CAREM-25: a Low-Risk Nuclear Option

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ABSTRACT

The future use of nuclear energy for electricity production is assumed as a viable alternative at present, mainly taking into account the high environmental impact of the fossil fuel alternatives (greenhouse effect, acid rain). In the worldwide context, however, it is desirable that the next generation of nuclear power stations to be safer than the present ones. To demonstrate the safety level of a particular nuclear installation, the Risk Analysis (or Probabilistic Safety Assessment) is the most appropriate tool. Quantitative risk estimations can be performed with PSA. The risk can be split as the product of two factors: the first one takes into account the occurrence probability of accidental sequences that involve the release of radioactive material, and the second takes into account the magnitude and consequences of such a release. In the present work, the reduction of both factors is analyzed. The probability is reduced by the use of simpler and more reliable systems to perform the safety functions, and the consequence by the use of small power production units, provided with passive mitigation systems and long response times. The work is illustrated with a risk comparison for electricity production with CAREM-25 units, towards classic production units (Atucha II). The results are based on PSAs performed for both plants. The conclusions show an effective risk reduction (both in probability and in consequence) for the innovative CAREM-25 plant, coming to doses so low as to prevent any acute effect in the nearby population.

Keywords: nuclear energy, risk, future reactors, environment

I. INTRODUCTION

The use of nuclear energy in the next future depends, among other considerations, on the safety level of the next generation of Nuclear Power Plants. The safety characteristics will determine the acceptability or not of a certain reactor design, and the safety objective is posed on plants that can withstand severe accidents without exposing the surrounding public to high doses of radiation.

This objective is not possible to fulfill for the present generation of nuclear power plants, where severe accidents likelihood can be reduced to acceptable low values, but their consequences, given their occurrence, may be catastrophic.

Several new designs are being studied and prototypes built, that try to reduce both the likelihood (probability) and consequences (doses), using inherently safe concepts, passive safety systems, and several inherent mitigation features. Among these, the CAREM-25 [1] is designed to have a very high safety level, and severe accidents are explicitly considered during its design stage, as recommended in [2] for all future nuclear power plants.

It is difficult to deterministically define which safety level is acceptable, and the Probabilistic Safety Assessment (PSA) becomes a suitable tool to evaluate different alternatives. The risk is expressed as the product of the probability of severe accidents multiplied by the consequence of those accidents, and combined over all the imaginable accidental sequences.

The effort should be posed not only in the severe accident probability reduction, but also in the consequence reduction, and emphasizing the completeness of the study. Several design alternatives for nuclear electricity production have been studied from this focal point, and the CAREM-25 also. A level III PSA was performed for this plant at a basic design stage, and some of
its results are presented in the following sections. It is important to take in mind that the performance of a PSA at an early design stage, allow for retrofitting the risk-based lessons into the design itself, and the process tries to optimize the design and cost of the plant, from a risk reduction perspective.

Figure 1. The CAREM-25 Pressure Vessel and Internals
II. THE CAREM-25

The CAREM-25 prototype is a 25 MW(e) nuclear power plant, designed for electricity production in remote areas, and therefore, designed to operate independently of external power supplies. This requirement implies not only normal operation but also operational transients and emergencies.

The plant may be used for other purposes besides electricity production, such as water desalinization or steam production, or a combination of them.

This prototype is scheduled to be built in Argentina at the beginning of the next century, and several support facilities are already built and operating.

The prototype has (Figure 1) a PWR-like compact design with twelve once-through steam generators inside the pressure vessel. The vessel is designed to operate at 120 bar.

The top of the pressure vessel constitutes the pressurizer, and the primary system light water circulates by natural circulation from the core (at bottom) through a chimney to the upper chimney part, then downwards through the steam generators. This natural convection based concept avoids the use of pumps and large diameter pipes.

The only penetrations through the pressure vessel are those for the secondary system, safety systems, auxiliary systems and instrument purposes (small diameter pipes), all of them in the upper part. By this design principle, all the loss of coolant related accidents are small.

The control rod hydraulic driven mechanisms are located inside the vessel, and the hydraulic fluid is also water connected through small-diameter pipes.

The fuel is enriched uranium (4%) and operates in the epithermal range to provide for large negative reactivity coefficients for easy operation. It has burnable poison (gadolinium) to flatten the flux profile and to provide for long operating periods between refuelling. The refuelling scheme is of the batch type, and it is going to be performed by a specialist's team.
The safety functions make full use of inherently safe processes and they do not need any electric supply. The plant has two independent shutdown systems (gravity-driven hydraulic rods and boron injection by natural convection), a two-stage gas-driven emergency injection system (providing a massive reflooding and a flow-controlled injection), and a passive gravity-driven two-phase emergency cooling system.

At least two redundancies are provided for each safety function performed by each system. The reactor protection system is software-based and uses a distributed logic approach. Besides the logical redundancies, all safety components are designed fail-safe and do not need any external power supply for actuation.

The containment has two separate premises, a drywell that contains the pressure vessel and the primary and secondary systems connections, and a metallic wetwell that includes a pressure suppression pool. See Figure 2. The accident heat can be evacuated to the external air by natural convection.

At present, the CAREM-25 project is in the detailed design stage, and several experimental facilities are set up to demonstrate the basic operating principles, including a full size critical facility, a high pressure thermal hydraulic loop, and low pressures set-ups for control rod hydraulic verification.
III. RISK ESTIMATION

A level III PSA was performed for the CAREM-25 at its 1995 design stage, and some results were presented in [3]. The PSA included only internal events and the siting was assumed to be at Atucha place, to allow for risk comparison to Atucha II NPP.

In this PSA a specific method was used to obtain a representative list of initiating events, which were developed in event trees, and the systems reliability was obtained using fault trees. The quantification data was taken from [4] and [5] and the quantitative analysis was performed with PSAPack [6].

The overall results of the PSA showed a core melt frequency of $1.6 \times 10^{-5}$/yr. Then containment event trees were developed and the risk results (release categories frequencies and related doses in the critical group) are indicated in figure 3, together with the licensing criterion curve of the Argentinean regulation [7]. In that figure, each point corresponding to each release category, is really comprised of six estimations which correspond to six different atmospheric stability classes.

An overall risk indicator was obtained, as the sum of the products of yearly frequency times the individual dose (Sv), which gave a value of $1.6 \times 10^{-7}$ Sv/yr.

IV. RISK COMPARISON

A risk comparison was needed for this plant, in order to compare the alternative of producing the same power by using a series of CAREM-25 plants as produced by the Atucha II nuclear power plant, which was analyzed by KWU for the same site in [8]. With these purpose, 28 units of CAREM-25 produce the same output as Atucha II (700 MW) and the comparison is indicated in Figure 4. Thick lines correspond to Atucha II, and thin lines to 28 CAREM-25 stations.

From the frequency point of view, it must be noted that the use of inherently safe systems provide for a significant reduction in the yearly probability of severe accidents, ranging from one to two orders of magnitude.

From the consequence point of view, the reduction is even more drastic, ranging from one to three orders of magnitude, for the same energy output. This is due to the reduced power of each CAREM unit, which makes the consequences of any single severe accident much reduced. This fact is
particularly important because in the CAREM case, the maximum expected doses are of about 1 Sv, and therefore the appearance of early fatalities is almost precluded for every case.

![Figure 4. Risk Comparison among Atucha II and 28 CAREM-25 Units](image)

V. DISCUSSION OF RESULTS

The results indicated in Figure 3 show a somehow unbalanced risk for different release categories (CLs). Release category 6 shows a high probability with associated very low doses. When analyzing this particular release category, it comes out that the contributing sequences imply no core melt, and the source term to the outside is only coming from the water of the primary system or from the refueling pool. For these particular sequences, no credit was taken in the PSA for corrective actions or control systems, and therefore the likelihood of such sequences was assumed conservatively high.

If more realistic approaches will be taken, this particular category will pose much lower in the probability axis.

The other five release categories correspond to core melt sequences, with different containment responses. They are grouped quite together showing a balanced risk. It must be noted, however, the very low probability values and the very low associated doses (up to about 1 Sv in the most exposed individual of the public, which implies a negligible life risk).

Several sensitivity calculations were performed on the PSA in order to evaluate the influence of several design modifications, from the risk point of view.

The suggested design modifications included: the use of a hardware protection system as a backup of the software based system, the use of a different actuation criteria for the second shutdown system, the use of manual actuation for those actions that did not require human actions before one hour, the reformulation of the protection logic, the consideration of electrical recovery actions, several modifications in the containment design, the use of more realistic data for component reliability, etc.

Many conclusions were drawn and retrofitted on the design. With these new risk oriented features, the overall core melt frequency was recalculated to be of the order of $10^{-9}$/reactor.yr.
Some design modifications took into account the severe accident response expected from the containment, and they included the inertization of the containment atmosphere, the reduction of the steam explosion likelihood (alpha-mode) and the use of isolation condensers for a new containment layout (with the pressure suppression pool at the bottom).

The overall risk indicator was also reduced by several orders of magnitude.

It is important to point out that all the sensitivity calculations were oriented from the PSA, using importance measures (Fussel-Vessely) and ranking considerations.

VI. CONCLUSIONS

The use of small power, innovative units for nuclear energy production has a definitive advantage from the risk point of view.

The comparison of the risk estimations from an equivalent series of CAREM-25 units to the 700 MWe Atucha II PSA results (properly scaled) show two important facts: the first one is the reduction in severe accident probabilities due to the inherently safe concepts of CAREM. The second one is the effective reduction on the expected doses in the public, due to the low power of each CAREM unit, which may shift the risk from catastrophic consequences to very limited effects, eventually eliminating the possibility for early fatalities.

The sensitivity studies performed, towards a more realistic evaluation of the CAREM-25 risk, and retrofitting the design, shows also a dramatic risk reduction by performing some relatively simple modifications.

Two important conclusions can, therefore, be withdrawn. The first one is that the use of PSA with design purposes is a powerful tool, that can effectively contribute to the risk reduction of design-stage NPPs. The second conclusion is that the use of small power NPPs, the overall risk can be substantially reduced due to the small power of each unit (and corresponding small radioactive inventory).

If a future generation of reactors is to come, the use of small units has a dramatic advantage from the risk point of view. More than that, it seems possible to completely override catastrophic accidents, by preventing any acute effect even in the vicinity of the power plants and even when severe accidents (i.e. core melt) occur.

REFERENCES