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CAREM: AN INNOVATIVE-INTEGRATED PWR

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ABSTRACT

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 is an Argentine project aimed to achieve the development, design and construction of an innovative, small and integrated Nuclear Power Plant (NPP). The reactor has an indirect cycle with some distinctive features that greatly simplify the design, and also contributes to a higher safety level. Some of the design highlight are: integrated primary cooling system, primary cooling by natural circulation, self-pressurised primary system and safety systems relying on passive features.

The innovative solutions are embraced in the "CAREM Concept" aimed to enhance safety by using simpler and more reliable solutions to tackle major safety design challenges of the nuclear generation industry. The goal is achieved by drastically reducing the conceivable list of initiating events jointly with a large primary water/power ratio that results in spontaneous slow and mild transients even after most severe system or component failure. In addition all Safety Systems are also based on simple and reliable solutions that increase sharply the overall plant reliability at reduced costs.

The concept has been engineering developed for the CAREM 25 (prototype, 100MWth, 27 MWe) considered an appropriate size to display the performance related with the reactor core cooling and safety systems. This module while not cost effective if compared with major sized NPP´s installation and operating cost, results appropriate for applications such as supplying domestic or industrial electricity and/or steam (i.e. for a water demineralising plant) at isolated or difficult to access, mid size, populations.

A promising market is envisaged for the evolution of the CAREM Concept towards higher Power levels. In this regard the cost effective sizes are 100 MWe (maintaining natural circulation for primary core cooling) and 300MWe (using integrated primary pumps)

Keywords: Integrated advanced reactor, Generation IV, inherent safety, passive safety systems, natural circulation reactors, Small and medium sized reactors (SMR).

1 INTRODUCTION

The Argentinean CAREM project, which is jointly developed by CNEA and INVAP, consists on the development, design and construction of an advanced, simple and small Nuclear Power Plant (NPP). CAREM concept was first presented in March 1984 in Lima, Peru, during the IAEA conference on small and medium size reactors. The criteria we call the "CAREM Concept", has been adopted by other NPP Plant designers, originating a new generation of reactor designs, from which CAREM was chronologically the first.

The first step of this project is the construction of the prototype of about 27 Mwe (CAREM-25). This project allows Argentina to sustain activities in the nuclear power plant design area, assuring the availability of updated technology in the mid-term [1,2].

The design basis is supported by the cumulative experience acquired in Research Reactors design, construction and operation, and Pressurized Heavy Water Reactors (PHWR) Nuclear Power Plants operation as well as the development of advanced design solutions [3].

2 DISTINCTIVE DESIGN CRITERIA

What strongly differentiates the CAREM Concept vs. traditional LWR´s design is the fact that several 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 lower costs Safety Systems.

Among the major benefit of the CAREM Concept applied to NPP design are:

- No large LOCA has to be handled by the safety systems since the maximum pipe connection to the Primary System is limited to 1.5 inches.
- The rod ejection is not possible since mechanisms (hydraulically driven) are completely placed inside the reactor pressure vessel. The solution has been also proved to be highly cost effective.
- Large coolant inventory in the primary results in large thermal inertia providing long response time and small perturbations following severe mechanical or electrical failures.
- Reduced shielding requirements due to the elimination of gamma sources of dispersed primary piping and parts.
- Long lasting RPV Wall since the larger water volume between the core and the primary/pressure boundary leads to a reduced fast neutron dose over the RPV wall.
- Lower operating cost and maintenance as well as higher availability and added safety is achieved by eliminating primary pumps and pressuriser

3 REACTOR DESCRIPTION

CAREM-25 is an indirect cycle reactor with some distinctive features that greatly simplify the design and also contributes to a high safety level. Some of the high level design characteristics are:

- Integrated primary cooling system.
- Primary cooling by natural circulation.
- Self-pressurised.
- Safety systems relying on passive features.

3.1 Primary System

The CAREM reactor pressure vessel (RPV) contains the core, steam generators, the whole primary coolant and the absorber rods drive mechanisms (Fig 1). The RPV diameter is about 3.2 m and the overall length is about 11 m.

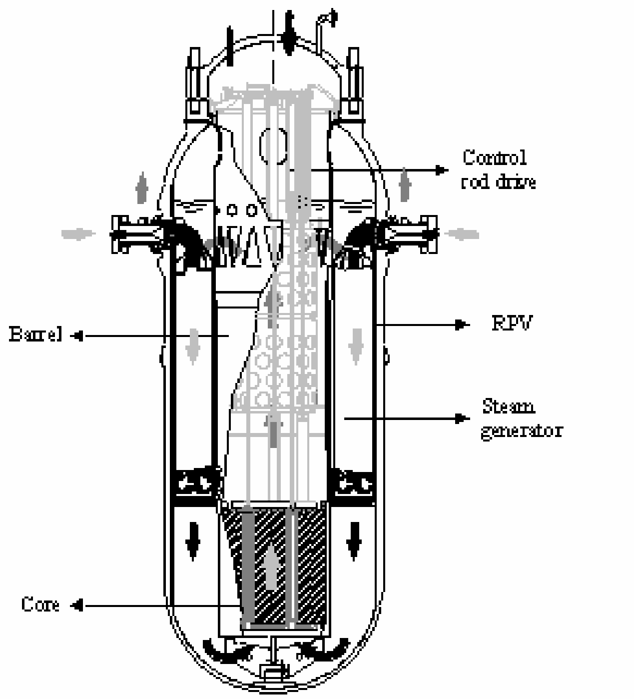

Figure 1. Reactor Pressure Vessel

The core of the prototype has 61 hexagonal cross section fuel assemblies (FA) having about 1.4 m active length. Each fuel assembly contains 108 fuel rods, 18 guide thimbles and 1 instrumentation thimble (Fig 2). Its components are typical of the PWR fuel assemblies. The fuel is enriched UO_2. Core reactivity is controlled by the use of Gd_2O_3 as burnable poison in specific fuel rods and movable absorbing elements belonging to the Adjust and Control System. Chemical compounds are not used for reactivity control during normal operation. Fuel cycle can be tailored to customer requirements, with a reference design of 330 full-power days and 50% of core replacement.

Each Absorbing Element (AE) consists of a cluster of rods linked by a structural element (namely "spider"), so the whole cluster moves as a single unit. Absorber rods fit into the guide tubes. The absorbent material is the commonly used Ag-In-Cd alloy. Absorbing elements (AE) are used for reactivity control during normal operation (Adjust and Control System), and to produce a sudden interruption of the nuclear chain reaction when required (Fast Shutdown System).

Twelve identical 'Mini-helical' vertical steam generators, of the "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 tubes, while the primary goes in counter-current flow. An external shell surrounding the outer coil layer and adequate seal form the flow separation system. It guarantees that the entire stream of the primary system flows through the steam generators.

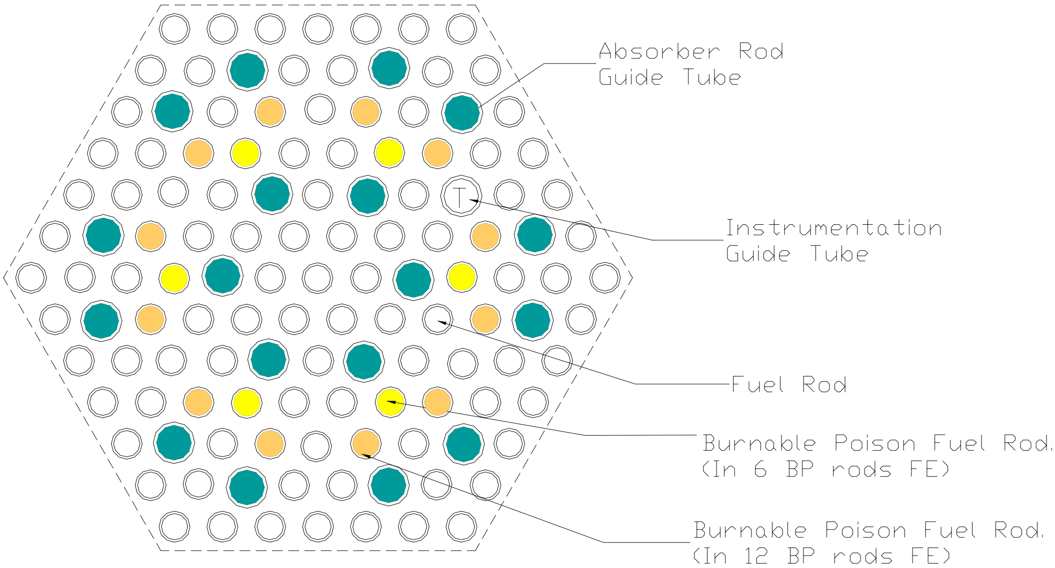

Figure 2. Fuel Assembly diagram. Fuel rods, guide thimbles and instrumentation thimble distribution.

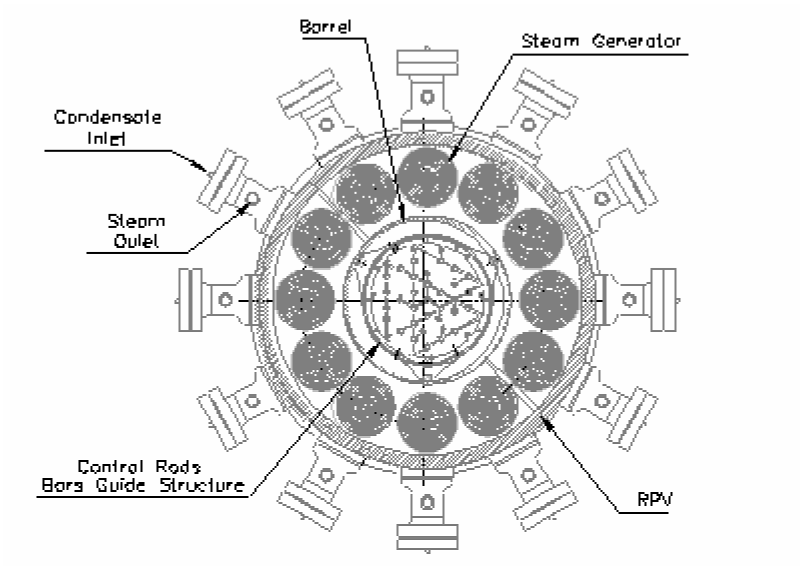

Figure 3. Steam Generation lay out

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. Thus, the outer coil layers will hold a larger number of tubes than the inner ones. Due to safety reasons, steam generators are designed to withstand the primary pressure without pressure in the secondary side and the whole live steam system is designed to withstand primary pressure up to isolation valves (including the steam outlet / water inlet headers) for the 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 ramps. 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 are based on passive features and guarantee no need of active actions to mitigate the accidents during long time (Fig 4). They are duplicated to fulfil the redundancy criteria. The shutdown system should be diversified to fulfil regulatory requirements.

The First Shutdown System (FSS) is designed to shut down 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 by dropping a total of 25 neutron-absorbing elements into the core by the action of gravity. Each neutron-absorbing element is a cluster composed of a maximum of 18 individual rods, which are together in a single unit. Each unit fits well into guide tubes of each fuel assembly.

Hydraulic Control Rods Drives (CRD) avoid the use of mechanical shafts passing through RPV, or the extension of the primary pressure boundary, and thus eliminates any possibilities of big Loss of Coolant Accidents (LOCA) since the whole device is located inside the RPV. Their design is an important development in the CAREM concept [5]. Six out of twenty-five CRD (simplified operating diagrams are shown in Fig 5) are the Fast Shutdown System. 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 CRD of the Adjust and Control System 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.

Both types of device perform the SCRAM function by the same principle: “rod drops 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. CRD of the Fast Shutdown System is designed using a large gap between piston and cylinder in order to obtain a minimum dropping time thus taking few seconds to insert absorbing rods completely inside the core. For the Adjust and Control System CRD manufacturing and assembling allowances are stricter and clearances are narrower, but there is no stringent requirement on dropping time.

The second shutdown system is a gravity-driven injection device of borated water at high pressure. It actuates automatically when the Reactor Protection System detects the failure of the First Shutdown System or in case of LOCA. The system consists of two tanks located in the upper part of the containment. Each of them is connected to the reactor vessel by two piping lines: 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.

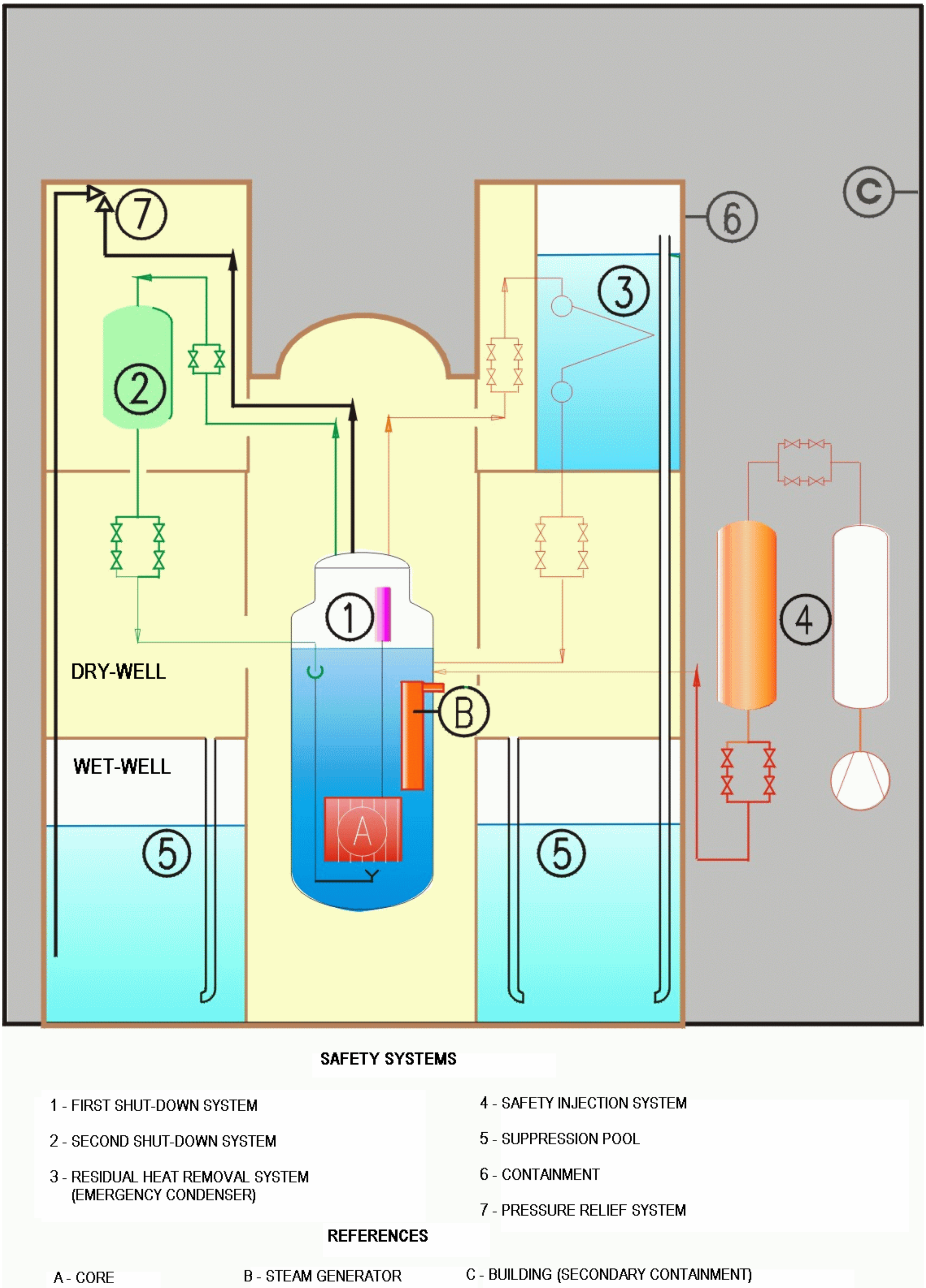

Figure 4. Containment and safety systems

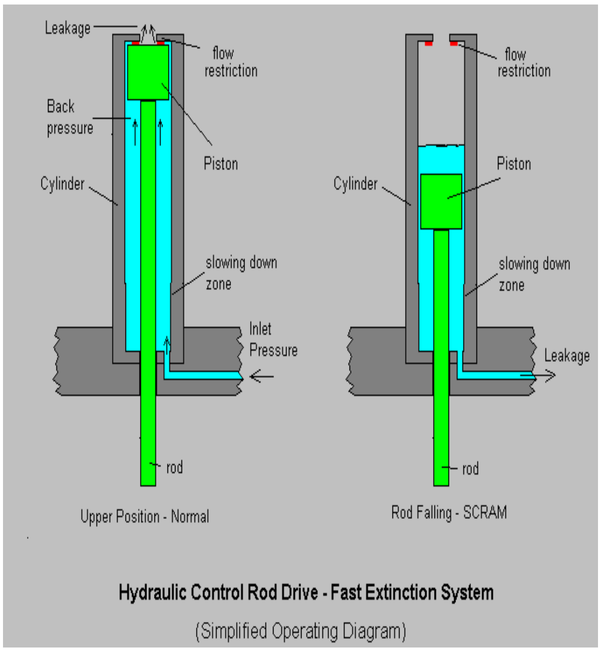

Figure 5. Simplified operating diagram of a hydraulic control rod drive (Fast Shutdown System)

The residual heat removal system has been designed to reduce the pressure on the primary system and to remove the decay heat in case of loss of heat sink. It is a simple and reliable system that operates condensing steam from the primary system in emergency condensers. The emergency condensers 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. This evaporated water is then condensed in the suppression pool of the containment.

The Emergency Injection System prevents core exposure in case of LOCA. In the event of such accident, the primary system is depressurised with the help of the emergency condensers to less than 15 bars, with the water level over the top of the core. At 15 bar low pressure water injection system comes into operation. The system consists of two tanks with borated water connected to the RPV. The tanks are pressurized, thus when during a LOCA the pressure in the reactor vessel reaches 15 bar, the rupture disks break and the flooding of the RPV starts.

Three safety relief valves protect the integrity of the reactor pressure vessel against overpressure, in case of strong unbalances between the core power and the power removed from the RPV. Each valve is capable of producing 100% of the necessary relief. 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 second shutdown system 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 that works as the condensation pool, and the upper part is a gas compression chamber.

For CAREM-25 accident analysis several initiating events were considered. They were grouped into Reactivity Insertion, Loss of Heat Sink (LOHS) and Loss of Coolant Accident (LOCA) [6]. As there are no primary pumps Total 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 placed inside a 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 standard steam cycle of simple design.

4 PROSPECTS FOR CAREM (DESIGN EVOLUTION)

The CAREM Concept can be directly scaled up to 100MWe in order to improve the cost effective curve while keeping all the basic design concept of the CAREM 25.

Though the encouraging target is to have an installed kw cost equal or below 1500 UDS. This target makes it necessary to adopt the Primary System driven by forced instead of natural circulation while keeping the remaining design basis 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.

5 CONCLUSIONS

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 have 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 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.

The second step of is to scale up the CAREM Concept to 100 MWe, nevertheless a full commercial scale NPP based in the CAREM Concept can be obtained reaching 300MWe using primary coolant driven by forced convection.

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