CAREM design and construction experience

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International Summer School on
Early-deployable Small Modular Reactors
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Comisión Nacional de Energía Atómica

CAREM Project

- CAREM project consists of the development, design and construction of small NPPs based on integrated pressurized water reactors (iPWRs).

- This project allows Argentina to sustain activities in the NPP design and construction area, assuring the availability of updated technology in the mid-term. The design basis is supported by the cumulative experience acquired in research reactors design, construction and operation, and pressurized heavy water reactors (PHWR) NPP operation, maintenance and improvement, as well as the finalization of the Atucha-2 and the development of advanced design solutions.

- Aimed to export NPPs in a competitive market, like previous experience with Research Reactors.

AIMS OF THE PROTOTYPE

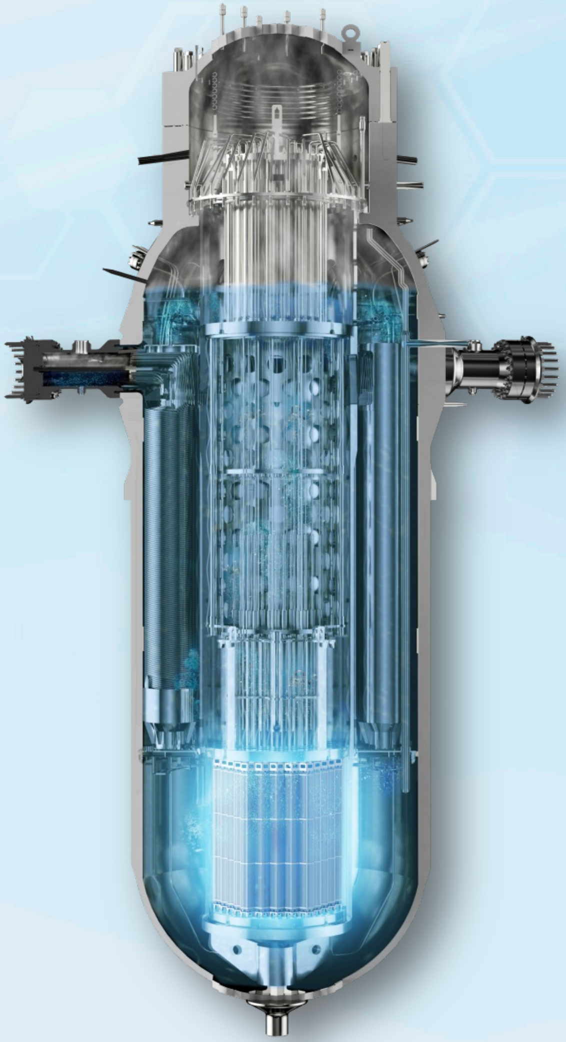
✓ To provide the design basis for the commercial CAREM NPP

✓To facilitate the licensing process of the commercial CAREM NPP

✓To generate developing abilities within the CNEA, its associate companies and the private industry in Argentina (supplier development)

✓To facilitate export of NPPs in a competitive market, like previous experience with Research Reactors.

✓The construction permits were obtained and the construction is ongoing at Atucha site.

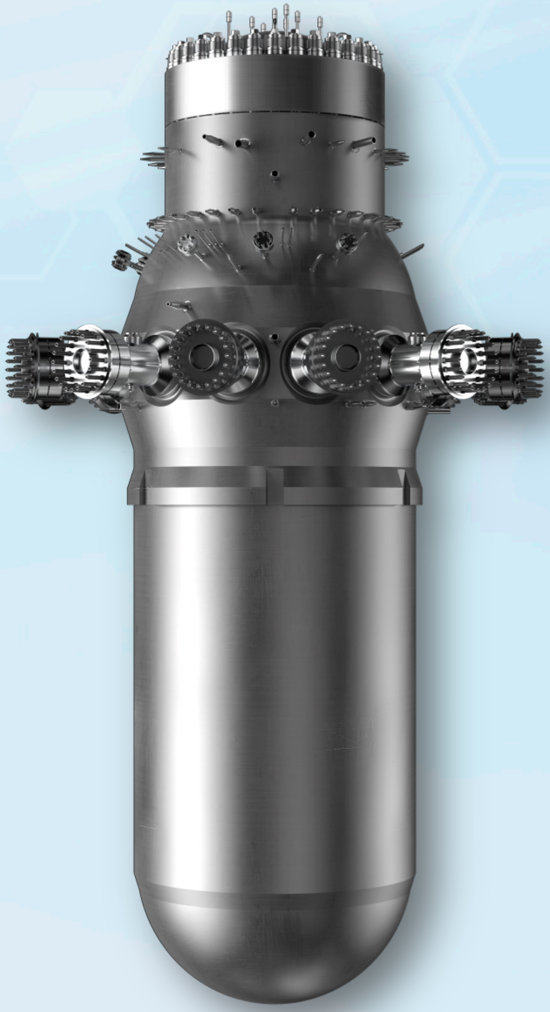


CAREM25 - main features

- Integrated primary cooling system
- Primary cooling by natural circulation
- Self-pressurized

These characteristics will be first analyzed.

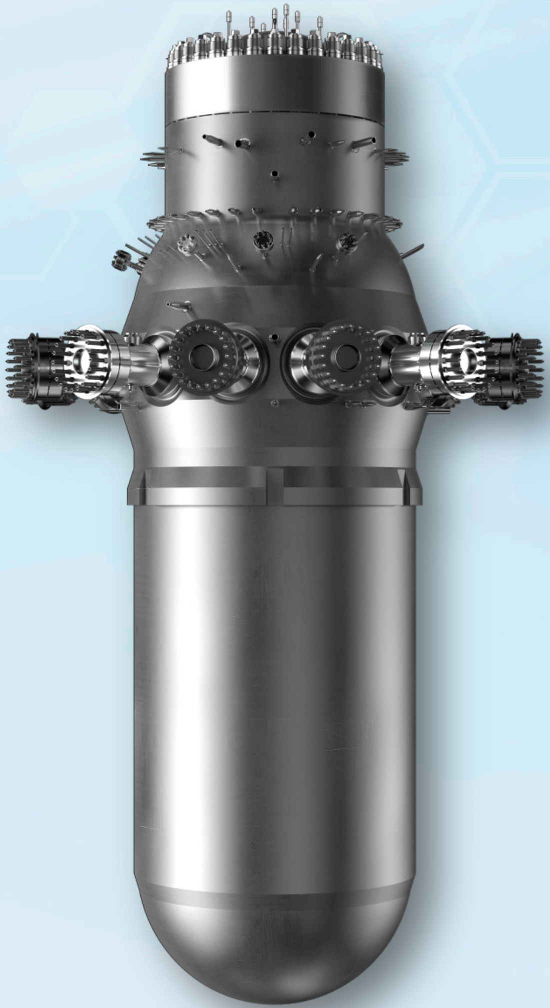
Then the construction status will be summarized.



Integral Type Pressure Water Reactors

In order to simplify the design the whole high-energy primary system, core, steam generators, pressurizer and pumps, are contained inside a single pressure vessel.

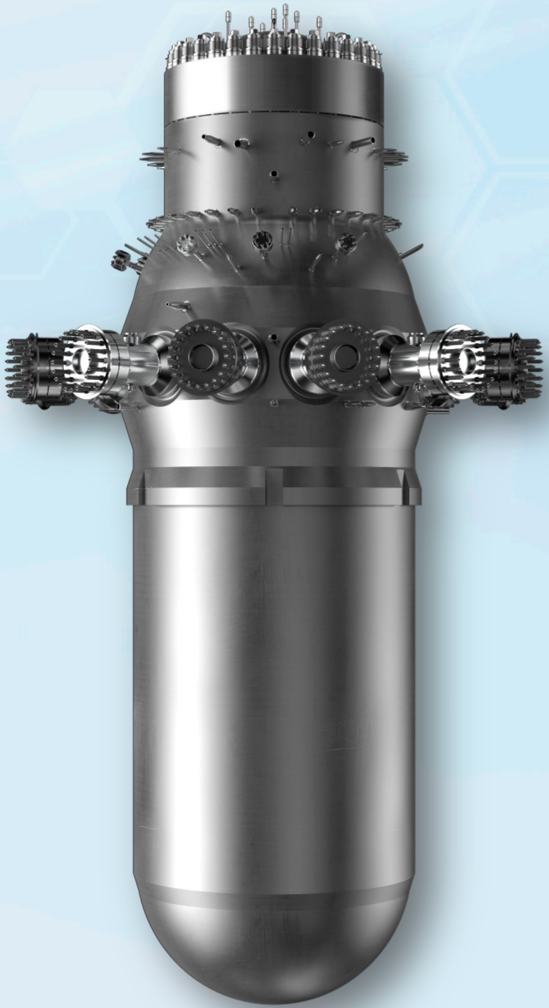
This considerably reduces the number of pressure vessels and simplifies the layout.



Integrated Primary System

- Due to the absence of large diameter piping associated to the primary system, no large LOCA has to be handled by the safety systems. The elimination of large LOCA considerably reduce the needs in ECCS components, AC supply systems, etc.

- Large coolant inventory in the primary results in large thermal inertia and long response time in case of transients or accidents.



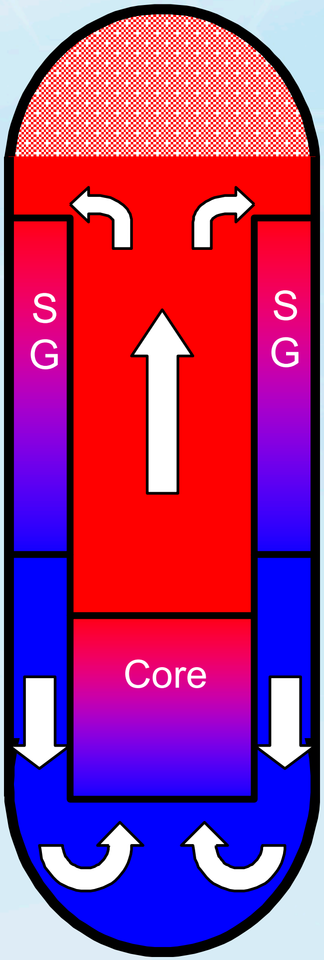
Self-pressurization and Natural Circulation

- Eliminating primary pumps and pressuriser results in added safety (LOFA elimination), and advantages for maintenance and availability.

- Self-pressurization of the primary system in the steam dome is the result of the liquid-vapor equilibrium. The large volume of the integral pressurizer also contributes to the damping of eventual pressure perturbations. Heaters and sprinkles typical of conventional PWR’s are thus eliminated.

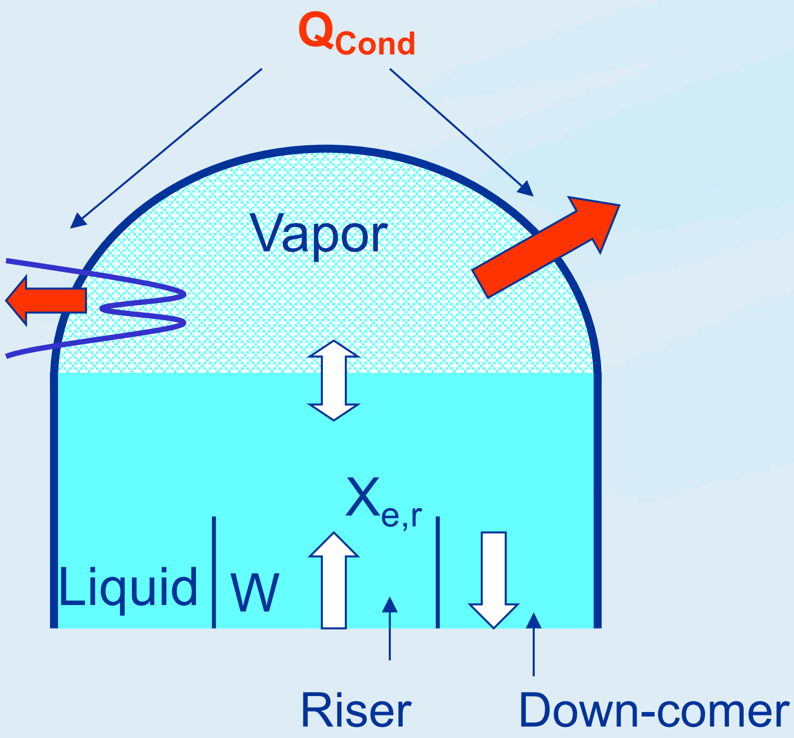
Self-pressurization and Natural Circulation

- The flow rate in the reactor primary systems is achieved by natural circulation.
- The driving forces obtained by the differences in the density along the circuit are balanced by the friction and form losses, producing the adequate flow rate in the core in order to have the sufficient thermal margin to critical phenomena.
- Reactor coolant natural convection is produced by the location of the steam generators above the core.



Self-pressurization

Dome

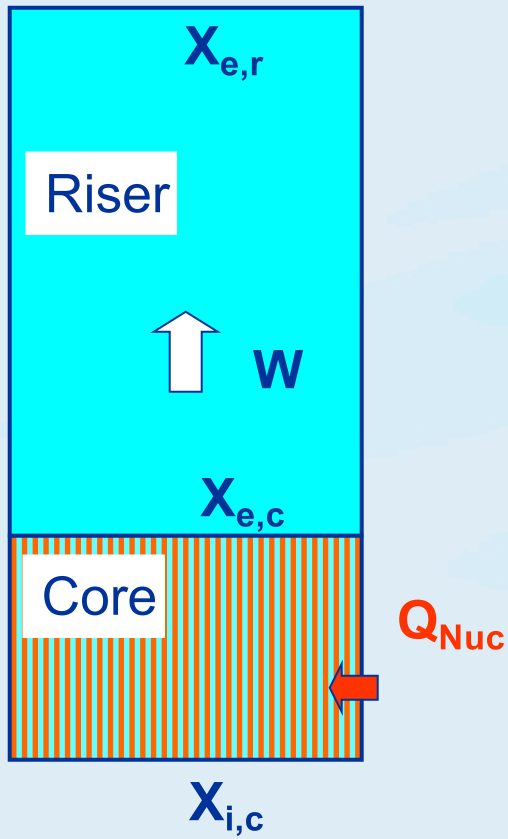


Thermal Balance

$$Q_{Cond} = W \,.\, X_{e,r} \,.\, h_{fg}$$

$$X_{e,r} = Q_{Cond} \,/\, (W \,.\, h_{fg})$$

Self-pressurization



Core Thermal Balance

$$Q_{Nuc} = W \cdot (h_{e,c} - h_{i,c})$$

$$Q_{Nuc} = W \cdot h_{fg} \cdot (X_{e,c} - X_{i,c})$$

Assuming an adiabatic riser and an uniform pressure

$$X_{i,c} = (Q_{Cond} - Q_{Nuc}) / (W \cdot h_{fg})$$

For constants $\mathbf{Q_{Cond}}$ and $\mathbf{Q_{Nuc}}$:

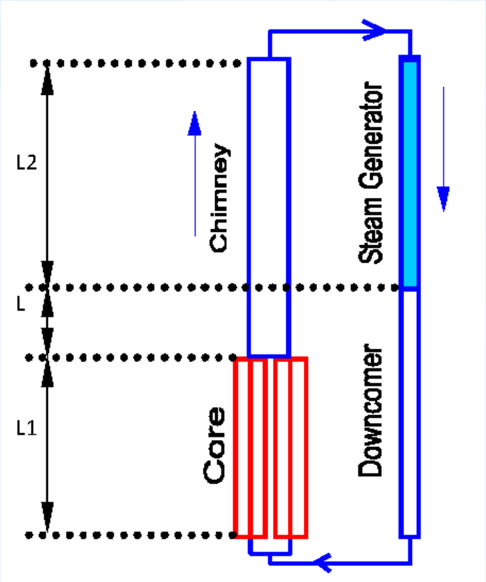
if Core Flow Rate decrease ⇩

then Core Quality decrease ⇩

Natural circulation

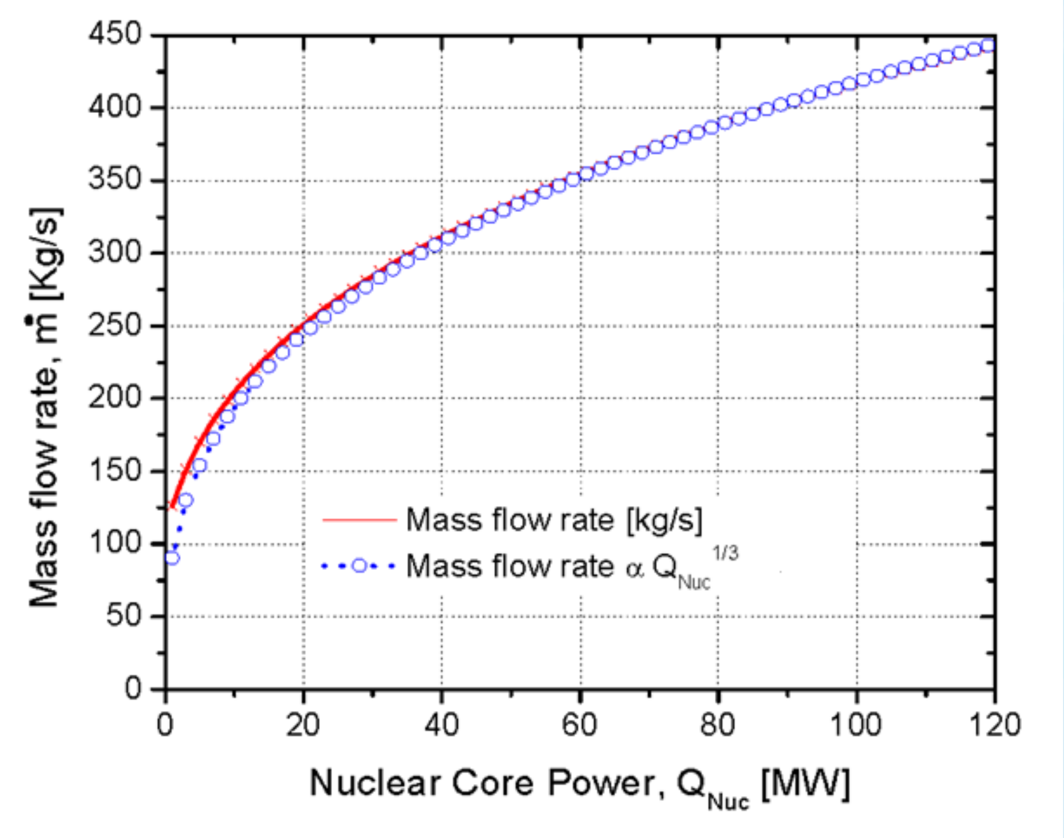
In CAREM-25 reactor the steam quality is very low and therefore the largest contribution driving term in the momentum balance is due to single-phase buoyancy forces. Considering:

- Only single-phase natural circulation,
- the Boussinesq approximation.
- And that the heat flux is uniform regarding the axial direction.



$$\dot{m} = \sqrt[3]{\frac{2A^2 Q_{Nuc}\, g \rho_l^{\,2} \beta}{K c_p}\left[L + \frac{L1 + L2}{2}\right]}$$

Natural circulation



C.P. Marcel, H.F. Furci, D.F. Delmastro, V.P. Masson.: "Phenomenology involved in self-pressurized, natural circulation, low thermo-dynamic quality, nuclear reactors: The thermal–hydraulics of theCAREM-25 reactor", Nuclear Engineering and Design 254 (2013) 218– 227.

CAREM25

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Natural circulation

From the energy balance equation, the enthalpy change across the reactor core can be computed.

$$h_{Nuc,e} - h_{Nuc,i} = \Delta h = \frac{Q_{Nuc}}{\dot{m}} = \sqrt[3]{\frac{K c_p Q_{Nuc}^{\ 2}}{2A^2 g \rho_l^{\ 2} \beta}\left[L + \frac{L1+L2}{2}\right]^{-1}}$$

The mean core enthalpy can be obtained in terms of the produced and condensed powers.

$$\bar{h}_{Nuc} = h_{sat} - \left(\frac{Q_{Nuc}}{2} - Q_{Cond}\right)\sqrt[3]{\frac{K c_p}{2A^2 Q_{Nuc}\, g \rho_l^{\ 2} \beta}\left[L + \frac{L1+L2}{2}\right]^{-1}}$$

Natural circulation

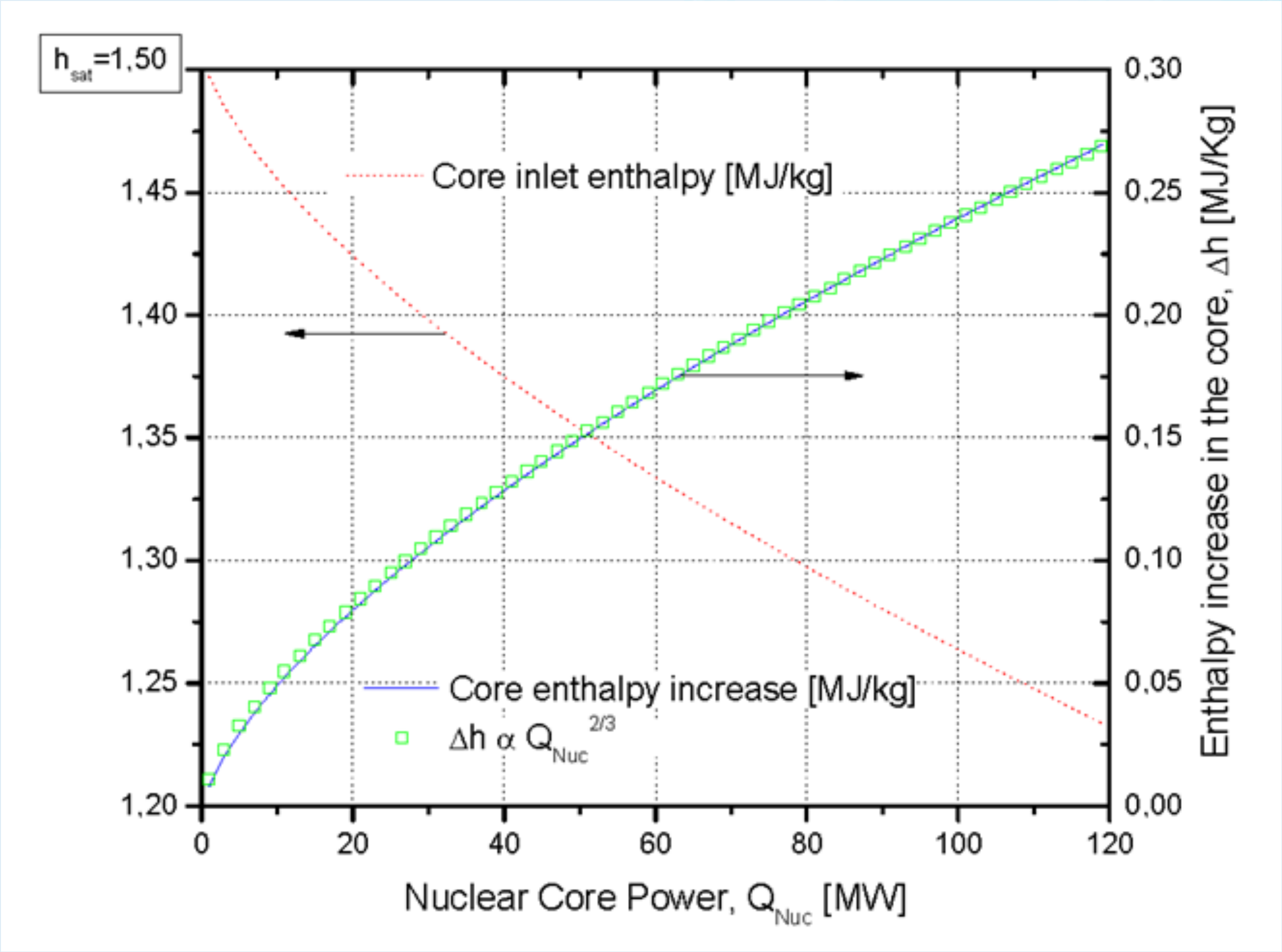
$$Q_{Nuc} = Q_{SG} + Q_{Cond}$$

$$Q_{Cond} = \dot{m}(h_{Nuc,e} - h_{sat})$$

$$h_{Nuc,i} = h_{sat} - (Q_{Nuc} - Q_{Cond})\sqrt[3]{\frac{Kc_p}{2A^2 Q_{Nuc}\, g\rho_l^2\, \beta}\left[L + \frac{L1 + L2}{2}\right]^{-1}}$$

From this result it can be observed that in a self-pressurized, natural circulation such as CAREM-25, the core inlet enthalpy cannot be controlled directly but it is a result of the combination of the produced and condensed power in the system.

Natural circulation



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Density wave instabilities

The Type-I instability mechanism is dominant in CAREM reactor since it operates at low quality flows. Under these conditions, the mass percentage of steam (the flow quality) at the core outlet becomes very small. For small flow qualities (and particularly at low pressures) the volumetric amount of steam (the void fraction) increases very rapidly as a function of the flow quality. A small decrease in the core inlet flow then leads to a large increase of the volume of steam produced at the core outlet.

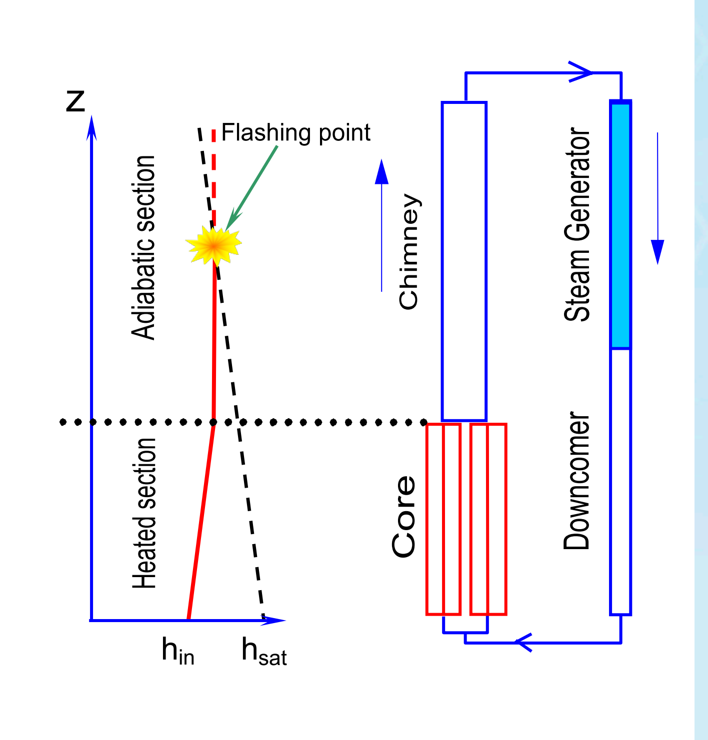
In a natural circulation reactor, this causes a low-density wave traveling through the chimney. This enhances the driving head, and the inlet flow will increase. Then the opposite process occurs, and the void fraction in the chimney decreases. Consequently, the driving head becomes smaller, and the flow rate will decrease. This completes one cycle of a Type-I oscillation.

The flashing phenomenon

As the heated coolant flows upwards, the hydrostatic pressure will decrease. Hence, the saturation temperature will also decrease. If the saturation temperature becomes equal to the (constant) fluid temperature in the chimney, boiling out of the heated reactor core starts.

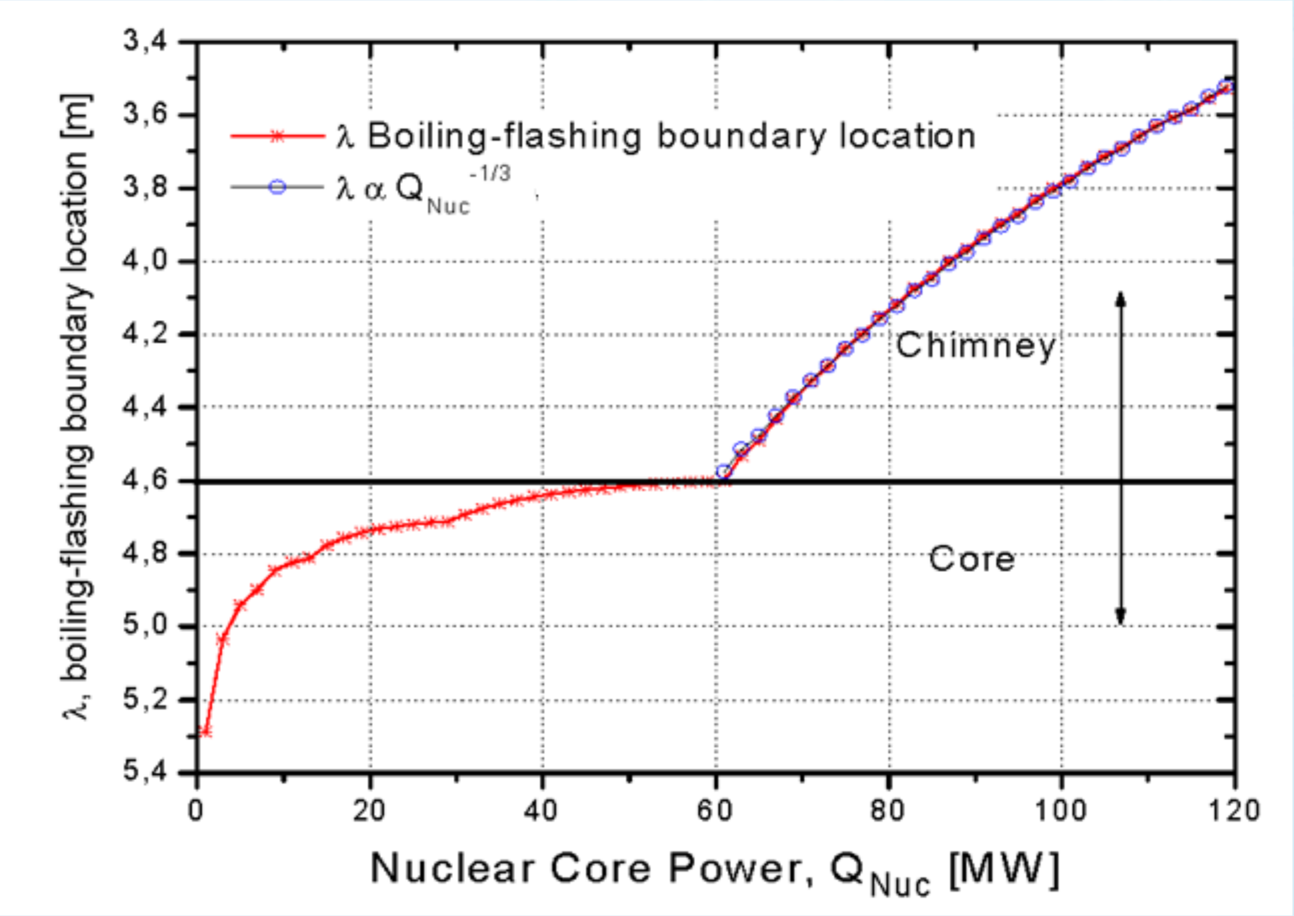
Vapor production in the chimney directly affects the gravitational pressure drop over this section.

$$\lambda = \frac{Q_{Cond}}{\left.\frac{\partial h_{sat}}{\partial P}\right|_{P=P_{sys}}} \sqrt[3]{\frac{Kc_p}{2A^2 Q_{Nuc} g^4 \rho_0^5 \beta \left[L + \frac{L1+L2}{2}\right]}}$$



Where λ is the distance from the top of the chimney to the flashing point. The previous equation has important implications: It is well known that the location of the boiling-flashing boundary has a strong effect in the void transport gain and delay which is the basis of density wave instabilities mechanism.

The flashing phenomenon



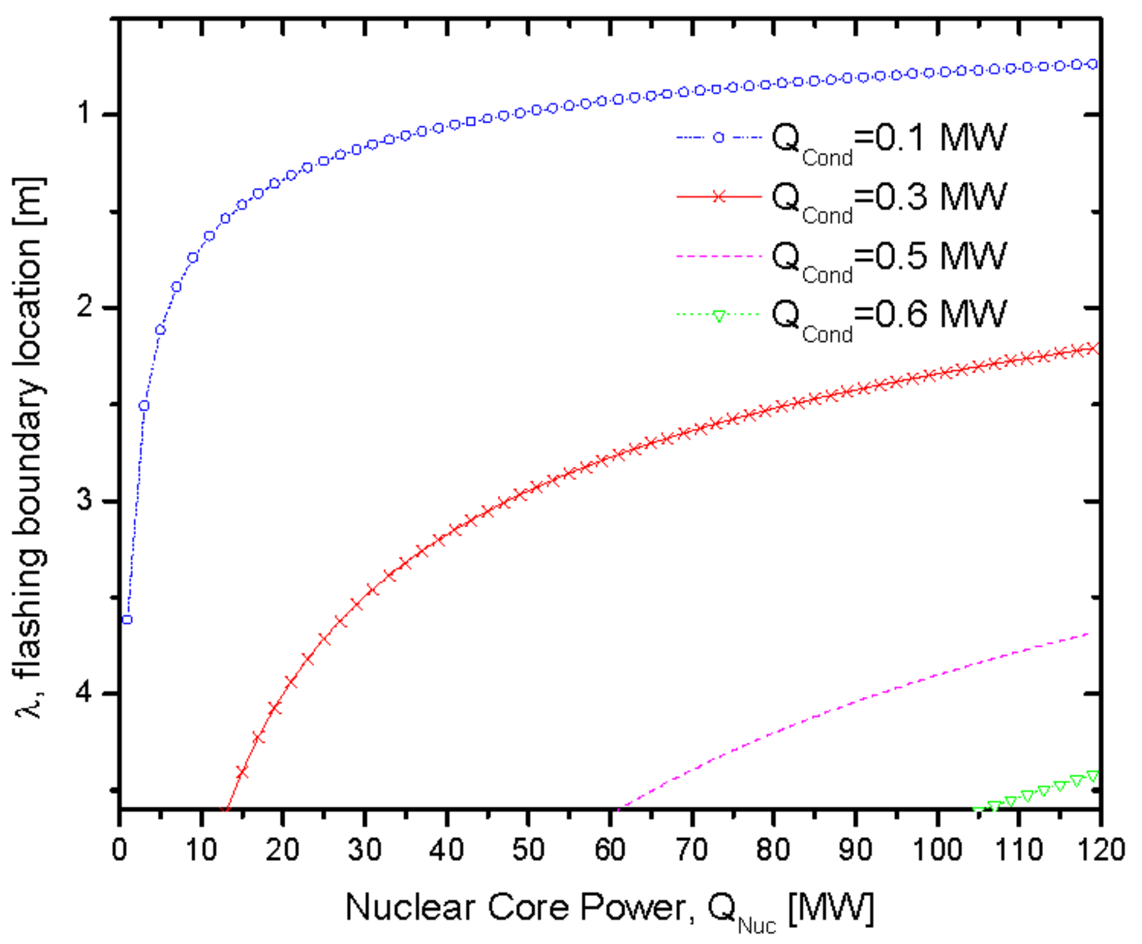
The flashing phenomenon

In order to have a constant pressure during normal operation, some vapor needs to be created inside the RPV. Besides some vapor created in the core (the vapor quality at the exit of such a section is practically zero), this amount of vapor is created by flashing in the chimney.

Thus, by assuming the coolant is saturated at the core outlet, the flashing phenomenon provides vapor in the steam dome carrying a power about 0.5MW. The presence of this vapor produces the necessary self-pressurization. Such amount of vapor is separated in the free region located above the chimney and condensed in the dome and in the surface of the control mechanisms. Due to the large area for the void separation and the low coolant velocities, it is expected no carry under of bubbles will take place.

Let us assume the vapor generation rate is larger than the condensation rate. Under such a condition, the system pressure will increase and the flashing effect will diminish. Such a feedback tends to maintain the pressure constant.

The flashing phenomenon

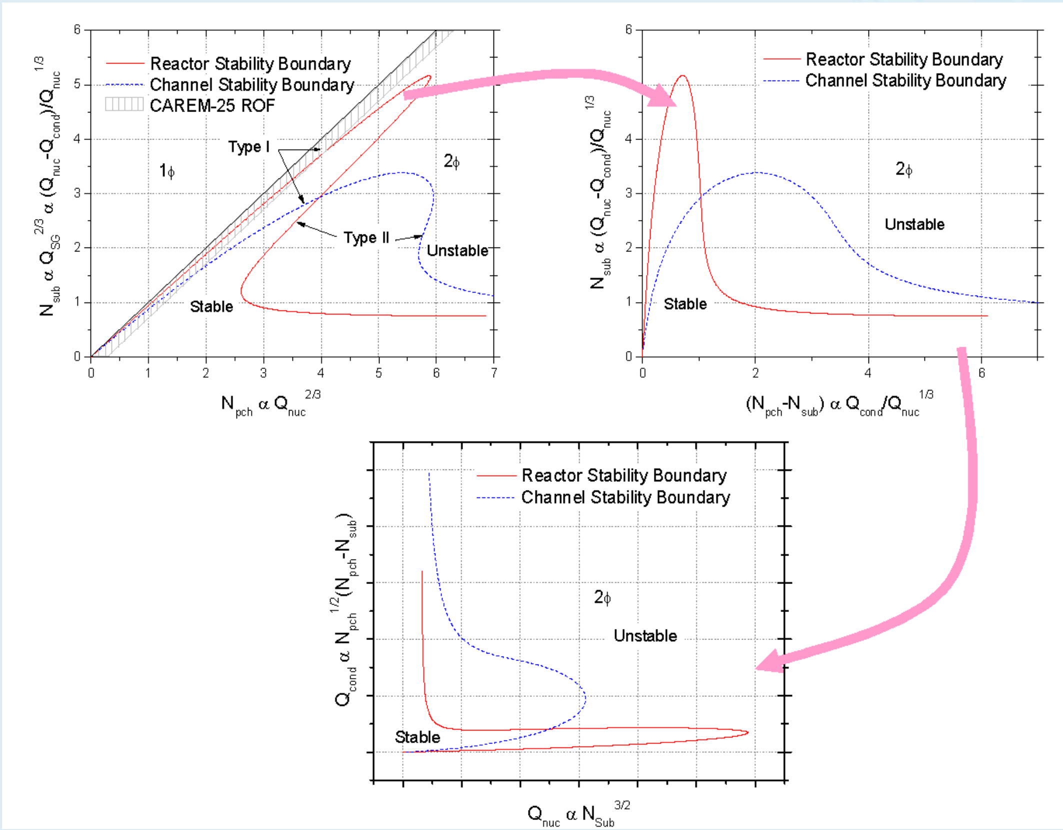


The natural variables of the system

All the relevant parameters identifying the status of the reactor (e.g. the mass flow rate, the core inlet enthalpy, the core mean quality, the location of the boiling-flashing boundary), can be expressed by using geometrical parameters and three system variables. For convenience the selected three variables, so-called natural variables, are:

- The system pressure, *Psys* (defined at the steam dome) which basically influences the fluid properties and the saturation enthalpy variation with the pressure,
- The nuclear core power, Q_{Nuc}, and
- The power which is condensed in the steam dome, Q_{Cond}.

The natural variables of the system



$$N_{PCH} \equiv \frac{Q_{Nuc}}{\dot{m}\, h_{fg}} \frac{\rho_l - \rho_v}{\rho_v}$$

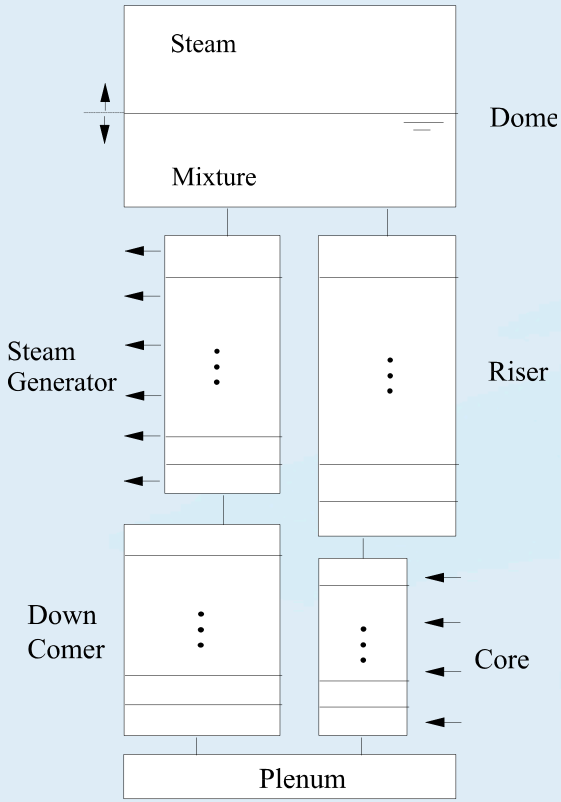
$$N_{sub} \equiv \frac{h_{l,sat} - h_{Nuc,i}}{h_{fg}} \frac{\rho_l - \rho_v}{\rho_v}$$

$$Q_{Nuc} \propto N_{sub}^{3/2}$$

$$Q_{Cond} \propto N_{PCH}^{1/2}\left(N_{PCH} - N_{sub}\right)$$

IAEA, IAEA-TECDOC-1705, Passive Safety Systems in Advanced Water Cooled Reactors (AWCRs), Vienna, Austria (2013).

Stability analysis – Discretization



The equations are discretized according to the explicit, up-wind scheme. A special effort was made in order to minimize the numerical diffusion in the mixture drift-flux energy equation.

$$\rho_j^n \frac{h_j^{n+1} - h_j^n}{\Delta t} = \frac{q'}{A} + \frac{\Delta P}{\Delta t} - \frac{G_j^n \hat{h}_j^n - G_{j-1}^n \hat{h}_{j-1}^n A_{j-1} / A_j}{\Delta z_j} + h_j^n \frac{G_j^n - G_{j-1}^n A_{j-1} / A_j}{\Delta z_j}$$

From this equation, an expression for the Courant limit can be deduced:

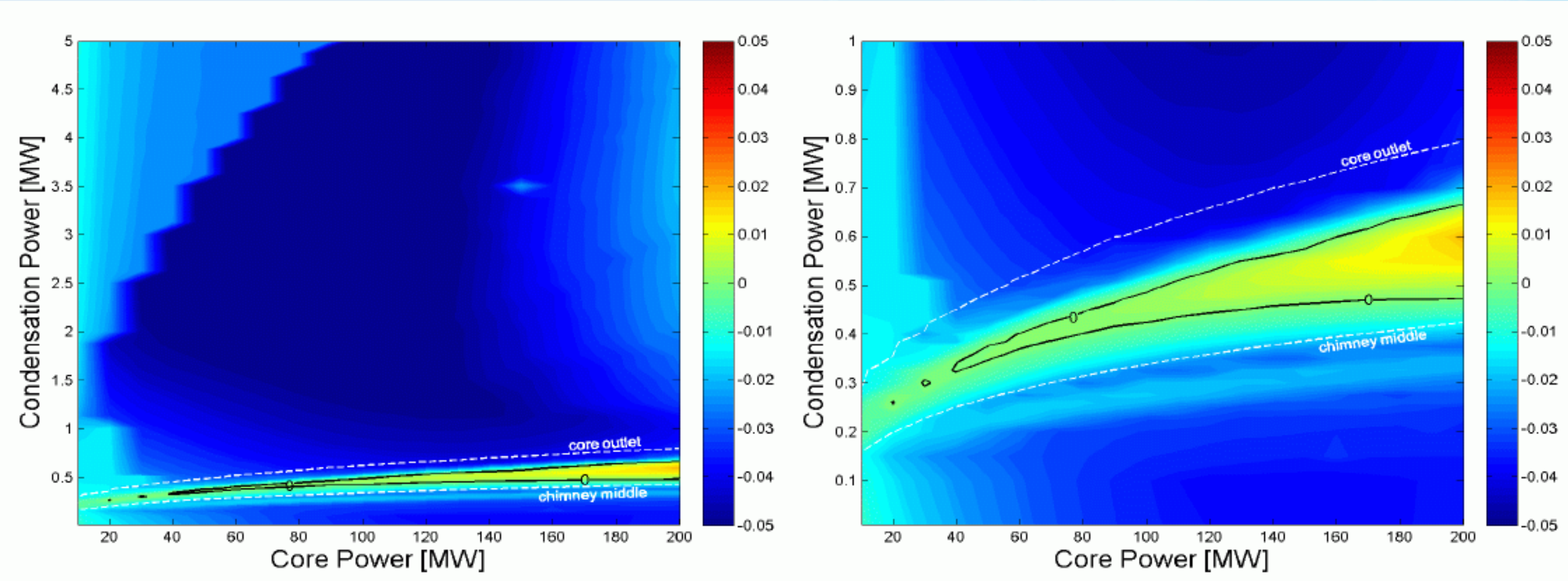
$$C_j = \frac{\Delta t G_j \partial \hat{h} / \partial h \big|_j}{\Delta z_j \rho_j}$$

When this relation approaches the value of unity, then diffusion effect through the volume is minimized.

Zanocco, P., Gimenez, M. y Delmastro, D.: "Modeling aspects in linear stability analysis of self-pressurized, natural circulation integral reactor", Nuclear Engineering and Design, Vol. 231, 2004, 283-301.

Stability analysis – Linear stability

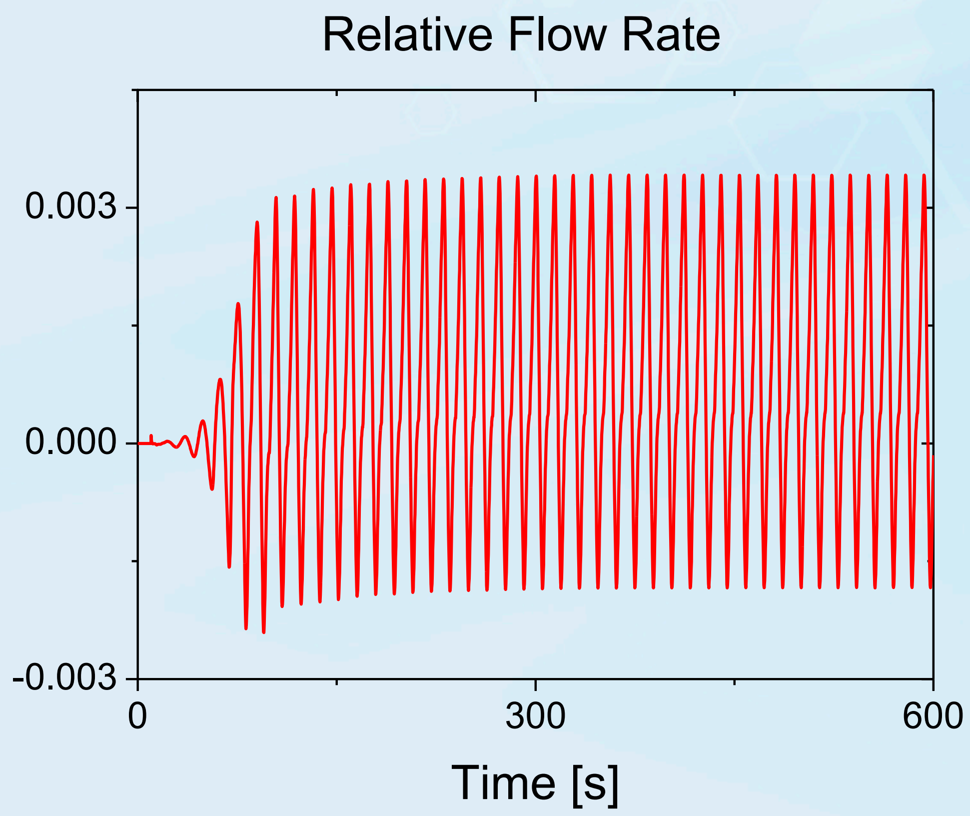
Stability at nominal conditions (P=12.25MPa)



Stability map for the case in which both the core dynamic and the feedback in the pressure are considered.

Acuna, F.M., Marcel, C.P., Zanocco, P.G., & Delmastro, D.F. (2012). "Phenomenology and thermo-hydraulic stability of the CAREM-25 reactor: Evaluation of subcooled boiling effect.", XXXIX Annual meeting of the Argentine Association of Nuclear Technology (AATN 2012), (p. v). Argentina: AATN. In IAEA INIS.

Stability analysis – Non-Linear Dynamic



Stability analysis – Remarks

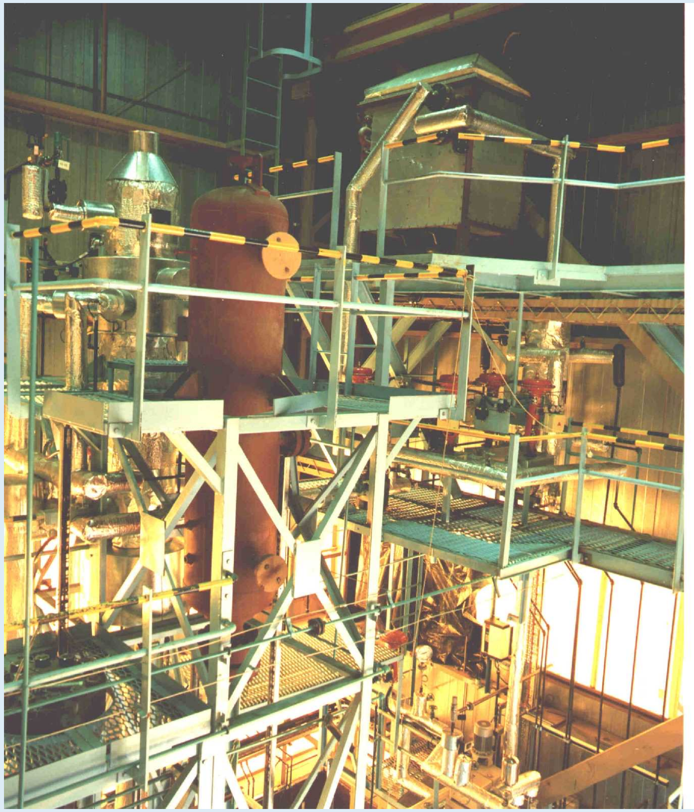
- Oscillation due to counteraction between mass flow and buoyancy force
- Amplification factor enlarged due to flashing phenomena
- Pressure feedback: stabilizing effect
- Core dynamic: stabilizing for low condensation and core power, destabilizing when they are high
- Non linear sources
  - Several boundary possition
  - Riser limits
- Mass flow and power oscillations amplitude could be very small.

Stability analysis – Remarks

- The condensation taking place in the steam dome has a great impact in defining the stability of the reactor and thus can be used to tune the CAREM-25 operational point. A condensing coil was included in the steam dome in order to tune the condensation value.

C.P. MARCEL, F.M. ACUÑA, P. ZANOCCO and D.F. DELMASTRO, Stability of selfpressurized,natural circulation, low thermo-dynamic quality, nuclear reactors: The stability performance of the CAREM-25 reactor, Nuclear Engineering and Design 265 (2013) 232–243.

Self-pressurization and Natural Circulation Assessment



A High Pressure Natural Convection Loop (CAPCN) was constructed and operated to produce data in order to verify the thermal hydraulic tools used to design CAREM reactor, mainly its dynamical response.

This was accomplished by the validation of the calculation procedures and codes for the rig working in states that are very close to the operating states of CAREM reactor.

Delmastro, D.: "Thermalhydraulics Aspects of CAREM Reactor", Natural Circulation Data and Methods for Advanced Water Cooled Nuclear Power Plant Designs, IAEA-TECDOC-1281, IAEA, Vienna, Austria, 2002.

CAREM PROTOTYPE BUILDING

ESTIMATED PROGRESS:

70%

CONTAINMENT LINER

ESTIMATED PROGRESS:

90%

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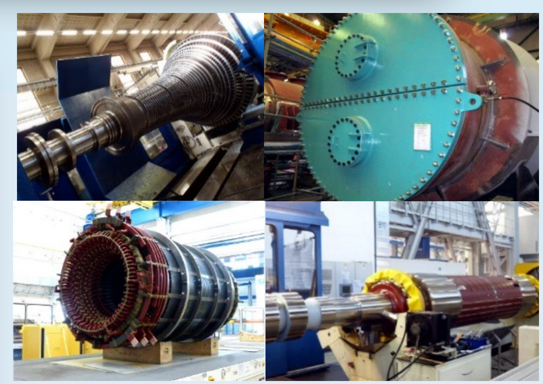
BALANCE OF PLANT

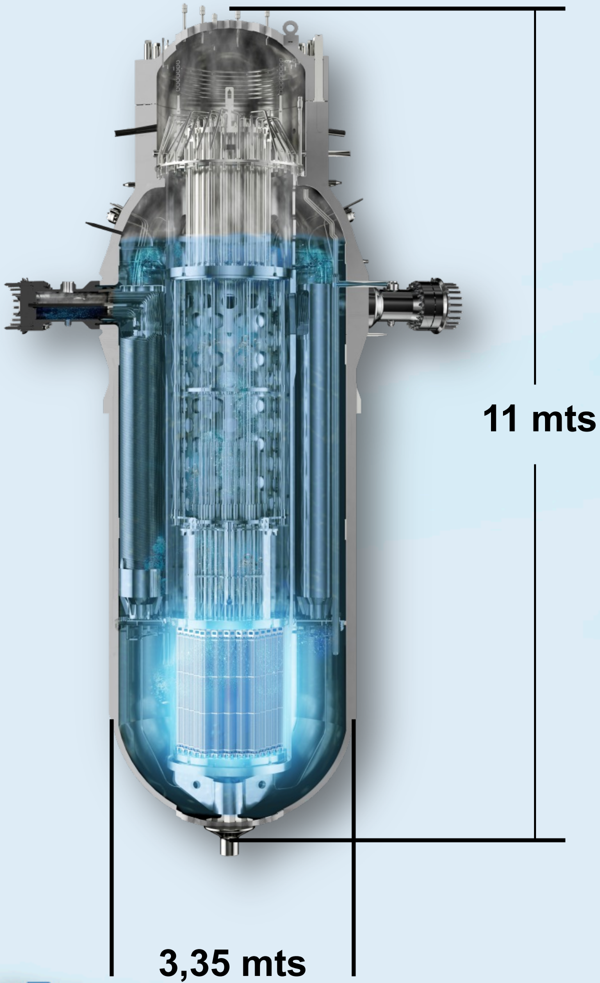
ESTIMATED PROGRESS:
63%



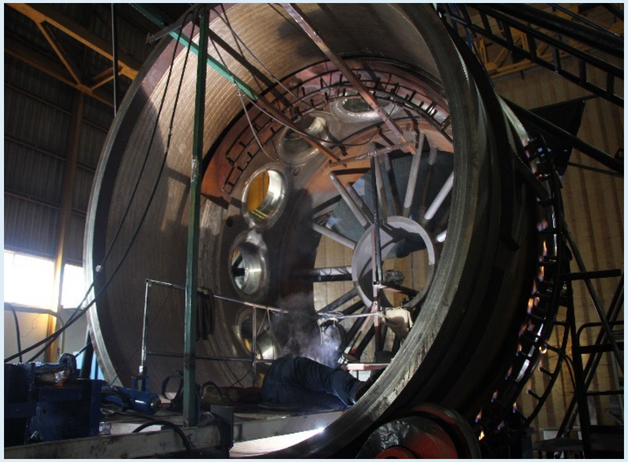
Turbo-generator and auxiliary equipment supply: 100%

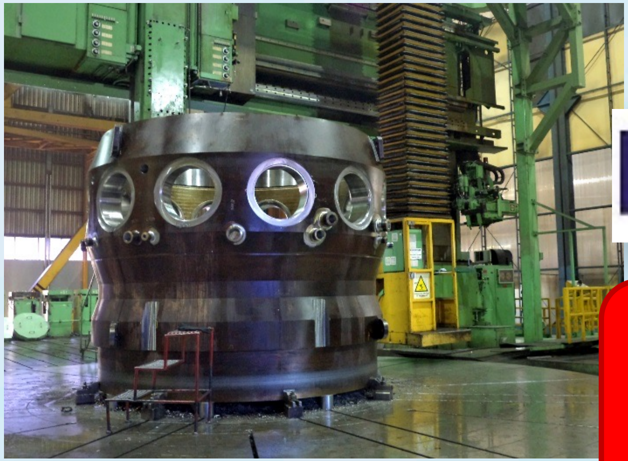
SIEMENS

PRESSURE VESSEL



PRESSURE VESSEL

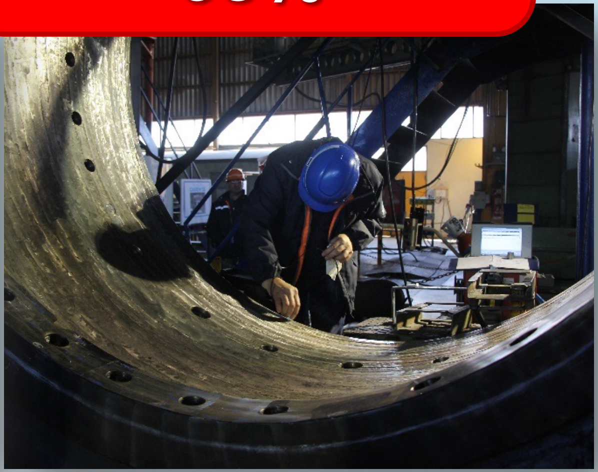




IMPSA

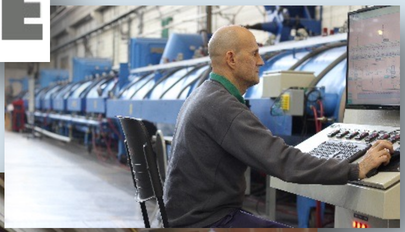
ESTIMATED PROGRESS:

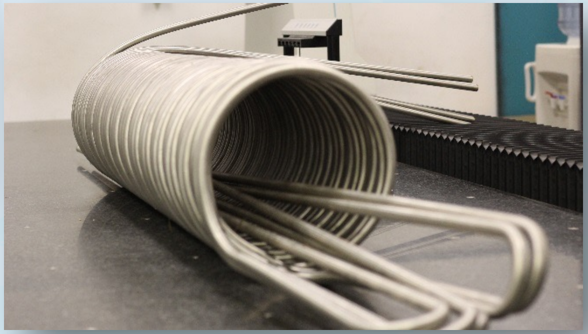
65%



STEAM GENERATORS

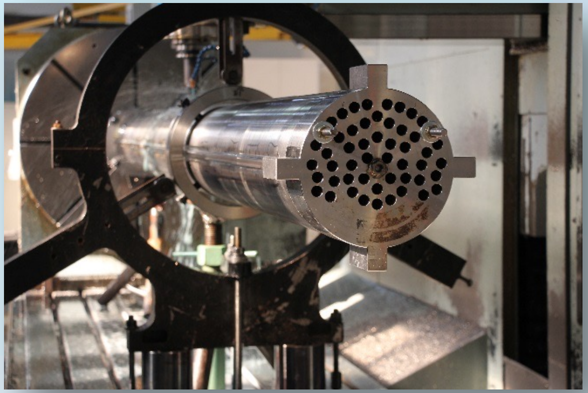
FAE





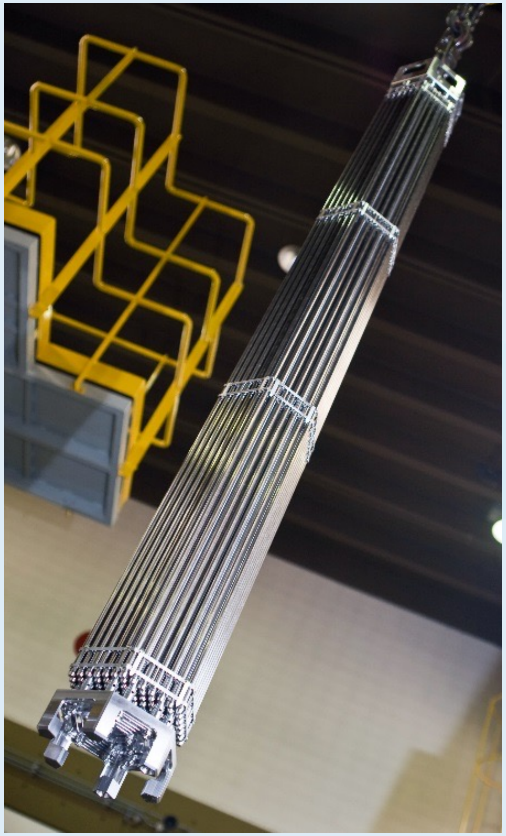
ESTIMATED PROGRESS:
52%

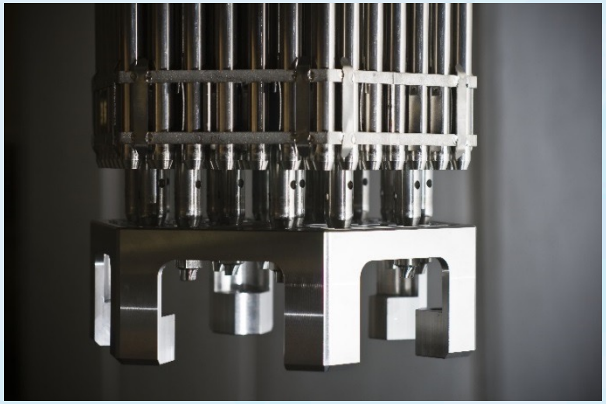
CONUAR



Already delivered:
700 Inconel-690 tubes, 35m long each

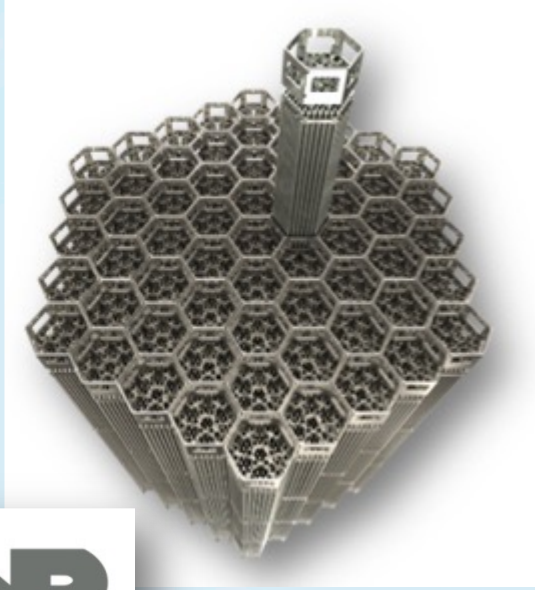
FUEL ASSEMBLIES





ESTIMATED PROGRESS:

56%



CONUAR

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CNEA Comisión Nacional de Energía Atómica

THANK YOU FOR YOUR ATTENTION

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de Energía Atómica