW in 1984. The CAREM was initiated as a joint development program of Comisión Nacional de Energía Atómica (CNEA) and its associated company INVAP. The reactor concept was first presented in March 1984 in Lima, Peru, during the IAEA conference on small and medium size reactors. CAREM is, chronologically, one of the first of the present new generation nuclear reactors with the primary system being integrated in a RPV. There is a variation in the CAREM concept: high power modules above 150 MWe with forced convection (FC) core cooling and low power modules below 150 MWe with NC cooling. However much information is not available for the larger version CAREM-300 (300 MWe). Therefore, in this article, we will concentrate on the CAREM-25. The design has been reviewed by international authorities in several opportunities up to now, all in favor of its viability and as one of the most promising small nuclear power reactors of the decades. The continuity of the project, however, has been certainly affected by the economic circumstances experienced in Argentina but a next step remaining would be construction of a prototype [6].

SMART (System-Integrated Modular Advanced Reactor) is a Korean small-sized advanced integral PWR that produces thermal energy of 330 MWth [1, 2, 7]. SMART has been developed on a long-term basis project carried out at Korea Atomic Energy Research Institute (KAERI) throughout the last decade. The conceptual design was launched in 1997 and completed in 1999. This study has been extended to the three year-term basic design phase to establish a concept of an integrated nuclear desalination plant coupled with SMART, which was begun April 1999 and completed in March 2002. From 2002 the six-year long 2nd phase project of the SMART-P was launched. The goal of this phase is to construct a 1/5 scale pilot plant. The SMART-P project will be carried out by a consortium of the government and domestic nuclear industry [2].

IRIS (International Reactor, Innovative and Secure) started in 1999 under the initiative of Westinghouse, sponsored by the US-DOE NERI (Nuclear Energy Research Initiative) program. The focus of IRIS then quickly changed from a research project to developing a potentially attractive commercial market entry [1, 2, 4]. The concept is now being pursued by an international group of 20 organizations from 9 countries. Its main features are: medium power (up to 1000 MWth or 335 MWe/module); a simplified compact design; a novel and effective safety approach; and optimized maintenance with intervals of at least 4 years. IRIS safety philosophy is based on "Safety by Design" where a variety of accidents are eliminated by appropriate design choices; alternatively, where this is not possible, their consequences and/or probability of occurring are greatly reduced. It employs a risk-informed design approach with the extensive use of the probabilistic safety analysis method. IRIS is currently undergoing a pre-licensing process with the US NRC, which started in late 2002. Design certification is projected for a 2008 - 2010 timeframe, with first-of-a-kind deployment in 2012 – 2015 [4, 8].

IMR (Integrated Modular water Reactor) started its design study in 1999 at Mitsubishi Heavy Industries (MHI) [1, 2, 9]. Currently, an industry-university group led by MHI is developing relevant key technologies funded by

Japan Ministry of Economy, Trade and Industry from 2001 to 2004. A unique feature of IMR is that it adopts a boiling two-phase flow NC in removing the rated core power output of 1000 MWth. Their design targets are to achieve the electricity generation cost comparable to that of a large-scale nuclear reactor and higher-level safety by removing the sources of fuel failures by design. Also basic characteristics of two-phase NC and passive heat removal system are investigated in this project. The conceptual design of a whole power plant is also studied funded by a utility company in parallel. The conceptual design has been completed in 2005 and efforts of basic design and verification tests are planned from 2006 to 2009 to prepare for licensing applications.

3. BRIEF DESCRIPTION OF PLANT DESIGNS

3.1 Characterization of the Integrated Primary System Nuclear Reactors

All IPSR designs emphasize both enhancing safety and reducing construction cost. The four concepts of interest are similar in the neutronics aspects. Fuel designs are not much different from each other except for the rod array configurations (square vs. triangular array of CAREM-25) and thermal hydraulics approaches are also much the same. Nevertheless the designs differ from one another if one looks at the following two branches where designers are asked to make a selection:

a) Forced circulation (FC) or natural circulation (NC) for core cooling at normal operation; then
b) Single-phase flow or two-phase flow cooling.

Both SMART and IRIS stay conventional at the branch point a). They use the MCP, and rely on the subcooled FC core cooling. The FC system is simple, reliable and more flexible in cooling as long as the power supply to the pumps is secured. In contrast, CAREM-25, and other CAREM versions below 150 MWe and IMR eliminate the use of MCPs and adopt NC cooling at normal operation. The MCP elimination aims at cost reduction and at enhanced safety for the events of loss of flows or loss of off-site power.

Then at the branch b), CAREM-25 selected a single-phase flow cooling where the coolant is saturated at the core exit. IMR makes a departure at this point by employing the boiling heat transfer and two-phase flow to facilitate the core cooling under the full power conditions. Note that the mass flow rate that is required to transport the rated power is much less in the case of boiling two-phase flow than the non-boiling single-phase flow heat removals. This means that the required NC driving head is much smaller. In alternative words, it was an inevitable selection to make the NC boiling cooling possible as long as the designer prefers the NC core cooling for the rated power in a limited size of RPV.

Another classification could be added from a different point of view. SMART employs the externally inserted CRDMs through the RPV head. IRIS, CAREM-25 and IMR intend to employ the internal CRDMs to eliminate the uncontrolled rod ejection accident (a class IV accident) because there is no potential differential pressure to drive out the CRDM extension shafts. These proposals include hydraulically or electro-magnetically driven mechanisms [5, 6, 8]. In addition, the recent vessel head degradation problems that was found at the Davis Besse Nuclear Power Plant in 2002 have prompted IRIS to resolve its concerns about the maturity of the internal CRDMs technology and to adopt it as the reference design [8].

In common to all the concepts, decay heat removal under accident conditions is accomplished by natural circulation although details of each safety system design

Reactor	Cooling mode during normal operation		Coolant at the core exit		Decay heat removals under accident conditions	Innovation
SMART	Forced Circulation	External motor/Internal impeller	Single-phase flow	subcooled	Natural circulation	Conventional technology
IRIS		Internal pump				↓
CAREM-25	Natural Circulation			saturated		
IMR			Boiling two-phase flow			More R&Ds required

Fig. 1. Approaches of IPSR

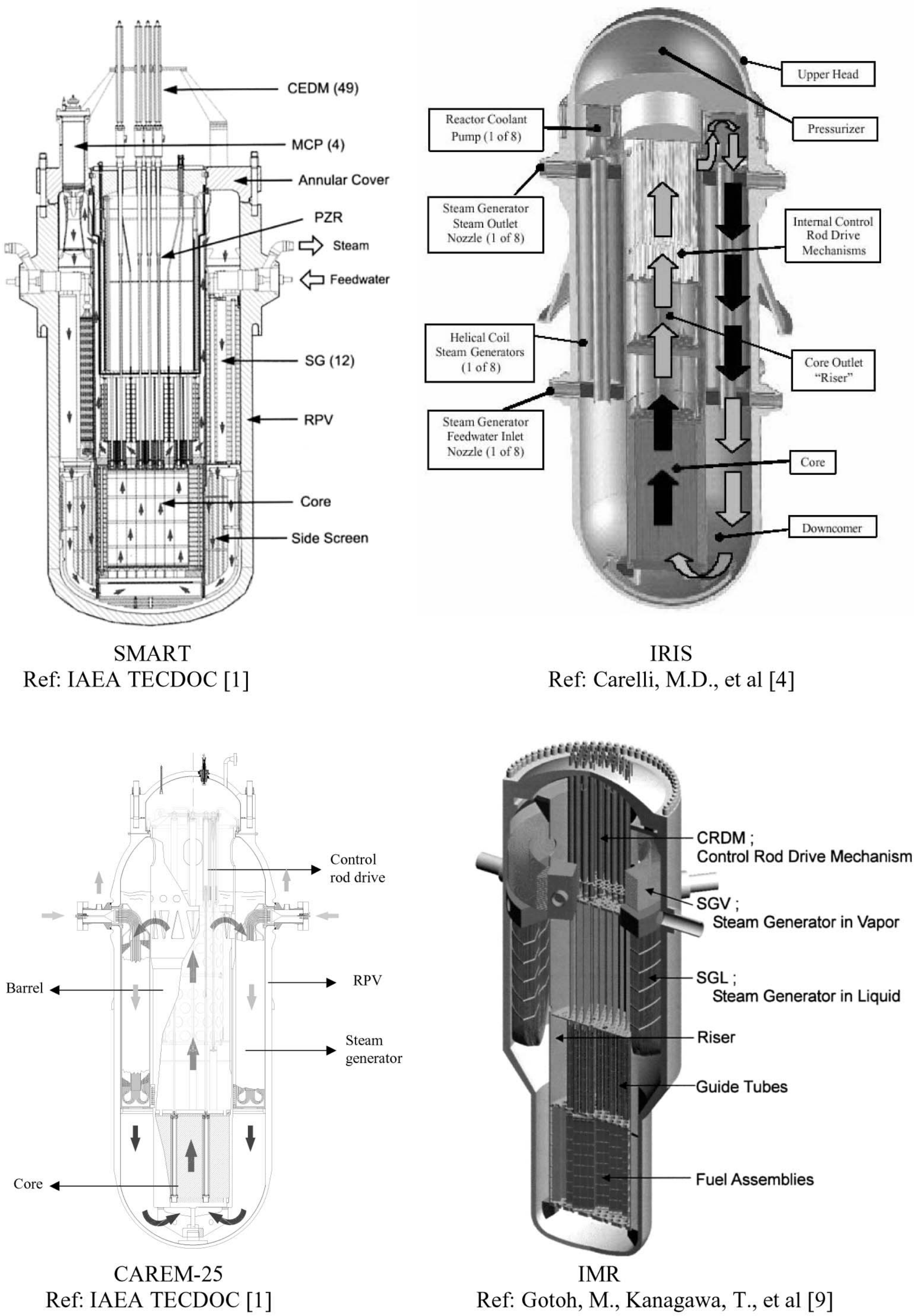

Fig. 2. Overviews of the Reactor Configuration

are different. The decay heat removal systems for normal shutdown and refueling are different per design but alike in the sense that they all transfer the decay heat through the SGs to the residual heat removal system.

In summary, Fig. 1 shows the thermal hydraulic approaches of IPSRs.

3.2 Key Component Arrangement and Coolant Path

Steam Generators

Figure 2 shows an overview of the reactor configurations. In all the designs, the steam generators are installed in an annular space between the core support barrel and RPV well above the core to gain more distance between the heat source and sink. Therefore the height of RPV is a limiting factor to the NC driving head. SMART, IRIS and CAREM -25 all use helical coil type SG.

In IMR, two types of SGs are installed in series: one is SGV that is located in the separated vapor portion in the RPV, and the other SGL located in the saturated liquid portion in the RPV. SGV is horizontal C-shape tube bundle and SGL vertical U-tube type. MHI calls the system that transports heat in the form of liquid enthalpy rise and vaporization as the hybrid heat transport system (HHTS). The HHTS allows heat transport of twice as much as that of the reactor of the same RPV size. The SGL has also a function of core power control, i.e., through the core inlet temperature which is controlled by the feed water flow rate [9].

Main Coolant Pump

IRIS installs eight internal spool type MCPs just above the SGs. Therefore no penetration through RPV exists except for the power lines, thus eliminating the potentials of small break LOCA (SBLOCA) associated with MCPs.

SMART installs four MCPs vertically through the top of RPV. The motor is outside RPV and pump is inside. The impeller draws the coolant from above and discharges downward directly to the SG. The SMART MCP is a canned type pump that eliminates the problems of conventional seals and thus a possibility of SBLOCA associated with a pump seal failure.

Pressurizer

The pressure in the primary system of SMART is automatically controlled by an in-vessel pressurizer. It is designated as PZR in Fig. 2 and is located in the uppermost part of RPV. It is filled with a mixture of water, steam and nitrogen gas. The system pressure is determined by a sum of steam and nitrogen partial pressures. Without using spray and heaters, it maintains almost constant pressure by minimizing the contribution of the steam partial pressure assisted by PZR cooler and wet thermal insulator. The pressurizer is connected to the gas tank located outside the RPV, from where high pressure nitrogen gas is supplied.

The IRIS pressurizer is integrated into the upper head of the RPV (Fig. 2). Heater rods are installed that control the pressure. This structure includes a closed cell insulation to minimize the heat transfer between the hotter pressurizer fluid and the subcooled primary coolant. This system provides a very large water and steam volume, as compared to plants with a traditional, separate pressurizer. The larger steam volume to power ratio is a key to eliminate the use of a spray function.

Both CAREM-25 and IMR do not require the pressurizer. For CAREM-25, the self-control of the pressure in the steam dome is the result of the liquid-vapor equilibrium. The large volume of the integral pressurizer also contributes to the damping of eventual pressure perturbations. As for IMR, also the pressure is self-controlled by SGV.

Control Rod Drive Mechanism

CAREM-25 is the first to employ the internal CRDM among the four IPSRs. It is driven hydraulically. IRIS has adopted the internal CRDM, hydraulic or electric-magnetic driven, as reference and traditional CRDMs remaining as backup. IRIS is currently evaluating candidate concepts for the internal CRDMs, and will be proceeding soon to the preliminary design of the chosen one [8]. IMR employs also hydraulic driven internal CRDM for the reactor scram and the motor driven internal CRDM for reactivity control during operation. The basic development of the motor driven CRDM has been made by Japan Atomic Energy Research Institute for the purpose of installation onto the Marine Nuclear Reactor (MRX) [10]. Because of the elevated temperature operation of IMR, further R&D is required to confirm reliability and integrity in the more severe environment. SMART originally adopted the classical CRDM and this choice is considered to be reasonable in consideration of the reliability and, especially, experiences gained in the long history of PWRs.

Coolant Path

As illustrated in Fig. 2, the primary coolant flows upward through the core, the upper core structure and riser, arriving at the top and enters into the shell side of the steam generators through MCPs (SMART and IRIS) or directly (CAREM-25 and IMR). After giving up enthalpy at the SGs, the coolant reaches the core inlet through the wide downcomer region and the bottom region of RPV. It should be noted that this wide downcomer region in common to all the IPSR concepts significantly reduces the fast neutron fluence on the RPV as well as the dose outside the vessel. Obviously this would contribute to cost reductions, e.g., by ensuring very long life vessel, reduced biological shield, operational doses and in decommissioning.

3.3 Summary of Plant Key Parameters

Table 1 shows a summary of the plant system data available from the open literature.

As mentioned in Section 3.1, four IPSR designs could be grouped into two groups: a first group of the FC system

Table 1. Summary of Plant System Data

		SMART	IRIS	CAREM-25 (prototype)	IMR
Designer		KAERI (Korea)	W / International Consortium	CNEA / INVAP (Argentina)	MHI (Japan)
Project period		1997– 99 SMART 99-02 Combined with Desalination; INTD 02- SMART-P Prototype construction	1999-02(DOE NERI) 02- Pre-licensing application; INTD 08-10 projected for design certification	1984 First CAREM presented; efforts continue; INTD	2001- METI project; also sponsored by JAPC; INTD 06-09 Basic design 10- license application
Development stage		Conceptual design completed	Pre-licensing	Construction of a proto-type awaited	Conceptual design on-going efforts
Power rating (MWth) (MWe)		330 90	1000 335	100 27	1000 330
Primary system pressure (MPa)		15	15.5	12.25	15.5
Main Coolant Pumps		External canned motor	Internal spool type	NONE	NONE
Steam Generator		Once-through helical coil (12 units)	Once-through helical coil (8 units)	Once-through 'Mini helical' vertical (12 units)	HHTS (two parts, one in vapor (C-type) and one in liquid (U-type))
Pressurizer		In-Vessel self pressurizer with water steam, Nitrogen, connected to gas tank outside RPV	Once-through helical coil (8 units)	Once-through 'Mini helical' vertical (12 units)	HHTS (two parts, one in vapor (C-type) and one in liquid (U-type))
Reactor vessel	Height (m)	10.6	21.3	11	20
	Inner Diameter (m)	4.07	6.2	3.16	6.0
Fuel Enrichment		4.95%	4.95%	3.4 %	4.95%
Operating Cycle Length		990 days	Up to 4 years	Reference 330 days 50% core replacement	3 years
Control Rods Drive Mechanism		External Fine Step movement	Internal CRDM (conventional external CRDM as backup)	Internal - Hydraulic (different SCRAM speeds)	Internal - Hydraulic for scram, motor driven for control
Chemical Shim		None	Low Boron Concentration	None	None
Emergency Boron Injection		Present	Present	Present	None
Burnable poisons		Burnable Poisons	Burnable Poisons	Gd2O3	Gadolinia fuels and burnable poison

and a second group of the NC system. It would be more interesting to compare these four concepts from a different view point. CAREM-25 generates the power about 1/3 of SMART for the same size of RPV. This is a result of the fact that the NC IPSR needs a larger RPV to accommodate a sufficient distance between the heat source (core) and heat sink (SG).

When we compare IRIS and IMR, both generating the same power, we should note that their RPV sizes are close, i.e., the inner diameter is about 6 m and the height is 20 m in spite of the fact that IMR operates with the NC cooling. It is not surprising to see this because, thanks to the latent heat transport through HHTS of IMR, it has been possible to make the RPV size much more compact, and comparable to that of the FC cooling IPSR.

Radial dimension of RPV would be dictated by the space required to install SGs. The sizes of RPV for 330 MWe IPSRs are larger than those of conventional PWRs generating 3 to 4 times more electricity. Also the radial size is limited by manufacturing capabilities. For the smaller reactor core, saving in radial dimension is not remarkable, less so if the core designers are asked to make the power density lower for any reasons.

More detail of the comparisons will follow in the next section.

4. THERMAL HYDRAULICS

Table 2 summarizes the key thermal hydraulics parameters of each reactor core and nuclear steam supply system.

4.1 Heat Removals at Rated Power

The forced circulation mass flow rate is of course determined by the pumping power. Alternatively, the FC mass flow rate is not influenced by the core power output and heat removals at the SG and uniquely determines the hot leg temperature. Therefore the optimization of thermal hydraulic design for a FC system is much easier than for a NC system. Since SMART and IRIS rely on the FC core cooling, the reactor system thermal hydraulics design is done as a matter of routine.

In contrast, the natural circulation mass flow rate is determined by the NC driving head which is a function of hot leg and cold leg temperatures that are determined by the NC mass flow rate. Therefore the NC cooling strategy is not as simple as the FC cooling. Also the use of the NC core cooling requires thorough understanding of the three-dimensional phenomena of local as well as global scales, intricate and meticulous design optimizing component arrangement and the NC flow path.

D'Auria and Frogheri [11] address the NC limits achievable in a conventional PWR. They conclude that the single-phase NC is effective for removing the heat up to 20% of the nominal power while two-phase NC, with the primary system in a boiling condition, up to 70% avoiding the occurrence of the dryout. As for IPSR, in order to remove 1000 MWth of core power output by pure single-phase NC, the required distance between the core and SG would be very large. In this regard, two-phase flow NC core cooling surfaces and attracts attentions. MHI, in their 1000 MWth IMR concept, adopts the heat transport by low quality boiling two-phase flow [9].

4.2 Decay Heat Removal During Normal Shutdown or Refueling

SMART removes the decay heat by the secondary system, through SG with turbine bypass to the condenser. IRIS uses the normal residual heat removal system NRHR consisting of RHR pump and RHR heat exchanger. The NRHR performs as it does in the reactors with a traditional NRHR loop-type layout. CAREM uses the shutdown cooling system and in IMR the residual heat removal is achieved by the auxiliary feedwater system, which is used for startup and shutdown also. The auxiliary feedwater is not a safety system because the plant safety is guaranteed by the Stand-alone Direct Heat Removal System (SDHS) is provided as the safety system as shown in the next section.

4.3 Decay Heat Removal Under Accident Conditions

In the existing water cooled reactors, NC allows the removal of the decay heat, should the forced circulation driven by pumps become unavailable. The NC is also essential as well for the core cooling in the unlikely events of LOCA. In this regard, NC principles are of fundamental interest to the designers in decay heat removals under accident conditions for IPSR. Overall, safety considerations are appropriately reflected onto all the ISPR designs.

As a consequence, in all the ISPR concepts, the decay heat removal under the accident conditions is achieved by the NC. The SMART passive residual heat removal system (in two trains) removes the core decay heat and sensible heat by NC in case of an emergency such as unavailability of feedwater supply or station blackout. The RHRS of CAREM is designed to reduce the pressure on the primary system and to remove the decay heat in case of Loss of Heat Sink by NC. Both SMART and CAREM are equipped with emergency core cooling system to prevent core exposure in case of LOCA.

IRIS and IMR do not need an emergency core cooling injection system, because the design is such to guarantee core coverage under all design basis accidents.

IRIS adopts the safety by design approach and is based on a risk informed design with the extensive use of probabilistic safety assessment technique. This approach allows the rational safety system design. The main components of the safety systems, relevant to thermal hydraulics, are systems for passive emergency heat removal, automatic depressurization, containment pressure suppression, long

Table 2. Thermal Hydraulic Characteristics

	SMART	IRIS	CAREM-25 (prototype)	IMR
Power	330 MWth	1000 MWth	100 MWth	1000 MWth
Electrical output	90 MWe	335MWe	27 MWe	330 MWe
Pressure	15 MPa	15.5 MPa	12.25 MPa	15.5 MPa
Primary coolant flows	Single-phase	Single-phase	Single-phase	Boiling two-phase
	Forced circulation	Forced circulation	Natural circulation	Natural circulation
Core outlet temperature	310 C	330 C	326 C (= T_{sat})	345 C
Core inlet temperature	270 C	292 C	284 C	Variable
Coolant temperature at RPV inlet	-	-	-	307 C
Core exit void fraction	-	-	-	20-30 %
Primary coolant flow rate	1550 kg/s	4700 kg/s	410 kg/s	3000 kg/s
Core equivalent diameter	1.832m[1)]	2.413 m	1.3 m[1)]	3.0 m
Active core height	2.0 m	4.267 m	1.4 m	3.7 m
Average power density	62.6 kW/l	51.26 kW/l	55 kW/l	42 kW/l
Average linear heat rate	11.9 kW/m	9.97 kW/m	11 kW/m[2)]	7 kW/m
Assembly data				
Fuel lattice configuration	Square 17 × 17	Square 17 × 17	Triangular	Square 21 × 21
Rod diameter	9.5 mm	9.5 mm	9 mm	9 mm
P/D	1.326	1.396	1.38	1.4
Number of fuel rods/assembly	264	264	108	385
Number of assemblies	57	89	61	97
Number of control rods	49	37	19	92
Residual Heat Removal under the emergency conditions	Natural circulation	Natural circulation	Natural circulation	Natural circulation

[1)]Estimated by the average power density
[2)]Estimated

term core make up, passive containment cooling, etc., and include other considerations like a small cavity where the RPV is located. This small cavity works as the guard vessel of sodium cooled fast breeder reactor system. All the decay heat removals are carried out by NC [8].

As one of the mitigation systems of IMR, there are two-trains of the Stand-alone Direct Heat removal System (SDHS) that branch out of the main steam lines and return to the main feedwater lines outside RPV. In this system, the decay heat is removed by NC via SGs directly from inside the reactor vessel to the atmosphere through passive SG coolers installed horizontally in a wind tunnel.

5. NATURAL CIRCULATION HEAT REMOVAL

In general no single unified method is available to evaluate NC heat removal due to a wide range of conditions (geometry, flow regime and thermodynamic conditions) and, because this review is not intended to assess the capabilities of each plant, we employ the following very simple method to clarify the NC characteristics.

For the single-phase flows, it is well known that the total NC mass flow W_{NC} is related to the heat flux q" (or reactor power Q) and the height difference between the heat source (core) and heat sink (SG) ΔH by:

$$W_{NC} \propto q"^{1/3} \Delta H^{1/3} K^{-1/3}, \qquad (1)$$

where K is related to the total of the pressure drop (form loss and friction through the coolant path) and depends also on the mass flow rate:

$$K = \sum K_i + \sum \frac{f}{D_h} \Delta L$$

with K_i: the form loss coefficient of i-th component, f: friction factor, D_h: equivalent hydraulic diameter and ΔL: associated length.

As for the boiling two-phase flow NC, it is possible to derive similar relationship but in a more complicated manner [12].

Under the steady-state condition, the following is pointed out:

1) The lower driving forces of single-phase flow NC systems leads more likely to larger equipment and the 3D phenomena become more important. Due to limiting the size of RPV, there is a limit in its NC driving head. Therefore application of the single-phase NC core cooling is recommended for such a small reactor as CAREM-25.
2) Because it is the rod bundle section and the SG section (shell side in the case of IPSR) that contribute to the major part of the total pressure loss, it is important to adopt a wider rod-to-rod spacing for rod bundles and low pressure drop SG design. In fact P/D (pitch to diameter ratio) in IMR and IRIS is 1.4 which is larger than that of conventional PWR, not only from thermal hydraulic reasons but also neutronics. Note that the bundle and SG section length are also included in K.
3) NC mass flow is totally system-dependent, in particular, with respect to the distance between the heat source and sink ΔH, and pressure drop characteristics represented by K in Eq. (1). The mass flow rate will change as the core power Q and heat removals at SG, i.e., the hot and cold leg temperatures. Therefore the NC mass flow rate cannot be determined as simply and freely as for the FC system.
4) NC mass flow in single- as well as two-phase can be controlled by changing the feedwater temperature or flow and heat removals at the SG that control the cold leg temperature and/or adjusting valve opening or orificing. The two-phase NC system, in particular, would require intricate and precise measurement as well as the state estimation system and more advanced, sophisticated control system.
5) In order to remove 1000 MWth of core power output by NC within the limited size of RPV, two-phase flow NC would be most favored. In this regard, MHI adopts the heat transport by low quality boiling two-phase flow being proposed as HHTS in their 1000 MWth IMR concept. However, two-phase flow NC system must be carefully designed such that the operating domain avoids the static instability, density wave oscillation as well as the other local instability phenomena.

Figure 3 shows the comparative view of the size of RPV as well as the rough estimates of ΔH the distance between the core and SG epicenters of the heat transfer. It should be reminded that some of the geometrical data are estimated with a ruler on downloaded figures or those illustrated in the published papers.

The size of reactor vessel, and the core and SG arrangement are similar for both IRIS and IMR, both of which produce 1000 MWth. In order to remove the same heat, IRIS relies on pump head and IMR goes to NC driving head and more efficient boiling two-phase heat transfer. If one compares SMART and CAREM-25 (see also Tables 1 and 2), one will find that the RPV of the same size can contain a core producing three times larger power if the system relies on the FC.

As a reference case, all the pressure drops through the circuit and NC driving head have been calculated for IRIS under normal operation. According to the results, the pressure loss across the core and SG is about 90% of the total pressure drop. The NC driving head is about 3.9 % of the total pressure drop. Namely, if we define the contribution of the NC driving force by:

$$NCR_2 = \frac{Total\ NC\ driving\ head}{Total\ NC\ driving\ head + \Delta p_{Pump}}, \text{ then} \qquad (2)$$

NCR_2 is 0.039. Then, by the term NCR we indicate the power the system could remove when MCPs trip, i.e.,

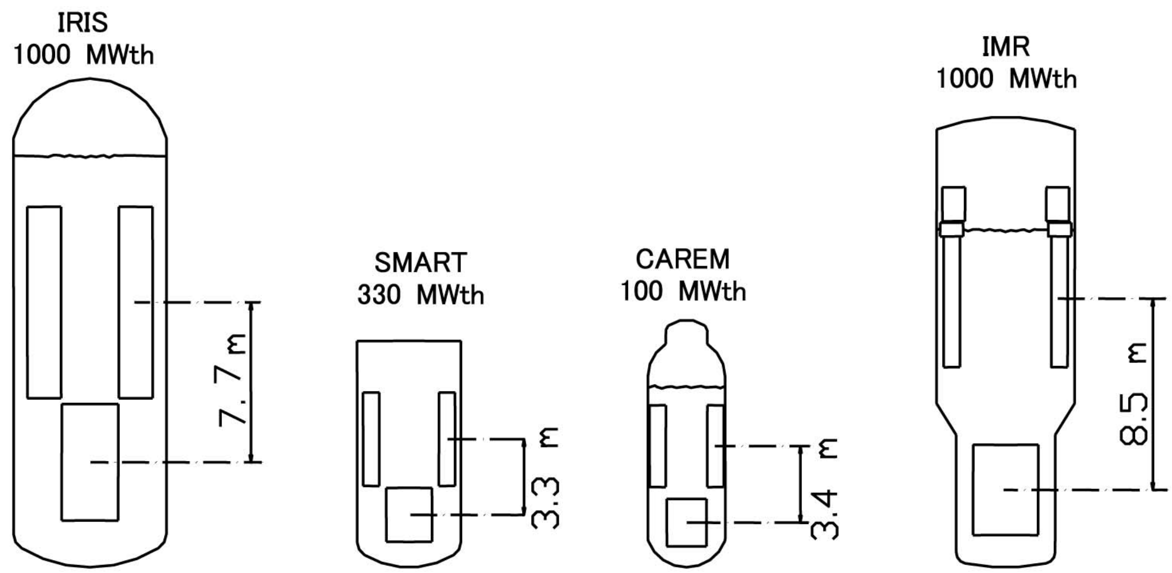

Fig. 3. Comparison of RPV Size and ΔH (Estimated)

$$NCR = \frac{Power\ that\ can\ be\ removed\ by\ NC}{Power\ that\ can\ be\ removed\ by\ FC}. \tag{3}$$

From these definitions we have:

$$NCR \cong \sqrt{NCR_2}\ . \tag{4}$$

For IRIS as an example, NCR is 0.2. Alternatively this indicates that 20% of the rated power can be removed by NC. Actual NCR would be between 0.2 and 0.3 depending on the ΔH. For a comparison, NCR for SMART is 0.25 [13].

The height of active core is 4.3 m, 2.0 m, and 1.4 m for IRIS, SMART and CAREM-25 (Table 2). Assuming each active core height to be approximately equal to the bundle length, and using the ΔH shown in Fig. 3, we find that the NC mass flow per MWth in IRIS and SMART are almost the same from Eq. (1). This confirms that NCR is around 0.25 for both plants.

In the same way, the total NC mass flow for the CAREM -25 can be calculated and the result is higher than that of SMART because of lower pressure drop across the core. However, to get reliable results, it is necessary to obtain more plant data, in particular, pressure drop data for the core, SG shell side as well as more specific plant geometry.

In summary, Table 3 shows the NC heat removal capability of each IPSR.

General Comments on NC

For such advanced water reactors as IPSR with passive systems, the importance of certain NC phenomena such as interactions between heat source and heat sink, turbulence mixing, buoyancy effects on the turbulence flows, NC CHF mechanisms, thermal stratification and striping, non-condensable gas behaviors and their influences on condensation, is greater than in current designs.

Table 3. NCR Fraction to the Rated Power Removed by NC

IPSR	NCR
IRIS	20 ~ 30 % (20 % extremely conservative)
SMART	25 %
CAREM-25	100 %
IMR	100 %

The uncertainties in phenomenology result in additional margins into system designs. Therefore thorough knowledge of natural circulation phenomena is required for the passive system to work as intended. In order to gain the knowledge, more acquisition of single- and two-phase flow data for complex geometry under low to high pressure conditions is required.

The neutronics and thermal hydraulic coupling phenomena also become important in the NC IPSR.

Computer simulation is extremely useful and has become more important. Nonetheless, computation stays in a position of a supporting tool for experimentation. Computational approaches must be more reliable. Although the development and popularity of CFD codes are enormous, the state of the arts of the methods is still far away from the sufficient level to be applied in the area of concern in this article. Continuous efforts in code validation and verification as well as improvement are encouraged.

Also, importantly, improved understanding of physical phenomena and improved modeling in computer codes that predict plant behavior facilitates more economic designs for future plants by removing the need to incorporate excessively large margins simply for the purpose of allowing for limitations in understanding the phenomena.

5. CONCLUSIONS

An overview of four concepts of integrated primary system nuclear reactor (IPSR), i.e., CAREM-25, SMART, IRIS and IMR, were reviewed with respect to cooling mode, plant key parameters with emphasis on thermal hydraulics and natural circulation heat removal capability.

The IPSR concepts can be grouped into forced circulation (FC) core cooling group and natural circulation (NC) core cooling group. The FC group consisting of SMART (330 MWth) and IRIS (1000 MWth) aims at earlier commercialization based on the conventional technology available. It takes advantages of the fact that optimization of thermal hydraulic system design and core cooling strategy is much easier than the NC system. Also the FC system is more flexible in plant control and operation.

CAREM-25 (100 MWth) and IMR (1000 MWth) are categorized into natural circulation (NC) group. Reliance on NC would result in simplified systems, and potentially reduced cost. However, the NC cooling strategy is not as simple as the FC cooling. It requires intricate and meticulous design in system optimization and NC flow path control. The lower driving forces of NC systems might lead to larger equipment, thus resulting in a contradiction against the cost reduction. In general, the NC core cooling would be practical for small sized nuclear reactors such as CAREM-25. Employment of the boiling heat transfer and two-phase flow transport in the IPSR system has been proposed by IMR as a direction to pursue in accommodating a larger core in a limited size reactor pressure vessel.

It has been pointed out that further R&Ds are required as the IPSR systems become more innovative. The more extensive use of the NC heat removal in the safety design as well as in normal operation requires more thorough knowledge on not only single-phase flow but also the two-phase flow natural circulation phenomena which are three-dimensional and of local as well as global scales.

Finally improved understanding of natural circulation phenomena and improved modeling in computer codes can facilitate more economic designs for future IPSR plants by removing the need to incorporate excessively large margins simply for the purpose of allowing for limitations in understanding the phenomena.

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