CAREM-25: A SAFE INNOVATIVE SMALL NUCLEAR POWER PLANT

CAREM-25 is an argentine SMR development which involves technical-engineering solutions and several innovative design features resulting in a high economic competitiveness and safety.CAREM-25 is an integral type PWR based on indirect steam cycle withdistinctive design characteristics such as: integrated self-pressurized natural circulation primary cooling system, in-vessel hydraulic control rod drive mechanisms and safety systems relying on passive features.After years of development, the CAREM-25 Project reached such a maturity level that the Argentine government decided on the construction of CAREM-25 prototype.

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INTRODUCTION

In recent years, small modular reactors (SMR) have attracted attention because they can meet the needs of emerging electricity markets. They use a proven technology together with novel designs, including new engineering solutions relying on passive features. Passive safety features do not require outside power input to work, instead depending only on physical laws.

Enhancement of safety is achieved without increasing cost of power generation. While the use of inherent and/or passive safety features results in some components being larger, the number of valves and pumps, and the instrumentation, piping, tubing and wiring requirements, are dramatically reduced. The quantity of safety grade components is also reduced. As a result, a competitive reactor comes into a market formerly closed to nuclear power: the small power plant market.

This new type of innovative reactors, offers a variety of possible applications:

– They are an attractive option to supply electric power to isolated areas which are not connected to main grids, at a cost that competes favorably with other types of electric generation for the same power range.
– SMR are an alternative to the traditional research reactor nuclear center, for those countries willing to enter nuclear technology. At a similar or lower cost, SMR offer the possibility of experiencing with power generation with a low-power plant that includes all systems present in large plants.
– They are suitable for water desalination.
– Even when a high energy demand needs to be satisfied SMR result in a more rational investment than large nuclear power plants, exploiting the so-called "Economy of Multiples," counterbalancing the loss of "Economy of Scale".

In this line is the CAREM-25 reactor from CNEA, which is an Argentine reactor designed to deliver 32MWe with minimum operator feedback control.

The CAREM-25 concept was first presented in 1984 during the IAEA conference on small and medium size reactors. CAREM-25 design criteria or similar ones have since been adopted by other plant designers, thus originating a new generation of reactor design, of which the CAREM-25 was, chronologically, one of the first [1].

This article describes the most important characteristics regarding CAREM-25 emphasizing the thermal-hydraulic phenomena, which differs from existing water-cooled reactors.

SMR ECONOMIC ATTRACTIVENESS

SMR concepts rely on the pressurized water technology, capitalizing thousands of reactor-years operations. Even more, recent evaluations of economic attractiveness show that despite smaller plants size pays a loss of economy of scale, when multiple SMR are deployed on the same site their cost effectiveness, along with investment profitability, is in line and of

CAREM-25: UN PEQUEÑO REACTOR NUCLEAR, SEGURO E INNOVADOR

CAREM-25 es un desarrollo argentino de tipo SMR el cual incluye soluciones de ingeniería junto con características innovadoras dentro del diseño permitiendo grandes mejoras económicas y de seguridad.

CAREM-25 es un reactor integral de tipo PWR de ciclo indirecto el cual cuenta con características distintivas en su diseño tales como: sistema primario de refrigeración auto-presurizado y de circulación natural, mecanismos de control integrados al recipiente de presión accionados hidráulicamente y numerosos sistemas de seguridad pasivos. Luego de años de desarrollo, el Proyecto CAREM-25 ha alcanzado un grado de maduración tal que el gobierno ha decidido la construcción del primer prototipo.

the same order with LNPP [2]. On the other side, design modularization and simplification account for the cost reduction of each single SMR unit and help in meeting an acceptable investment return/levelized cost of electricity targets. Financial analysis also shows a better behaviour of multiple SMR versus LNPP against higher capital costs and construction delays [2]. This "robustness" of the economic performance lies on the following:

(i) Protection against construction delays: (a) the possibility to learn from the past reduces the probability of an "intrinsic" delay in later SMR deployment; and (b) investment modularization of SMR decreases the exposure of the whole SMR project to "external" delay events.

(ii) Better financial behaviour: shorter construction periods of SMR limit the financial cost escalation and allow to better cope with high capital costs and, in general, with construction delays and unfavourable scenario conditions.

CAREM-25 MAIN FEATURES

CAREM-25 is an integrated reactor: the whole high energy primary system - core, steam generators (SG), primary coolant and steam dome - is contained inside a single reactor pressure vessel (RPV) with some characteristics which make it slightly different from conventional PWRs in operation nowadays:

- Integrated and self-pressurized primary system
- Cooling by natural circulation
- Passive safety systems
- Plant control performed by a distributed software system

These features make the CAREM-25 reactor highly safe and economic.

Safety enhancement is basically the result of two facts:

- Many events that would lead to accidental conditions are rendered impossible by the innovative design and
- the reliability of the CAREM-25 engineered safety systems is higher than standard, because they are passive and simple (Table 1).

The combination of these two characteristics implies a reduced risk of accident for the plant, the probability of accident being much lower than that of conventional designs.

Due to self-pressurization heaters and sprinklers characteristic of conventional PWRs are thus eliminated (Figure 1).

Name	CAREM-25
Reactor type	PWR int.
Thermal power	100 MW(t)h
Electric power	32 MW(e)
Fuel type	LE UO_2
Cooling method	Nat. Circ.
Coolant volume	39 m^3
Mass flow rate	410 Kg/s
Nominal pressure	12.25 Mpa
Core outlet temp.	284 °C
Core inlet temp.	326 °C
Core height	1.4 m
Chimney height	4.6 m
N° of SG	12
Feedwater temp.	200 °C
Secondary pressure	4.7 MPa

Table 1. Basic CAREM-25 data.

As a result of these simplifications technical and economic advantages are obtained compared to traditional designs:

- No large Loss of Coolant Accident (LOCA) is possible due to the absence of large diameter external piping associated to the primary system. The largest possible break in the primary is 38 mm.
- Large thermal inertia and long response time in case of transients or severe accidents are the result of the large ratio between primary coolant inventory and power.
- Eliminating primary pumps results in lower costs, added safety, and advantages for maintenance and availability.
- Quality control, construction schedules and costs, strongly benefit from the elimination of difficult welding at construction site and off-site assembly of the primary system.
- Shielding requirements are reduced by eliminating gamma sources inside dispersed primary piping and components.
- A very low fast neutron dose over the RPV wall is achieved by the large water volume between core and wall.
- Lower costs, added safety, and maintenance and availability advantages are the result of eliminating primary pumps and pressurizer.

REACTOR MAIN COMPONENTS

Steam Generators

Twelve identical 'Mini-helical' vertical SG of the ´once-through´ type, equidistant with each other around the inner surface of the RPV, transfer to the secondary circuit the heat from the primary, producing dry steam at 4.7MPa, 30°C superheated.

The location of the SG above the core favors natural circulation. Coolant in the primary and secondary sides flows in countercurrent, with primary coolant flowing downwards inside the tubes.

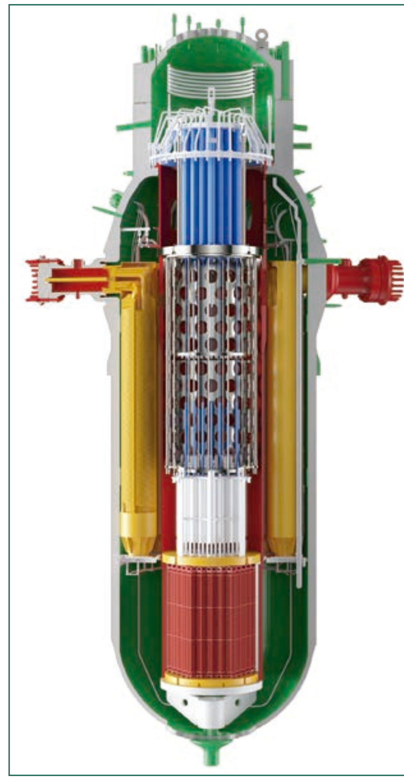

Figure 1. Reactor pressure vessel.

Core

The core has 61 fuel elements (FE) of hexagonal cross section which hold 108 fuel rods 9mm in diameter and 1.4m active length, 18 guide tubes for absorption rods, and 1 instrumentation thimble each. The use of natural circulation requires a low head loss design.

The reactor core design is based on:

- A strongly negative density and temperature feedback coefficients
- Adequate thermal margins
- Low power density
- Avoidance of boron for reactivity control during normal operation.

The FE do not have channels, allowing cross coolant circulation which has some benefits: FE generating higher than average power, have a lower static pressure component due to the lower density of the coolant

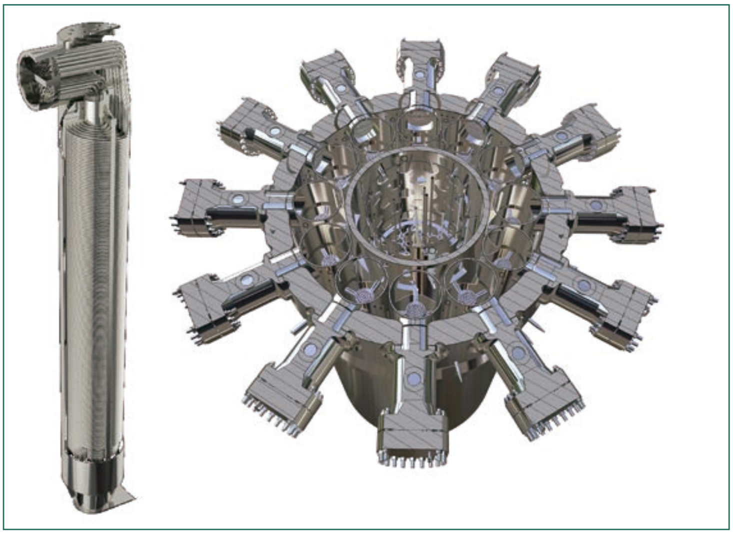

Figure 2. One of the twelve integrated helically coiled steam generators.

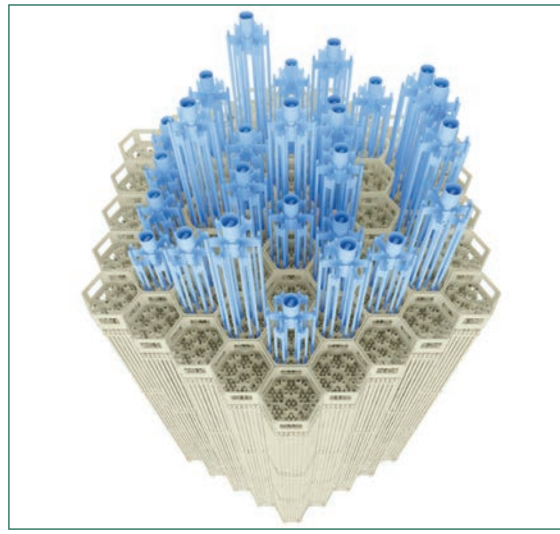

Figure 3. Detail of the fuel elements with control drive systems.

around them. As all FE have the same pressure drop, lower static pressure is compensated by higher dynamic pressure, thus FE generating higher power will have higher mass flux.

Fuel elements

The fuel is uranium with 1.8 and 3.1% enrichment. An 8% weight of Gd203 is used as burnable poison placed in specific fuel rods of 60 FE to keep reactivity approximately constant along the fuel cycle.

The fuel element is designed to withstand fast power ramps, providing the reactor with excellent load-following characteristics.

Control elements

Twenty five independent drive systems move vertically the 25 neutron absorbing elements in and out of the core according to the needs of the Regulation and Control System (RCS) and the Fast Shutdown System (FSS).

The drives are of the hydraulic type and included in the RPV. Absorbing elements are maintained at fixed positions while hydraulic flow is being circulated through the drives. Controlled changes of rod position are achieved by means of flow pulses. In the event of a blackout rods fall automatically due to the interruption of hydraulic flow.

THERMALHYDRAULICS

The entire high-energy primary system is contained inside a single 11m high, 3.5m-diameter RPV. Self-pressurization of the primary system is the result of the liquid-vapour equilibrium in the steam dome. The large vapour volume in the RPV also helps damp pressure perturbations. The self-pressurization means that bulk temperature at the core outlet is at saturation temperature at primary pressure (12.25MPa).

Physical phenomena

The physics in CAREM-25 involve different phenomena such as self-pressurization, flashing, natural circulation, condensation, density wave instabilities and neutronic coupling. Despite these are relatively well known, in combination they give rise to feedback loops that influence the reactor dynamics, creating novel situations some of which are described below.

In the CAREM-25 reactor the steam quality is very low and therefore the largest contribution to the momentum balance is due to single-phase buoyancy forces. In order to have a constant system pressure some vapour needs to be created inside the RPV fixing the core outlet temperature close to the saturation value. Vapour condensation takes place in the upper part of the RPV and is a direct consequence of the heat losses and the interaction between the vapour and cold structures in the steam dome, such as those from the RCS.

It has been shown in previous works that under operational conditions, when the power level is reduced while all other parameters are kept constant, the core mean enthalpy approaches saturation value, that is, the core at low power levels is hotter than at nominal conditions. This counter-intuitive result is related to the fact the core inlet enthalpy is not a controlled variable as in conventional reactors [3][4].

Since the core exit vapour quality is practically zero, a certain amount of vapour is produced by flashing in the chimney which enhances the self-pressurization of the system: if the vapour production rate is greater than the condensation rate, the system pressure will increase and the flashing effect will diminish helping keeping the pressure constant [3][4].

The CAREM-25 reactor operates in a particular region of the critical heat flux q_{cr} versus mass flux G curve which is characterized by a *decrease in* q_{cr} *when increasing* G. For this reason the mass flow rate must remain within a certain range to avoid any undesired consequences. In particular, it must not exceed the design value in order to preserve the thermal margin [3].

Despite this constraint, the fact that CAREM·25 operates in such a particular region of the q_{cr} vs. G curve has certain benefits in accidental conditions. When the reactor is scrammed, the mass flux decreases since the power is considerably reduced. As a result the reactor starts operating in a region with a higher critical power which helps *increase* the thermal margin. The same argument can be made if the coolant level accidentally decreases in the RPV [3].

DYNAMICS, CONTROL ARCHITECTURE AND FUEL MANAGEMENT

The reactor has very good transient response and load following capability. As mentioned previously reactivity control during normal operation is achieved by means of movable control elements and burnable poisons.

The control system is capable of keeping the reactor pressure practically at the operating set point through transients, when the plant is subject to demanding power ramps.

The strong negative temperature coefficient and the large water inventory of the primary circuit make possible this behaviour with minimum control rod motion.

CAREM-25 allows using smart equipment and predictive maintenance technology which provides a system-level integration of plant maintenance information and real time sensor data utilizing the self-monitoring and self-diagnostic characteristics built into the equipment [5]. The system is designed around a distributed software architecture that allows scale up to enterprise-wide applications and provides the ability to view real time equipment performance and safety-related data from remote locations.

Fuel cycle can be tailored to customer requirements, with a reference design of 400 full power days and 50% core replacement.

Figure 4. Control room with a distributed software system.

SAFETY

Engineered safety systems

Safety systems are designed on the basis of simplicity and reliability. They are mainly of passive type since they do not need any external input to operate.

- *First or Fast Shutdown System (FSS):* Each absorbing element is made up of a set of Ag-In-Cd absorbing rods that move as a single unit. The 25 absorbing elements of the FSS are dropped into the core by the action of gravity and produce the immediate extinction of the nuclear chain reaction. Absorbing elements of the Regulation and Control System (RCS) are equal to those of the FSS.
- *Second Shutdown System (SSS):* High pressure emergency boron injection. When the system is triggered, two tanks with 1m^3 capacity each drop borate water into the RPV by the action of gravity in less than 35 minutes. Although the SSS is a backup for the FSS, each tank is able to produce by itself the complete extinction of the reactor.
- *Pressure Relief Valves (PRV):* Two relief valves are included. Each valve is capable of producing 100% of the relief required to protect the mechanical integrity of the RPV against overpressure arising, for example, from strong unbalances between the power generated at the core and the power extracted by the heat removal systems.
- *Passive Decay Heat Removal System (PHRS):* Designed to reduce the pressure on the primary system and to remove the decay heat in case of Loss of Heat Sink by 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 RPV steam dome, while the lower header is connected to the RPV at a position below the 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. 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 condenses on the cold surface of the tubes. The condensate returns to the RPV closing the natural circulation circuit. 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.
- *Emergency injection system (EIS):* It prevents core exposure in case of a Loss of Coolant Accident. Following the initiation of a Loss of Coolant Accident (LOCA) the primary system is depressurized and, with the participation of the passive heat removal system, or the boron injection system, pressure goes down to less than 1.5MPa with the core fully covered. At 1.5MPa the low pressure water injection system comes into operation. The system consists of 2 borate water tanks connected to the RPV. In the event of a LOCA, tank pressure of 2.8MPa produces the break-up of a 1.5MPa pressure seal, flooding the RPV. The system provides 36 hours of protection to the core.
- *Containment system:* It is of the pressure suppression type. It has a dry premise surrounding the RPV, and a wet premise containing the pressure suppression pool. Leaks in the primary system produce a pressure rise in the dry premise, which forces vapor into the pressure suppression pool, where it is condensed producing a temperature rise in the wet premise. In case of a LOCA with fuel element damage, a high portion of fission products are retained in the pressure suppression pool. It is built with 1.2 m thick walls made of reinforced concrete with an 8mm steel liner.

PLANT RESPONSE TO ACCIDENTS

Total power failure: It is one of the major factors contributing to core meltdown probability in a conven-

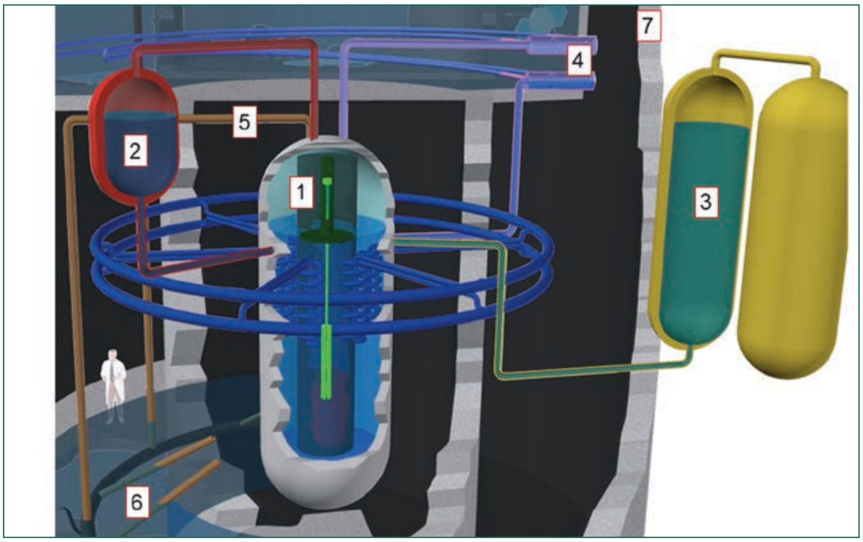

Figure 5. Plant safety systems layout: 1-First Shutdown System (FSS); 2-Second Shutdown System (SSS); 3-Emergency Injection System (EIS); 4-Passive Heat Removal System (PHRS); 5-Pressure Relief Valves (PRV); 6-pressure suppression pool; 7-Containment system.

Figure 6. Details of the ongoing construction: first stage of the liner placement.

tional light water reactor. In CAREM-25 the primary cooling system and the PHRS will continue in operation, and reactivity feedback coefficients will produce the reactor self-extinction. At the same time, depressurization of the absorbing element hydraulic control rod system due to power cut off, will produce automatic release of all absorbing elements into the core, in approximately 2 seconds.

In the case of loss of heat sink or station black-out, safe core temperature is assured due to availability of one of the condensers of the PHRS for the grace period of 36 hours.

Loss of coolant accident: Since only small LOCAs are possible, and due to the large water inventory of the primary, there is a long time span between the initiation of the LOCA and core exposure, in comparison with conventional PWR. The largest possible break of 38mm in the primary system allows for about 20 minutes of depressurization, before the EIS comes into operation with RPV pressure at 1.5 MPa and the core fully covered.

Main steam pipe break: It produces a transient that can be easily handled by the safety systems due to the small water inventory of SG and large inventory of the primary.

PROJECT STATUS

The licensing process for the construction of CAREM-25 prototype was approved by the Argentina Regulatory Body (ARN) in 2010. Preliminary Safety Analysis Report and the Quality Assurance Manual were submitted to ARN (Federal Authority) for review. In September 2013, the ARN delivered the authorization to start the construction of the Prototype: Stage1, auxiliary buildings. After completion of licensing process, construction of the Prototype started. Contracts with different Argentinean stakeholders for manufacturing of components issues have already been signed. Environmental Impact Study was approved by the Local Authority. Non-nuclear buildings first concrete was poured in February 2014.■

REFERENCES

[1] Delmastro, "Thermal-hydraulic Aspects of Self-Pressurized Natural Circulation Integral Reactors". Int. Workshop on Thermal-Hydraulics of Innovative Reactor and Transmutation Systems–THIRS, Germany, April 2008.

[2] Boarin and Ricotti. An Evaluation of SMR Economic Attractiveness. Science and Technology of Nuclear Installations. ID 803698, Vol. 2014.

[3] Marcel, Delmastro, Furci, Masson. "Stability of self-pressurized, natural circulation, low thermo-dynamic quality, nuclear reactors: Phenomenology involved in the thermal-hydraulics of the CAREM-25 reactor". Nuclear Engineering and Design 254, 2013.

[4] Marcel, Delmastro, Furci, Masson. "Stability of self-pressurized, natural circulation, low thermo-dynamic quality, nuclear reactors: Phenomenology involved in the thermal-hydraulics of the CAREM-25 reactor". Nuclear Engineering and Design 265, 2013.

[5] International Atomic Energy Agency. "Improving economics and safety of water cooled reactors: Proven means and new approaches". IAEA-TECDOC-1290, 2002.