ARGENTINEAN INTEGRATED SMALL REACTOR DESIGN AND SCALE ECONOMY ANALYSIS OF INTEGRATED REACTOR

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1. ABSTRACT

This paper describes the design of CAREM, which is Argentinean integrated small reactor project and the scale economy analysis results of integrated reactor.

CAREM project consists on the development, design and construction of a small nuclear power plant. CAREM is an advanced reactor conceived with new generation design solutions and standing on the large experience accumulated in the safe operation of Light Water Reactors. The CAREM is an indirect cycle reactor with some distinctive and characteristic features that greatly simplify the reactor and also contribute to a highly level of safety: integrated primary cooling system, self pressurized, primary cooling by natural circulation and safety system relying on passive features.

For a fully coupled economic evaluation of integrated reactors done by IREP (Integrated Reactor Evaluation Program) code transferred to IAEA, CAREM have been used as a reference point. The results shows that integrated reactors become competitive with power larger than 200MWe with Argentinean cheapest electricity option. Due to reactor pressure vessel construction limit, low pressure drop steam generator are used to reach power output of 200MWe for natural circulation. For forced circulation, 300MWe can be achieved.

2. INTRODUCTION

Present active nuclear power programs take place in countries with high GNP growth and related electricity energy demand are far away of expectancies in the '80. For developing countries focused in high economic growth and rationale energy use, the nuclear power will be an inevitable power source in several countries. Construction of power plants in these countries depend on the electric grid size to fit the power output of a competitive NPP and budget limits.

Traditionally, nuclear countries have large economies and electric grids or strong national nuclear commitment [1]. However, in the near future the demand of nuclear reactors seems to move towards faster growing economies and countries [2], with new electrical grids. From the point of view of the competitiveness, higher power nuclear plants are seriously questioned in this new market.

An example of the disadvantages of the classical technology approach is the new effort to increase even more the huge power output evolutionary LWR as the main way to improve the economics to be competitive with Combined Cycle Gas Turbines (CCGT) [3].

When an old technology is replaced by a new one, it is very unusual that new technology leadership will be in the same hands that the old one. In a changing environment, the inertia of the well-proved technologies is a strong disadvantage to developed innovations.

The attractiveness of only introduce minor changes in the design is a big problem to developed a really new design. In well-proved leadership, the new technologies are looked as "enemies". The candidates of the new leadership look new technologies as real "advantages".

Figure 1 shows new reactor designs proposed in last decade and power demand distributed by regions, and figures 2 show the power of the commercial new reactor designs in the last decade together with the power output of available CCGT. Its clear that countries and power ranges of proposed new reactors are strongly different than present commercial technologies, trying to design reactors with power output as flexible as CCGT.

Figure 1: Power Demand and New Reactor Design Distribution by Regions

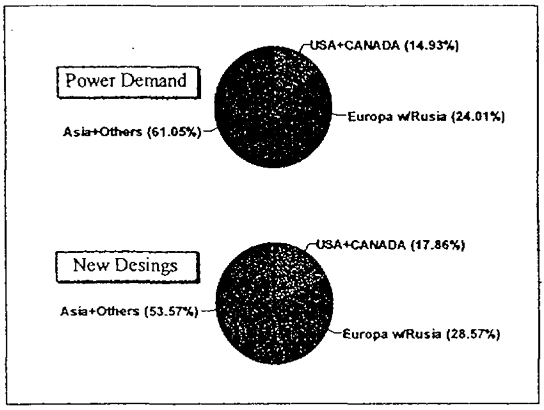
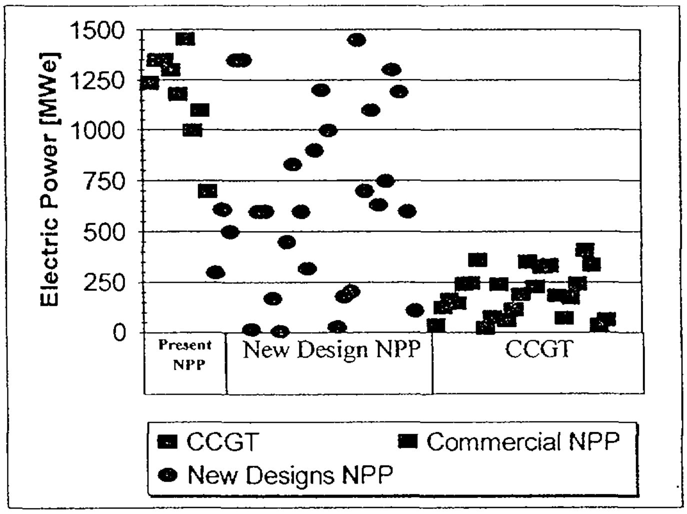


Figure 2: Power Output of Commercial/New Design NPP and CCGT.



3. ARGENTINA AND CAREM PROJECT

Argentina is a developing country with medium incomes and open economy. Its open electrical market evolved to the cheapest energy price and this situation it's usually taken as an example of a market driven system. Argentina has huge natural gas resources, with a developed gas transport system. This gas situation produce that the cheapest electricity option are gas turbines (GT) and combined cycle gas turbines (CCGT) in short and medium time scale. Power range for new plants added to the systems are GT and CCGT around 300 MWe

CAREM is a CNEA (Comisión Nacional de Energía Atómica) project, which is jointly developed by INVAP. CAREM is a project for an advanced, simple and small nuclear power plant, conceived with new generation design solutions and standing on the large world wide experience accumulated in the safe operation of Light Water Reactors. The CAREM is an indirect cycle reactor (100 MWt, approx. 27 MWe) with some distinctive features that greatly simplify the reactor and also contribute to a higher level of safety:

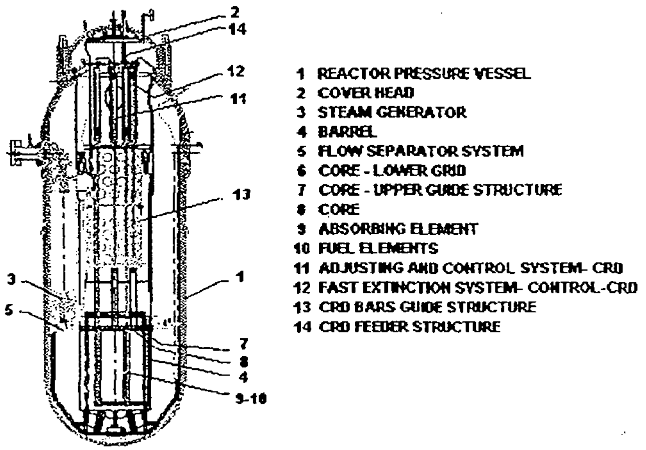
- Integrated primary cooling system.
- Primary cooling by natural circulation.
- Self-pressurised.
- Safety systems relying on passive features.

CAREM-25 may be seen, as a product, under several points of view. First, as a National Project part of Argentine Nuclear Policy, assures the availability of updated technology in the mid-term. This implies working with the technology already acquired in design, construction and operation of Research Reactors and operation and improvements of Pressurized Heavy Water Reactors, and developing advanced design solutions. Then, as a "Bridge Project", connecting R&D nuclear activities with full scale Nuclear Power Plants. It allows the development of human resources, technical/industrial capabilities and licensing and management infrastructure. Finally, as a very Small NPP, well suited to provide electricity in isolated areas, competes in restricted isolated markets. In addition, CAREM may be implemented for co-generation applications as seawater desalination or process heat production.

4. CAREM TECHNICAL DESCRIPTION

4.1. PRIMARY SYSTEM

Figura 3: Reactor Pressure Vessel



The Core has 61 Fuel Assemblies (FA) of hexagonal cross section. Its components are typical of the PWR fuel assemblies. The fuel is UO_2 enriched at 1.8 and 3.4%. Burnable poison are used to keep reactivity approximately constant along the fuel cycle. Chemical shim is 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, so the whole cluster moves as a single unit into guide tubes in positions not occupied by fuel rods. 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 Extinction 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). 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 does so 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.

In order to achieve a rather uniform pressure-loss and superheating on the secondary side, the length of all tubes is equalised 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. The natural circulation of the 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.

Due to the self-pressurising 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.

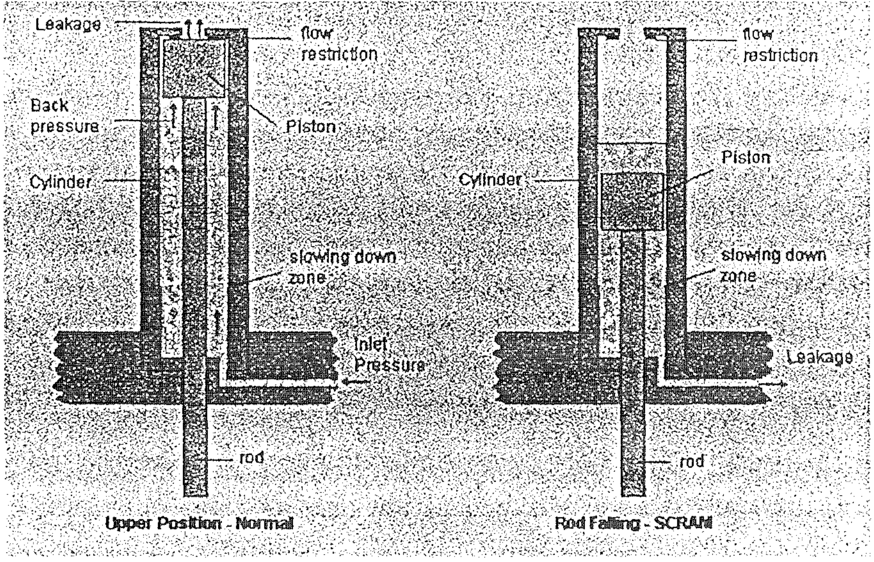
4.2. SAFETY SYSTEM

Hydraulic Control Rods Drives avoid the use of mechanical shafts passing through, or the extension of the primary pressure boundary, and thus eliminates 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. Six out of twenty-five CRD (simplified operating diagram are shown in figure-2) are the Fast Extinction 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 devices, 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 extinction of the reactor. CRD of the Fast Extinction 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 of 2 m^3 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: Simplified Operating Diagram of Hydraulic Control Rod Drive



The residual heat removal system is 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 via piping 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 of 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.

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 bar, with the water level over the top of the core. At 15 bar a low pressure water injection system comes into operation. The system consists of two tanks with borated water connected to the RPV. The tanks are pressurised to 21 bar, 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.

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 wetwell. 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 wetwell. The lower part of wetwell volume is filled with water that works as the condensation pool, and the upper part is a gas compression chamber.

Since only small LOCA's are possible, and due to the large water inventory of the primary system, there is a long time span between the initiation of the LOCA and core exposure, in comparison with conventional PWR's. The largest break in the primary system allows some minutes of depressurisation before the Emergency injection system comes into operation with the RPV pressure at 15 bar and the core fully covered.

Main steam line break produces a transient that can be easily handled by the safety systems due to the small water inventory of the steam generators in the secondary side and the large water inventory of the primary system.

4.3. 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 surrounding 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

4.4 MAIN ADVANTAGES OF CAREM DESIGN

Technical and economical advantages are obtained with the CAREM design compared to the traditional design:

- No large LOCA has to be handled by the safety systems due to the absence of large diameter piping associated to the primary system. The size of maximum possible break in the primary is 38 mm.
- Large coolant inventory in the primary results in large thermal inertia and long response time in case of transients or accidents.
- Shielding requirements are reduced by the elimination of gamma sources of dispersed primary piping and parts.
- The large water volume between the core and the wall leads to a very low fast neutron dose over the RPV wall.
- Eliminating primary pumps and pressuriser results in lower costs, added safety, and advantages for maintenance and availability.
- Its steam generator, control rod design, pressure vessel, pressure control system and safety system are consistent with a generall design criteria of a reactor technology with excellent scaling up capabilities for an integrated PWR.

5. SMALL REACTOR COMPETITIVE FOR MEDIUM SIZE GRID USING IREP AND CAREM

Small nuclear power plants (around 300 MWe) has been studied for a long time. These designs never have reached commercial level in industrialized countries. One reason has been that the reactor technology naturally moves towards the best economy, i.e. the greater power. The second reason has been that the nuclear designers were always in countries with large electric systems. Consequently the utilities never have been attracted by prototypes of small reactors. The only option to develop a competitive medium nuclear reactors is to develop a design with different scale economy, like the scale economy of CCGT, if it used LWR technology the design could be the best alternative for the utilities because availability of present LWR are one of the main advantages as a proved power source. The most promising type of LWR with this possibility is the integrated type.

Then its very interesting to study if the Argentinean experience on CAREM project could be used at higher power output, in order to expand the market in a second step, adding an addtional target of to be competitive with CCGT under argentinean electrical grid condition.

The economical and technical study of CAREM 25 scaling up has been done using the IREP code [4], transferred to the IAEA. The IREP code is a program specially developed in order to be used in many different ways. This code is a simple and fast tool to design or evaluate at conceptual level an integral type PWR. With a simple and interactive input performed neutronic, thermal hydraulic, mechanical and economical evaluation of the reactor, and gives the leveled electricity generation costs as a main result. They provided all the technical results of the different subjects, and show the results with interactive screens similar to the user – friendly environment for the data input.

Integrated PWR usually used different engineering solutions for steam generator type and coolant driving force. To evaluate the technical and economical advantage or disadvantages of some solutions, the IREP code could be run with two different types of Steam generator and with natural convection or forced convection. The mechanical design of the nuclear power plant takes into account the main components of the pressure vessel, including the main dimensions and total weight. Mechanical design includes gaps and distances between different components. Primary circuit pressure drop includes core, riser, and steam generator and down – comer one dimensional pressure drop calculation. Core pressure drop includes the distributed friction and inlet, outlet and spacers concentrated pressure drops. Force and natural convection designs have been calculated using mass, energy, and impulse one-dimensional single-phase equations. IREP neutronic model includes the Beginning of Life (BOL) reactivity, extraction burnup, and void reactivity coefficient calculation. The batch irradiation time is calculated together with the load factor of the plant.

IREP code calculate the cost for NPP calculated by the specific weight of the main components designed in the mechanical routine, and all the other equipment of the total investment is estimated using classics scaling methods for different variables. The financial cost are calculated using the detailed data provided by the user, and then calculate the net present value of the total capital investment at the time of initial commercial operation.

The fuel cycle costs is calculated by the code using the user provided data, and includes the first core amortization, together with the investment of the refueling costs. With the load factor calculated by the code, the Total Unit Energy Cost (TUEC), in mills/kWh, is calculated. All the investment costs breakdown and other typical economical data are provided by the code, automatically adjusted with the scaling factors.

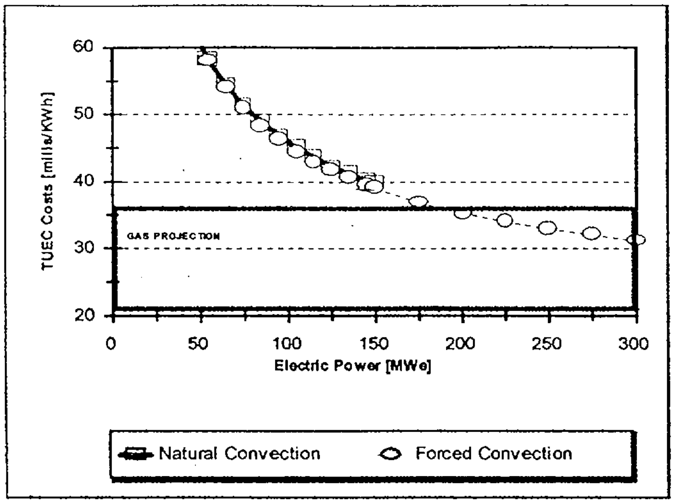
5. ECONOMICAL FEATURES OF UPRATED CAREM VERSIONS

Using IREP code, with RPV length limit of 15 meter, natural convection design could reach up to 65 to 200 MWe and forced convection design could reach up to 160 or 300 MWe depending on the design of steam generator.

The results for the total generation costs including the corresponding power limit for the best steam generator could be seen in figure 5. Natural convection design could reach competitive power output only when low pressure drop steam generators are included because the RPV limit put strong restriction on power increase. For natural convection design at 200 MWe the reactor reach the competitive Argentinean CCGT region. In forced convection design the power limit is at 300 MWe, and the competitive region starts at 200 MWe.

These results have been checked using other costs breakdown and scaling up methodologies with similar result. The confidence on extrapolations methods have been strongly improved using the IREP , because these code takes into account all the main engineering feedback.

Figure 5 Leveled energy costs using CAREM 25design data with IREP code, compared with the leveled energy costs of CCGT in Argentina



The total cost variation decreases substantially above 200 MWe for the O&M costs and the economics impact of maintenance and salaries at low power. On the other hand the fuel cycle cost is the less sensitive even with the reactivity and burnup penalties of the small cores. The O&M costs at higher power are in good agreement with the data from Argentinean Atucha NPP (340 MWe).

6. CONCLUSIONS

The CAREM project consists on the development, design and construction of the prototype of an advanced small nuclear power plant. The CAREM is an indirect cycle reactor with some distinctive features that greatly simplify the reactor and also contribute to a higher level of safety: integrated primary cooling system, self-pressurised, primary cooling by natural circulation, safety systems relying on passive features. Therefore, many technical and economical advantages are obtained with the CAREM design compared to the conventional designs.

In oder to study the technical features of CAREM at higher power output, the IREP (Integrated Reactor Evaluation Program) code has been used, together with CAREM engineering and economical data. The results shows that integrated reactors become competitive with power larger than 200MWe with Argentinean cheapest electricity option. Due to reactor pressure vessel construction limit, low pressure drop steam generator are used to reach power output of 200MWe for natural circulation. For forced circulation, 300MWe can be achieved.

7. REFERENCES

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