CAREM: AN INNOVATIVE-INTEGRATED PWR

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Abstract

Presented on March 1984 in an international conference for the first time, “CAREM Concept” focused on engineering solutions from early stages of the design that minimize requirements to safety and safeguards systems being the product simpler, highly reliable and cost effective.

The overall idea was widely adopted by worldwide designers, originated a new category of small a medium size nuclear power plants frequently know as “integrated reactor” and/or “Advanced-passive safety-reactor”.

This paper describes the main design features, progress and prospects of the CAREM project as well as proliferation resistant conditions applicable to the design.

1. Introduction

The CAREM project, which is jointly developed by CNEA and INVAP (Argentina), comprises the development, design and construction of an advanced, simple and Small Nuclear Power Plant (SNPP).

The concept was first presented in March 1984 in Lima, Peru, during the IAEA conference on Small and Medium Size Reactors (SMSR). Basic design criteria supporting the “CAREM Concept”, has been adopted by other NPP Plant designers, originating a new family of designs, from which CAREM is frequently referred as the leading one.

The simple and robust design makes the CAREM particularly appropriate for its use in medium size grids and/or remote areas (i.e. typical conditions found in development countries or isolated industrial areas).

The actual design is supported by the cumulative experience acquired along more than thirty years working in the design and construction of Research Reactors and several Nuclear Facilities, operation of NPP as well as the development of advanced design solutions [3].

The first step towards the validation of the concept is the construction of a 27 MWe prototype (CAREM-25). This project will consolidate the Argentinean capabilities in nuclear power plant design while will make available, a medium size NPP (300MWe) in the near term to both local and international nuclear generation markets [1, 2].

Its "mature modern concept" jointly with its simple and robust design has deserved a bold consideration from several international forums and experienced companies (i.e. Mitsubishi Heavy Industries JPN-1999, US/DOE-2001, IEA-NEA-IAEA study -2001, GIF-2002, INPRO-2004), being worldwide considered as one of the "promising" Near Term Deployment Reactor designs.

2. Distinctive design criteria

What strongly differentiates the CAREM Concept from traditional LWR´s is the fact that major initiating events are eliminated early from the design stage. This feature lightens the requirements (i.e. time response and capacity of the safety systems) and allows the use of simpler, highly reliable and costs-effective Safety Systems.

Among the major safety benefit of the CAREM Concept compared with traditional NPP designs, are:

- <u>Lost Of Coolant Accident (LOCA)</u>: Primary System is fully contained in the Reactor Pressure Vessel (RPV) while the maximum pipe size connected is 1.5 inches, then intrinsically from its design Large LOCA is not an issue for this reactor
- <u>Rod Ejection</u>: Control Rod Drive Mechanisms (CRDM) are fully contained in the RPV and maximum uncontrolled rod ejection is limited by design.
- <u>Longer Response Times Allowed</u>: Large coolant inventory in the primary results in large thermal inertia providing long response times and mild transients even during the most severe flaws conceived
- <u>Confined High Radiation Areas</u>: The lack of primary piping and large external components connected to the RPV allows a proper confining of the high radiation gamma and neutron sources reducing shielding requirements and complexity
- <u>Lower Radiation Damage to RPV</u>: the larger water thickness between the core and the primary/pressure boundary leads to a reduced fast neutron dose over the RPV wall
- <u>Reduced O&M cost</u>: Its simplified and robust design allows lowering the O&M cost

Additionally CAREM 25 does not use primary pumps and <u>No Lost of Flow Accident (LOFA)</u> is possible.

3. Reactor Description

CAREM-25 is an indirect cycle reactor with distinctive features that greatly simplify the design and contributes to get a higher safety level.

Some of the design features are:

- Integrated Primary Cooling System.
- Core Cooled by Natural Circulation.
- Self-Pressurised
- Safety Systems relying on Passive Features.

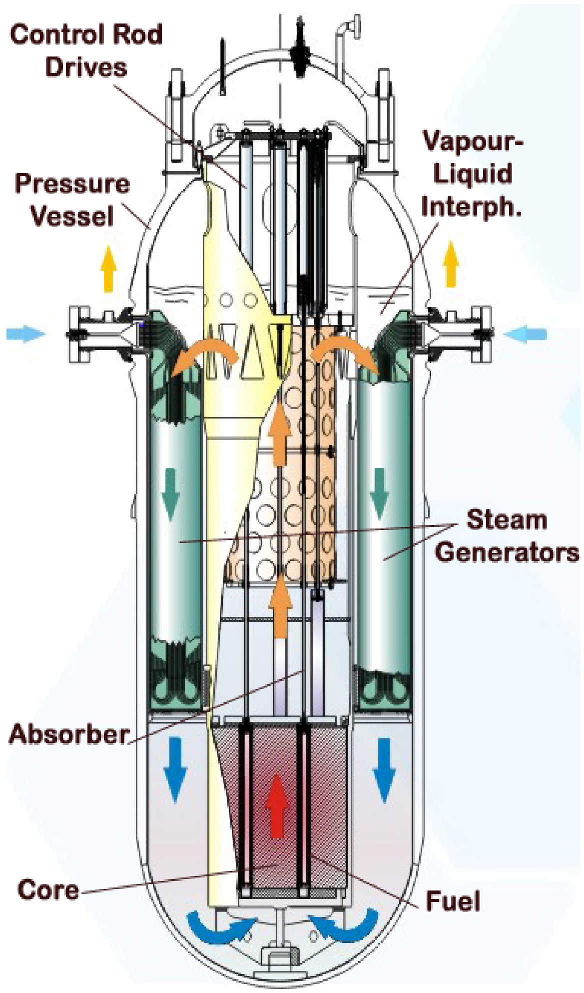

Figure 1: Reactor Pressure
Vessel

3.1 Primary System

A single RPV contains: the core, the twelve steam generators, the whole primary coolant inventory and all the control rods drive mechanisms.

The RPV diameter is 3.2m and the overall length is 11m.

The core contains sixty one (61) Fuel Assemblies (FA), 2m high, while some of them contain movable Absorbing Element (AE) for reactivity control.

Each fuel assembly contains the Fuel Rods, Burnable Poison Rods, guide tubes for the Absorbing elements of the Control Rods and one instrumentation tube guide.

Fuel pins resembles typical PWR fuels UO_2.enriched from 1.8 to 3.4% sheathed by y-4 tubes. Gd_2O_3 is used as burnable poison

Each AE consists of a cluster of rods linked by a structural element (namely "spider"), so the whole cluster moves as a single unit.

Chemical compound (i.e. Boron) is not used for reactivity control during normal operation, which results in a great simplification to operation.

The Fuel cycle can be tailored to customer requirements between 330 and 390 full-power days (FPD) while the maximum BU is reaches 26,000MWd/TU.

Twenty five AE made of Ag-In-Cd alloy are used for reactivity control and shutdown of the reactor.

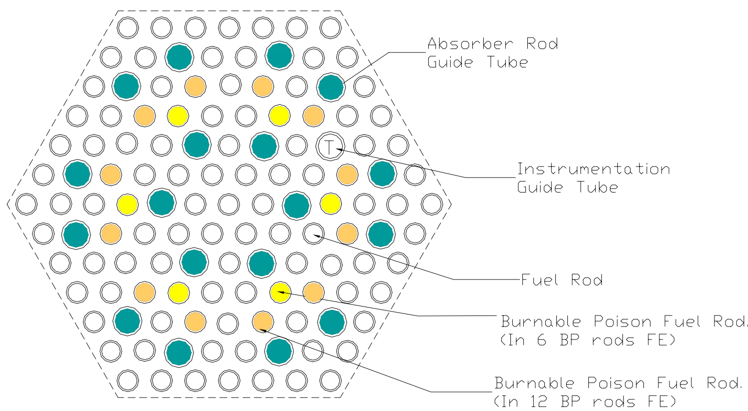

Figure 2 Fuel Assembly diagram. Fuel rods, guide thimbles and instrumentation thimble distribution

Twelve identical 'Mini-helical' vertical steam generators, "once-through" type, are placed equally distant from each other along the inner surface of the Reactor Pressure Vessel (RPV) (Fig. 3). They are used to transfer heat from the primary to the secondary circuit, producing dry steam at 47 Bar, with 30°C of superheating.

The location of the steam generators above the core produces natural circulation in the primary circuit. The secondary system circulates upwards within the helical tubes, while the primary goes in counter-current flow direction. An external shell surrounding the outer coil layer and an adequate seal provides the flow between primary and secondary systems.

In order to achieve a rather uniform pressure-loss and superheating on the secondary side, the length of all tubes is equalized by changing the number of tubes per coil layer.

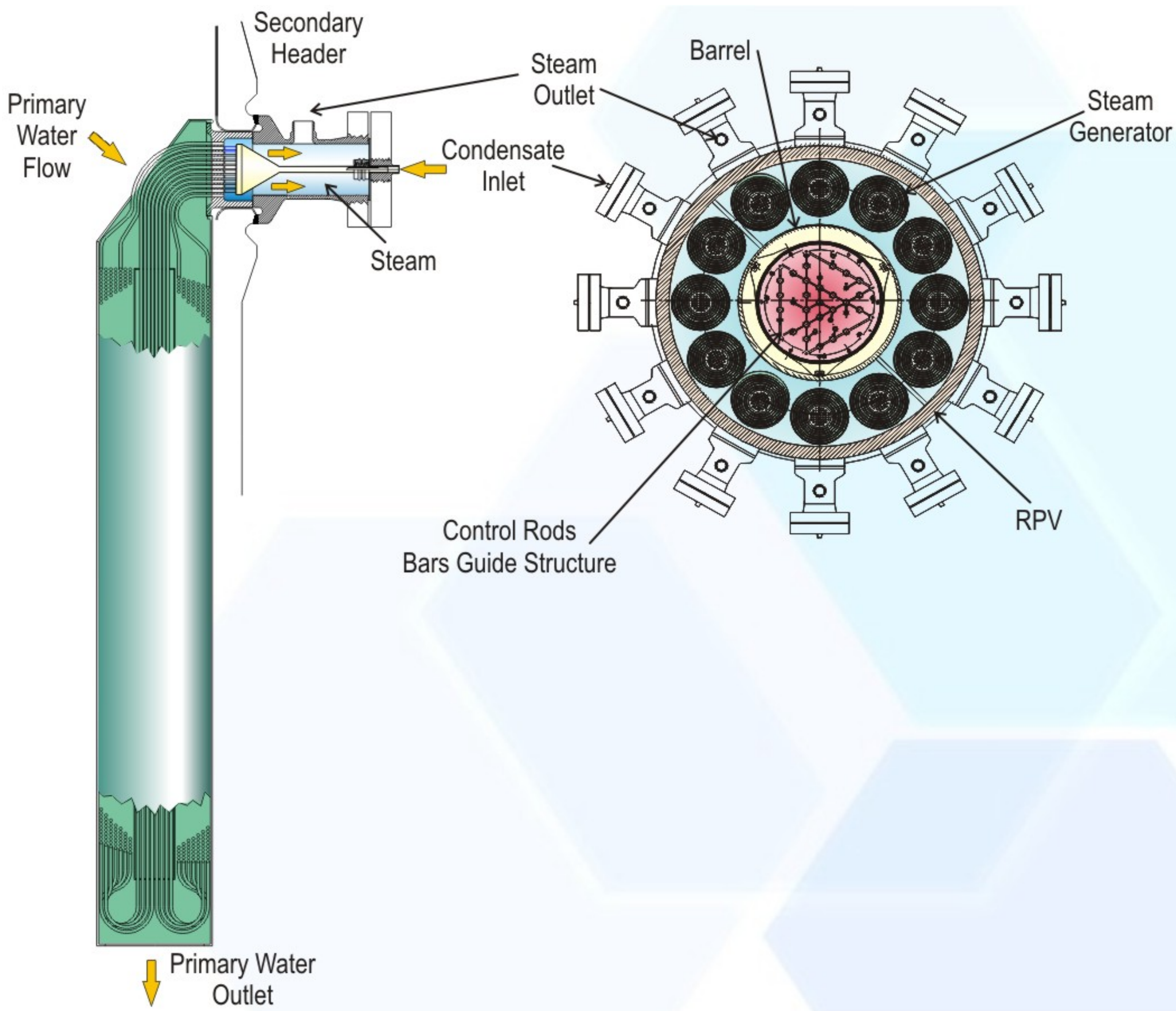

Figure 3 Steam Generation lay out

Steam generators are designed to withstand the primary pressure without counter pressure in the secondary side. Also the whole live steam piping is designed to withstand primary pressure up to isolation valves (including the steam outlet / water inlet headers) to prevent a LOCA in case of SG tube brake.

The natural circulation of de coolant produces different flow rates in the primary system according to the power generated (and removed). Under different power transients a self-correcting response in the flow rate is obtained [4].

Due to the self-pressurizing of the RPV (steam dome) the system keeps the pressure very close to the saturation pressure. At all the operating conditions this has proved to be sufficient to guarantee a remarkable stability of the RPV pressure response. The control system is capable of keeping the reactor pressure practically at the operating set point through different transients, even in case of power transients. The negative reactivity feedback coefficients and the large water inventory of the primary circuit combined with the self-pressurisation features make this behaviour possible with minimum control rod motion. It concludes that the reactor has an excellent behaviour under operational transients.

3.2 Safety Systems

CAREM Safety Systems relays on passive features (Fig. 4) and no there is no need for active actions to mitigate accidents during very long times. All Safety Systems has 100% redundant while the shutdown system is also diverse to fulfil regulatory requirements in force in Argentina.

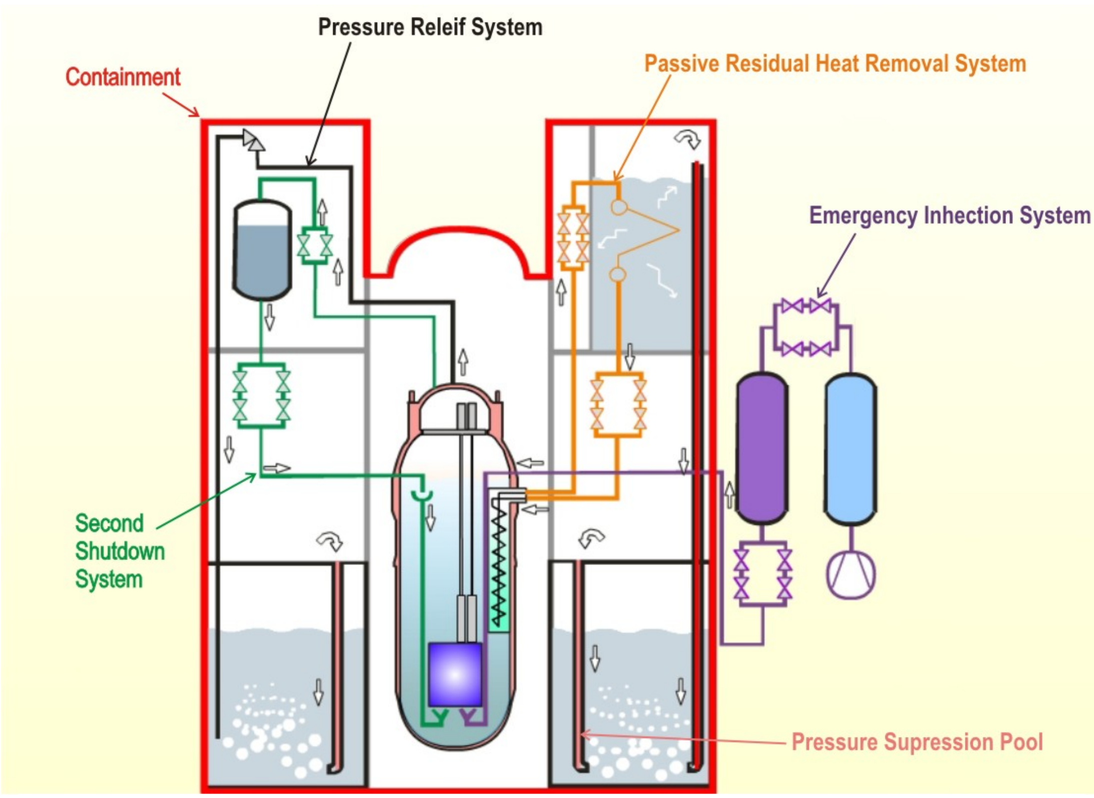

Figure 4 Safety Systems

The First Shutdown System (FSS) is designed to shutdown the core when an abnormality or a deviation from normal situations occurs, and to maintain the core sub-critical during all shutdown states. This function is achieved with the fast insertion of neutron-absorbing elements into the core driven by gravity.

Movement of the AE is done using an innovative design of the Hydraulic Control Rods Drive Mechanism (HCRDM). The HCRDM are located completely inside the RPV avoiding the use of mechanical shafts passing through. In this way it the possibilities of a fast Reactivity Insertion Accident (RIA) caused by rod ejection is avoided by design.

HCRDM is an important development of the CAREM concept [5]. Six out of twenty-five CRDM (simplified operating diagram is shown in Fig 5) are for the Fast Extinction System (FES).

During normal operation they are kept in the upper position, where the piston partially closes the outlet orifice and reduces the water flow to a leakage. The CRDM of the Reactivity Control System (RCS) is a hinged device, controlled in steps fixed in position by pulses over a base flow, designed to guarantee that each pulse will produce only one step.

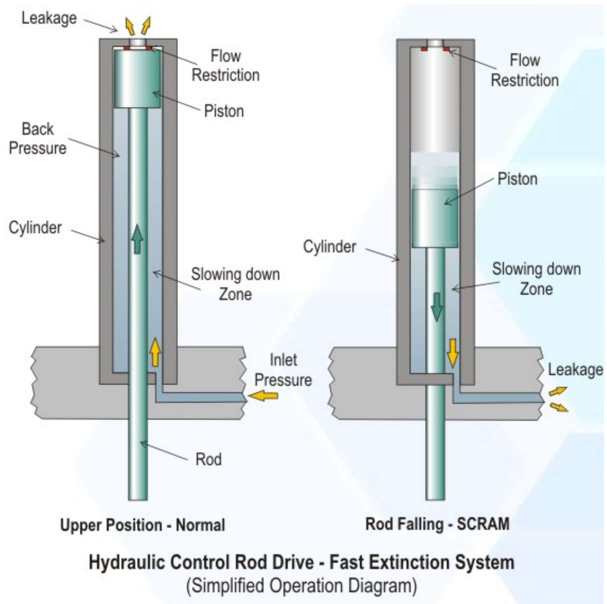

Figure 5 Simplified diagram of Fast Extinction HCRDM

Both types of device perform the SCRAM function by the "fail safe & passive" principle, i.e. rod falls by gravity when flow is interrupted, so malfunction of any powered part of the hydraulic circuit (i.e. valve or pump failures) will cause the immediate shutdown of the reactor. The Fast Shutdown System has differential velocity between upwards (low) and falling (fast) movements. The Reactivity Control System complements the shutdown margin necessary to cope with reactivity changes due to temperature of the coolant during shutdown states.

The Second Shutdown System (SSS) is an injection device of borated water gravity-driven (Natural circulation). It actuates automatically when the Reactor Protection System detects the failure of the First Shutdown System or in case of LOCA. Two tanks are located in the upper part of the containment. Each one connected to the reactor vessel by two pipes: one from the steam dome to the upper part of the tank, and the other from a position below the reactor water level to the lower part of the tank. When the system is triggered, the valves open automatically and the borated water drains into the primary system by gravity. The discharge of a single tank produces the complete shutdown of the reactor.

The Residual Heat Removal System (RHRS) has been designed to reduce the pressure on the primary system and to remove the decay heat in case of Loss of Heat Sink (LHS). The system condenses steam from the primary coolant using emergency condensers. They are heat exchangers consisting of an arrangement of parallel horizontal U tubes between two common headers. The top header is connected to the reactor vessel steam dome, while the lower header is connected to the reactor vessel at a position below the reactor water level. The condensers are located in a pool filled with cold water inside the containment building. The inlet valves in the steam line are always open, while the outlet valves are normally closed; therefore the tube bundles are filled with condensate. When the system is triggered, the outlet valves open automatically. The water drains from the tubes and steam from the primary system enters the tube bundles and is condensed on the cold surface of the tubes. The condensate is returned to the reactor vessel forming a natural circulation circuit. In this way, heat is removed from the reactor coolant. During the condensation process the heat is transferred to the water of the pool by a boiling process. Evaporated water is then condensed in the suppression pool of the containment.

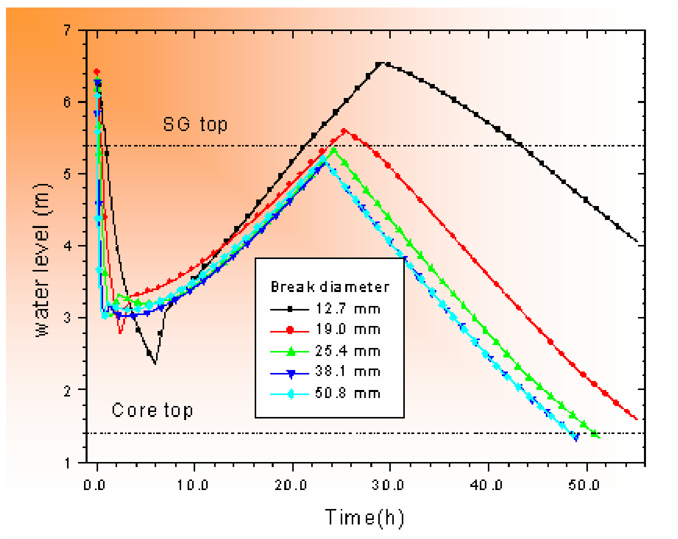

Figure 6. Dynamics response after LOCA

The Emergency Injection System (EIS) prevents core uncovering when pressure is below 15 Bar. In case of a LOCA (limited by design to pipe openings up to 1.5 inches) the Emergency Condensers reduces the primary pressure up to 15 Bars while maintains the water level over the top of the core. Below 15 Bar EIS is necessary to keep the core uncovered for a minimum 48hs after the accident. The system consists of two tanks with borated water connected to the RPV. The tanks are pressurized, thus when the pressure in the reactor vessel reaches 15 Bar, the rupture disks blows-up and the core is flooded.

Three Safety Relief Valves (SRV) protect the integrity of the reactor pressure vessel against overpressure, in case of strong unbalances between the core power and the removed heat. Each valve is designed for 100% relief capacity being the system 300% redundant. The blow-down pipes from the safety valves are routed to the suppression pool.

The primary system, the reactor coolant pressure boundary, safety systems and high-pressure components of the reactor auxiliary systems are enclosed in the primary containment - a cylindrical concrete structure with an embedded steel liner. The primary containment is of pressure-suppression type with two major compartments: a Drywell and Wet well. The Drywell includes the volume that surrounds the reactor pressure vessel and the SSS rooms. A partition floor and cylindrical wall separate the Drywell from the Wet well. The lower part of Wet well volume is filled with water for the condensation pool, and the upper part is a gas compression chamber.

Accident analyses of initiating events considered were grouped into Reactivity Insertion Accident (RI), Loss of Heat Sink (LOHS) and Loss of Coolant Accident (LOCA) [6]. As there are no primary pumps Loss of Flow Accident (LOFA) is not applicable in this case.

As a general conclusion after the accident analysis, it could be said that, due to the large coolant inventory in the primary circuit, the system has large thermal inertia and long response time in case of transients or severe accidents.

3.3 Plant Design

The CAREM nuclear island is located inside the Containment System, which includes a pressure suppression feature to contain the energy of the reactor and cooling systems, and to prevent a significant fission product release in the event of accidents.

The building around the containment has been designed in several levels and it is placed in a single reinforced concrete foundation mat. It supports all the structures with the same seismic classification, allowing the integration of the RPV, the safety and reactor auxiliary systems, the spent fuels pool and other related systems in one block. The plant building is divided in three main areas: control module, nuclear module and turbine module.

Finally, CAREM NPP has a typical PWR steam cycle.

4. Fuel management

Refuelling is done by flooding the Auxiliary Pool located above the RPV. After opening the lid, the internals of the Reflector Vessel (i.e. HCRDM, supporting plates, Barrel, I&C Guides, upper core grid, etc.) are disassembled and transferred to the Auxiliary Pool for temporary storage. The Core remains with the Absorbing Elements in place while a Refuelling Machine, remotely operated, is placed over to replace the Fuels one at a time. The Spent fuels are moved to the Spent Fuel Pool positions via the Transfer Channel.

The spent fuel pool is sized to host up to 10 fuel cores. Starting from 5 years after irradiation, the spent fuels can be stored in Concrete Shielded Dry Storage facilities outside of the reactor building for 200 years.

5. Proliferation Resistance: CAREM is Safeguarded Friendly

Application of the GIF, IAEA Gen IV and GNEP concepts requires the adoption of some basic criteria to address the Proliferation Resistance issue in a proper way.

Several designs show a trend in using Long Life Cores as a way to reduce safeguard requirements and costs on site at NPP. The common approach means for LWR core designs:

a) Higher U Enrichment,
b) One Batch-Full Core Refuelling and
c) Low Power Density

In this way Longer Refuelling Times, higher Burnup and reduced Pu discharge for the Spent Fuel are obtained.

Nevertheless a holistic approach requires also including the whole Fuel Cycle including Front End stages to asses properly the generation and safeguard cost.

The higher amount of fissile material required at the beginning of each operating cycle (BOC) stresses the cost upwards (even more, considering the high discount rate normally seen in most development countries). Also higher enrichment levels reduce the Significant Quantities (SQ) pulling up safeguard cost at the Front End.

A trade off analysis of the levelled cost for and Integrated LWR resembling the CAREM, design was done [7, 8] using enrichment levels between 3 and 5%. It concludes that the optimal solution, considering all fuel Cycle safeguard cost, is obtained for a core design of two refuelling zones, 4% U enriched and pwer density 29kW/kgU. The previous matches the CAREM design.

Safeguards control practices during operation are greatly simplified. Lay CAREM Plant lay out defined two Material Balance Areas (MBA) in which all the existing fissile material at the Plant it is located.

They are:

- MBA1:Upper part of Dry Well &RPV
- MBA 2: Spent Fuel Pool.

The CAREM´s MBA are physically isolated with no way to access to fissile materials during operation (see Figure 7). They could be easily sealed and their integrity checked by a remote sensing systems in an effective way (i.e. using a fiber optic seal or similar).

Then Spent Fuel (SF) and Reactor I/O safeguards costs are dramatically reduced.

6. PROSPECTS (DESIGN EVOLUTION)

In order to improve the cost effective curve, the CAREM can be scaled up to 100MWe keeping all the basic design features of CAREM 25.

The encouraging target is to obtain a NPP competitive in electricity markets with installation cost per kW comparable to current LWR. The previous makes it necessary to adopt the Forced Circulation instead of Natural at the Primary Cooling System keeping the remaining design basis (i.e. Safety Features) almost unchanged. Prospect analysis have shown that one NPP unit of

300MWe based on CAREM Concept Modified (i.e. inclusion of Primary Pumps allowed) would meet successfully this ultimate goal at competitive prices.

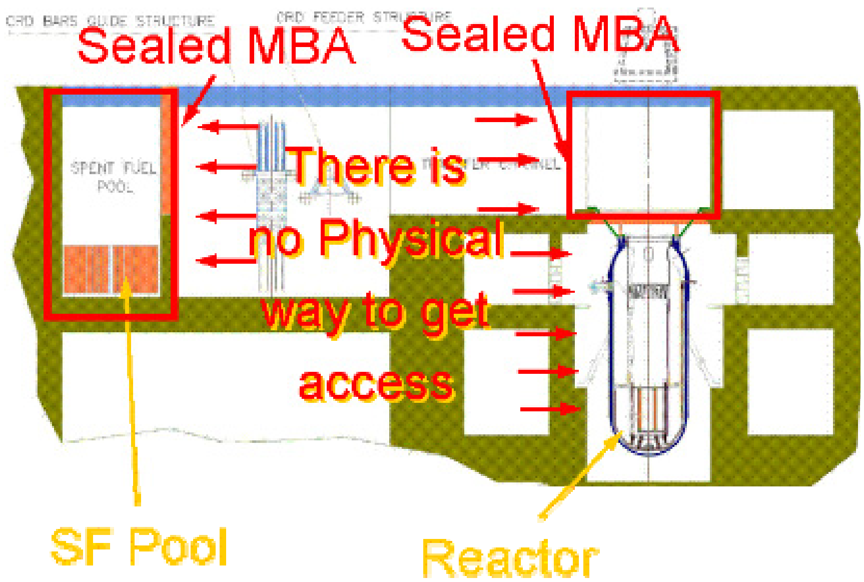

Figure 7: CAREM Safeguard Friendly Design

7. CONCLUSIONS

The CAREM 25 is an indirect cycle reactor with some distinctive features that greatly simplify the reactor and also contribute to a higher level of safety. Some of the high level design characteristics of the plant are: integrated primary cooling system, self-pressurised, primary cooling by natural circulation, safety systems relying on passive features.

A promising future in view of the increasing worldwide acknowledgment of the Nuclear Power as a bulk-environmentally friendly energy source is envisaged; nevertheless the widespread concerns about nuclear safety means the uppermost challenge to the nuclear designers to achieve massive public acceptance of NPP.

CAREM Concept results in a set of design criteria to improve safety by simplifying the design and minimize the use of active features among the systems related to Reactor Safety. The concept drawn more than two decades ago was also adopted by other designers worldwide.

Argentina through CNEA and INVAP sustained several R&D as well as engineering design activities in order to improve and implement these ideas. The resulting solutions were applied to the CAREM 25 prototype actually mature as to be constructed.

The further step of is to obtain a fully commercial scale NPP Design based in the CAREM Concept of 300MWe using primary coolant driven by forced convection.

8. References

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