Multipurpose Advanced "inherently" Safe Reactor (MARS): Core design studies

H. Golfier[1], S. Caterino*, C. Poinot, M. Delpech, G. Mignot, A. Naviglio*, A. Gandini*
Collaboration University of Rome / CEA

University of Rome "La Sapienza"
Department of Nuclear Engineering and Energy Conversion
Corso Vittorio Emanuele II, 244 00186 Rome, Italy (*)

DM2S/SERMA/LCA
C.E.A. Saclay
91191 Gif-sur-Yvette Cedex, France

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I. Introduction

For this century, we can expect an increasing in energy demand. Owing to limited initial investment needed for plant construction and to limited electrical grid capacity, it seems that a solution for these countries could be Small and Medium sized Reactors (SMR_s) with a strongly simplified architecture, even if the specific production electricity cost is larger than the large-size reactors.
In the past, the trend in nuclear reactor technology development showed an emphasis towards large reactors due to the economies of scale: reactors able to produce up to 1600 MW_e have been built.
SMR_s may be a solution in case of limited capacity grid, but may even become competitive with respect to large-size nuclear reactors, if they incorporate specific design features that result into simplification, modularization and mass production. Several approaches are being under development and consideration, including the increased use of passive features for reactivity control and reactor shutdown, decay heat removal and core cooling.
Some SMRs incorporate, also, increased proliferation resistance and may offer a very attractive solution for the implementation of adequate safeguards in a scenario of increased deployment of nuclear power.
Moreover, SMR_s [1], [2], [3] for which an important effort has been carried out to simplify the operation and the maintenance, more easily may be constructed in developing countries with a further reduction of costs.

Since 1983, the University of Rome "La Sapienza" has been developing the design of a Multipurpose Advanced "inherently" Safe Reactor (MARS), a 600 MW_{th} PWR, with the aim at proposing a new concept of fission-type nuclear plant to be used for a wide range of applications, including desalination and district heating.

1 *Corresponding author:* *hgolfier@cea.fr*
Tel: *33 1 69 08 32 87*
Fax: *33 1 69 08 99 35*

MARS NPP may include several reactor modules: with one module only, it generates about 150 MW_e. The modularity helps satisfying progressively increasing power requirements: using identical reactor units would have an advantage in achieving high capacity utilization together with adequate flexibility and redundancy.

Fig.1 shows the primary cooling system, enveloped by pressurized containment. The primary cooling system has only one loop, with 25'' ID pipes, one canned pump and one vertical axis U-tube steam generator. The pressure of the primary cooling system is lower than in traditional PWR_s. Each component of the primary system is enclosed by an outer shell (pipes around pipes and vessels around vessels) filled with high-pressure low-temperature water, to eliminate the possibility of a loss of primary coolant in the case of failure of the primary coolant pressure boundary.

The reactor operating temperature and the energy conversion efficiency of a MARS NPP are lower than in conventional PWR_s (234 ºC and 25%, respectively). But the lower operating temperature and pressure of the primary coolant significantly reduce the corrosion of all materials in the core. The main reactor parameters are listed in **Tab.1**.

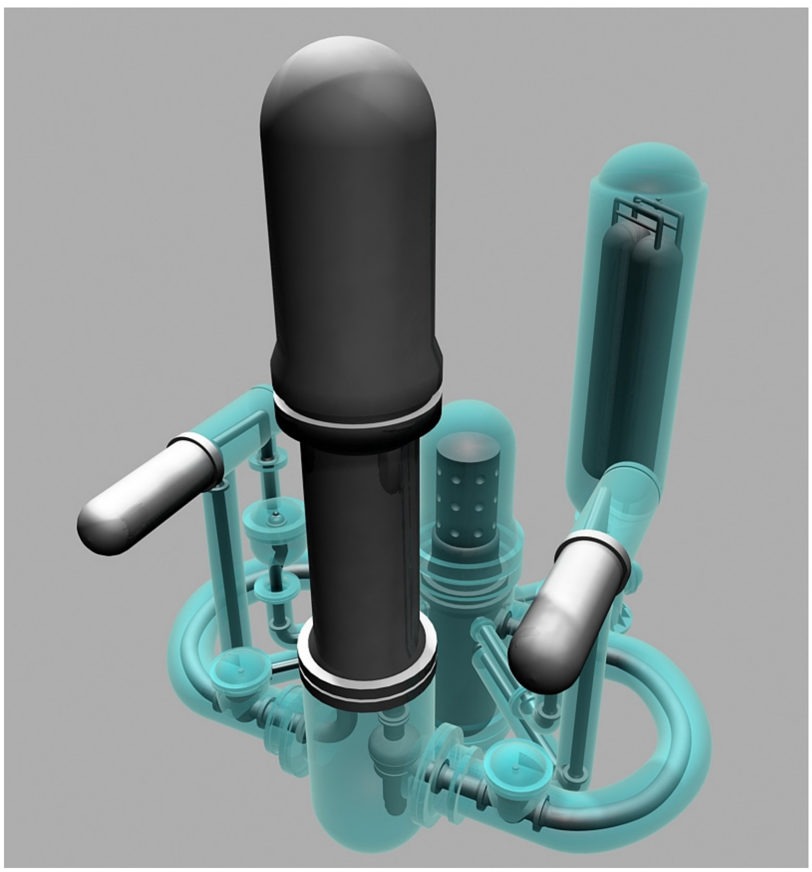

Figure 1 - MARS Primary Cooling System (enveloped by pressurized containment)

Fuel	UO_2
Thermal output	600 MW
Core diameter	2.4 m
Core height	2.6 m
Average coolant temperature	234 ºC
Coolant pressure	75 bar
Number of fuel assembly	89
Number of rods/Assembly	289
Average linear heat rate	98.2 W/cm
Cladding material	Zircaloy

Table 1 - Reactor parameters

The reference MARS core was designed in the 90's by the University of Rome "La Sapienza" and ENEA [1]: it is characterized by a burn-up of 35 GWD/t and by assemblies with a fuel enrichment of 1.8, 2.4, 3.1 %.
In the year 2005, in collaboration with CEA, the University of Rome "La Sapienza" investigated a new core model with the aim at increasing the performances of the reference one, by extending the burn-up to 60 GWD/t in the case of multi-loading strategy and investigating the characteristics and limitations of a "once-through" option, in order to enhance the proliferation resistance. In the first part of this paper, the objectives of this study and the methods of calculation are briefly described, while in the second part the calculation results are presented.

II. Scope of the research

Different core design options were analysed, in order to identify the configuration allowing the highest burn-up complying with all safety criteria of the reference design.
Different fuel management strategies were taken into consideration to maximize the benefits. The study led to focus the attention on a four-batch fuel cycle, achieving a discharge burn-up of about 60 GWD/t (cycle length of about 6.7 EFPY) and on a once-through fuel management that doesn't involve reprocessing of the spent fuel: in this case, a discharge burn-up of about 37 GWD/t (cycle length of about 4 EFPY) is achieved.

The main phases of the study included:

- **Definition of assembly design in infinite environment.**

  A sensitivity study was carried out on assembly model to evaluate different solutions: UO_2 enrichment in the fuel, burnable poison composition and burnable poison rod number. The analysis of a simplified model (assembly calculations in infinite medium with critical buckling) allowed to investigate the global behavior of the core model before performing a complete core calculation.
  The geometrical constraints (rod pitch, guide tube locations, etc) of a standard 17 x17 PWR assembly were assumed. An assessment of burn-up performance, control rod efficiency and power peak was also carried out.
  The feasibility of boron reduction or boron suppression were also analysed: the analysis was limited to the assembly level but some conclusions could be extrapolated to the whole core model.

- **Core analysis at "equilibrium state"**

A preliminary core investigation allowed to identify the core loading strategy. Two models were selected: four-batches fuel cycle and once-through loading model.
Each core model was built on the basis of only one type of assembly and using burnable poisons to flatten power distributions. At this stage, a heavy reflector, made of steel, was used.

The core investigations included:

- The calculation of burn-up and power distribution map
- The evaluation of DNB margins under overpower conditions typical of anticipated operational transients. They were evaluated with conservative axial power peaking and thermal-hydraulic input.
- The check of neutronic coefficients at isothermal and nominal conditions for the core
- The shutdown safety margins under Hot Zero Power (HZP) and Cold Zero Power (CZP) conditions. Different absorber materials for control rods were used: B_4C with, respectively, 20%, 40 % and 90 % with hafnium cladding.
- Sub-critical state analyses.

III. Calculation tools

The analysis codes used were APOLLO2 ([4],[7]) for lattice calculation and CRONOS2 ([5],[6]) for whole core calculations. APOLLO2 and CRONOS2 are part of the package SAPHYR ([6]) developed by the French Atomic Energy Commission. Nuclear cross-section libraries derived from JEF2.2 evaluation.
APOLLO2 is a modular computer program for transport multi-group analysis in 2-D and 3-D geometries, and for burn-up calculations. The program calculates the heterogeneous flux inside the fuel assembly, the critical buckling and fissile depletion. It solves the transport multi-group equation either by the method of collision probabilities, by method S_n or by the method of characteristics. The numerical method applied for this study was the method of collision with an energy mesh of 99 groups. The analyses were carried out in 2-D assembly geometry (reflexion conditions at the boundaries of the assembly). APOLLO2 allows to generate the two-group macroscopic cross-sections used in the core code CRONOS2, using the Method of Collision Probability (P_{IJ}). These cross–sections are tabulated in function of burn-up, boron concentration, water density, fuel temperature and, rod cluster insertion. For these calculations, the cross-section libraries generated by APOLLO2 contain microscopic cross-section for each isotope (heavy nuclides or fission products) explicitly described in order to evaluate very precisely the mass balance in the core.

CRONOS2 has a modular structure too: it was designed to provide all the computational means needed for reactor calculations, including design, fuel management and accidents. It allows steady state, kinetic and transient multi-group calculations of power distribution taking into account the thermal-hydraulic feedback effects. It solves either the diffusion equation or the even parity transport equation with isotopic scattering and source.
For this study the numerical method was based on finite elements. The core was radially described with 4 nodes per assembly and 28 axial nodes, including 24 nodes in the fuel active height. A scheme of the calculation processes is in **Fig.2**.

IV. Assembly analysis: parametrical study.

A parametrical study was addressed to find a compromise among different physical parameters (the effect of UO_2 enrichment variation in the fuel, burnable poison composition and burnable poison rods number), in order to meet the requirements:

- **To compensate the reactivity effect at BOC.** The research of higher cycle length than the reference core imposed a considerable reactivity excess at BOC/BOI that had to be controlled during irradiation. Different fuel enrichments was analyzed: 4.0, 4.5, 4.9, 5.5, 6.0 %.

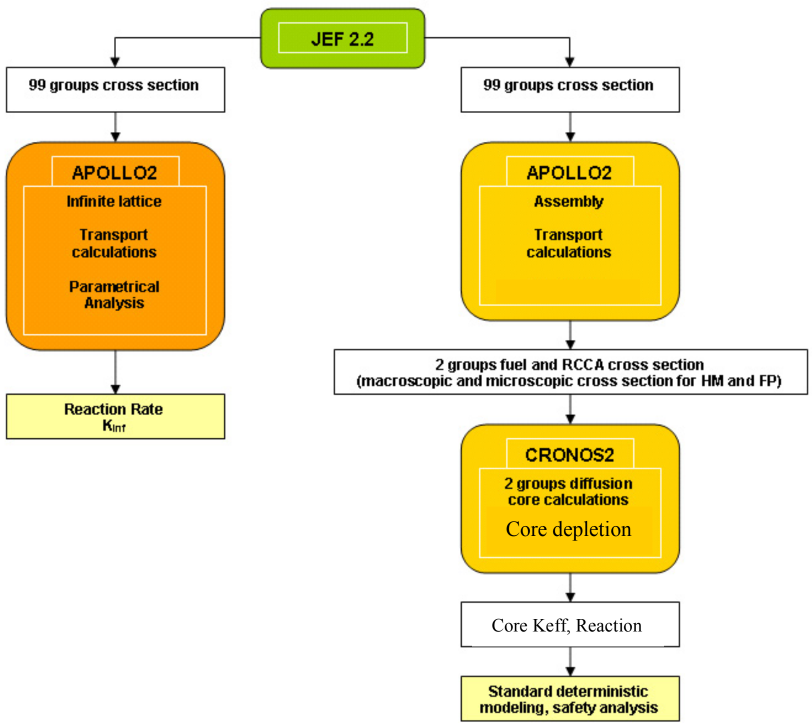

Figure 2- Description of the different calculation processes used

To control the reactivity excess, different burnable poison configurations were analyzed, involving the variation of composition (concentrations of gadolinium of 6, 7, 8, 9, 10, 11, 12 wt% with isotope composition of natural abundance ratio) and the number of poison rods (8, 12, 16, 20, 24, 32). The poison strategy optimization involved, also, the variation of initial amount of fissile material (U_{235}) in the burnable poison rods: 0.25, 1, 1.5, 2.5 % were considered;

- **To reduce the rod power peaking factor and thus to improve thermal-hydraulic margins.** Thermal-hydraulic limitations were specially strict, owing to the special safety features required to the MARS NPP. The maximum power peak calculated is 1.25 in the assembly;

- **To obtain negative reactivity coefficients and acceptable control characteristics.** In order to check the suitability of control, a control rod efficiency analysis was performed. Eight different absorber materials were used: AIC, HF, B4C (with 3 different boron enrichments: 20%, 40%, 90%), B4C + HF in the clad (with 3 different boron enrichments: 20%, 40%, 90%);

- **To obtain sufficient shutdown margins at HZP and CZP conditions.**

The study of different configurations by parametrical analysis allowed to identify the following assembly design which maximizes the benefits in the case of using boron dilution:

Four batches fuel management	Once through fuel management
UO_2 enrichment: 4.9% Poison rods number: 20 UO_2 enrichment in poison rods: 2.5% Fraction of gadolinium: 8%	UO_2 enrichment: 4.9% Poison rods number: 24 UO_2 enrichment in poison rods: 2.5% Fraction of gadolinium: 8%

The indications on control rod worth (in assembly study) suggested to selected three materials for control rods in the core shutdown margin analysis: B_4C with natural boron concentration (20%), B_4C with a boron concentration of 40%, B_4C with enriched B_{10} at 90% and Hafnium cladding.

V. Core Analysis

Two sets of core calculations were carried out with the core models selected.

Four batches fuel management

The loading map is shown in **Fig.3**. The assembly characterized by "C.0" is a fresh fuel, the assembly with "C.1" was irradiated once, "C.2" two times, "C.3" three times. The advantage of this scheme is that it gives an uniform power distribution throughout the core, and thus leads to lower power peak.
With this core configuration, a burn-up around 60 GWd/t can be reached with only one type of assembly, corresponding to a cycle length of 600 EFPD. The results obtained, in terms of hot channel power rod peak *(Fq)*, radial power assembly peak (*Fxy)*, axial power *peak (Fz)* and *axial offset (AO)*, are shown in **Fig.4**. The hot channel power peak (Fq), ranges between 2.2 and 2.7 which is largely below the maximum value allowed of 6.07, calculated on the basis of minimum DNBR.
At the beginning of cycle (BOC), the most thermally stressed assembly is located in the core at D6 and F4 coordinates. The value of maximum Fxy (*these values correspond to the maximum of assembly radial power*) is 1.63. At end of cycle (EOC), the assembly power peak is located at E5 coordinates with a maximum Fxy value of 1.57. The critical boron concentration required at BOC is 900 ppm: it becomes nearly zero (20 ppm) at EOC. Concerning the "stability" of the core in terms of reactivity feedback due to the power variation, a good behavior of the core in isothermal and nominal conditions was verified: all neutronic coefficients are negative.

An assessment was carried out on the shutdown margins: the margins of anti-reactivity guaranteed when the control rod clusters are inserted must be higher than 1700 pcm in the case of transition from Hot Full Power (HFP) to HZP and from HFP to CZP at the end of cycle.
The anti-reactivity of all control rods clusters was calculated considering the most effective control rod stucked out of the core and this value was decreased by 10%. Besides a value of uncertainty equal to 1500 pcm due to the approximations introduced in the evaluation of the different physical effects. The criterion of 1700 pcm, for the transition from HFP to HZP, is satisfied with a small margin in the case of using B_4C at natural boron concentration (20%) with 36 (40% of all assemblies equipped with control rods) Rod Control Clusters Assemblies ($RCCA_s$). In this core configuration, the shutdown margin is equal to 3457 pcm.

Nevertheless, the standard criteria impose to check that the shutdown margins are satisfied in the case of transition from HFP to CZP. In this case, the margin decreases and it imposes to adopt absorber material with higher impact or to use all the 45 $RCCA_s$ positions of the reference MARS core (50% of all assemblies equipped with control rods). The margin obtained changing the absorber material in control rods clusters becomes, respectively in the case of B_4C with natural boron concentration, B_4C with enriched B_{10} at 40% and B_4C with enriched B_{10} at 90% with hafnium cladding, 1975pcm, 2330 pcm and 2990 pcm, respectively. The impact of the absorber material in control rods on sub-critical core states (shutdown and refuelling) was investigated. It permitted to define which configuration reduces the boron requirements: B_4C with enriched B_{10} at 90% and hafnium cladding is a promising option in order to reduce boron concentration in sub-critical states. In the calculations, all $RCCA_s$ were considered inserted with the exception of the RCCA with the highest control worth.
The *minimum shutdown boron concentration* at CZP requires always boron dilution: around 100 ppm with 36 $RCCA_s$. No boron dilution is required if all 45 $RCCA_s$ are used.
Moreover, the *minimum refuelling boron concentration* at CZP requires between 646 and 464 ppm in the case of using 45 $RCCA_s$, depending on the absorber materials of control rods.

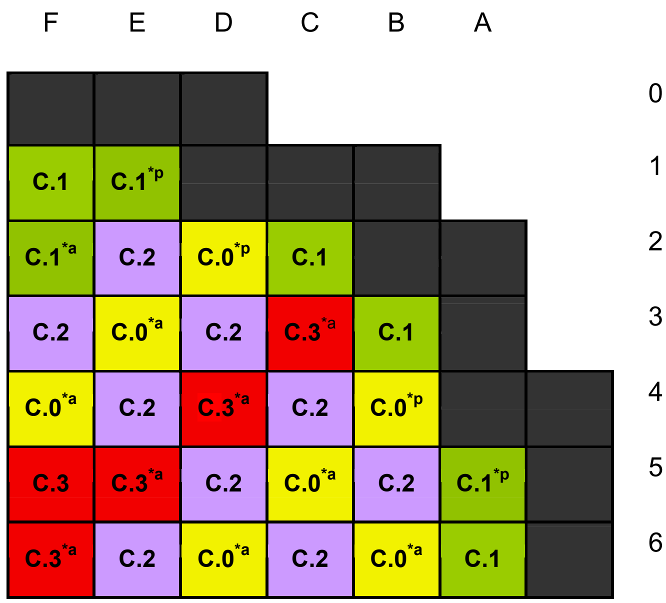

Figure 3-Loading map of the four batches core model (*a active RCCA, *p passive RCCA)

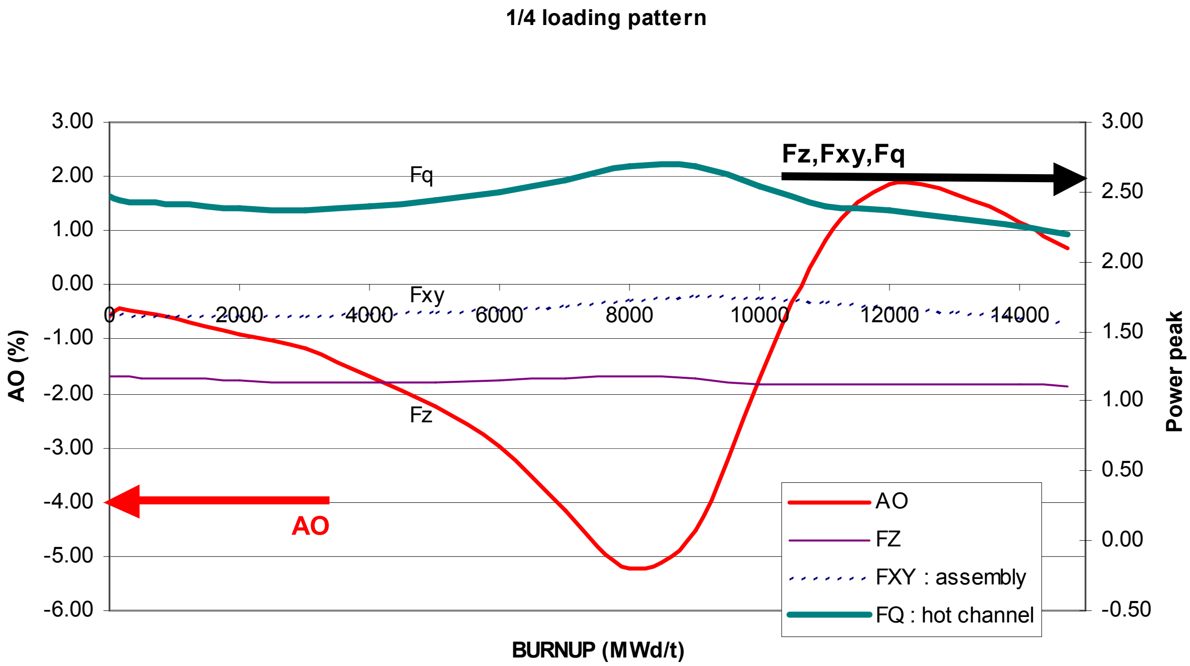

Figure 4-Core with heavy radial reflector (steel)

Once-through fuel management

The study was carried out to identify a simplified solution in terms of fuel management. The fuel assemblies are loaded in the core and remain in the same position for all irradiation period until their unloading. The average burn-up of spent fuel is about 37 GWd/t, corresponding to a cycle length of 1494 days. The hot channel power peak (Fq) ranges between 1.42 and 2.67. Its maximum value is reached when the burn-up is around 6 GWd/t. The variation of axial power (Fz) is contained during irradiation. The axial offset (AO) ranges between -4% and +2%.
For this core model only preliminary analysis were carried out as for burnable poison: the poisoning strategy will have to be revised. In fact, the poison strategy adopted at BOI has a critical boron concentration required of 1950 ppm but, when the burnable poisons disappear, the critical boron concentration required increases to 2180 ppm, reaching its maximum and then it decreases progressively. In the range of boron concentration above 2000 ppm, the moderator coefficient becomes positive. The goal of a moderator reactivity coefficient always negative is achievable.

Preliminary investigation on boron-free core

A preliminary study was carried out with a simplified model to evaluate the limitations in the case of boron-free core. Some preliminary results were obtained, but a dedicated core analysis is needed.
According to the preliminary analysis, the reactivity inserted in the core during the transition between Hot Full Power (HFP) and CZP due to the Doppler Effect, moderator temperature coefficient and Xenon effect was ~11000 pcm at zero burn-up (the most penalizing situation).
A suppression of boron could be considered during operation at "*nominal conditions*": the analysis of the sub-critical states demonstrated that both in the case of four-batches and once-through fuel cycle, a minimum refueling boron concentration at CZP is required (~300 ppm).

The power peak in the assembly due to the control rod insertion increases. The higher the absorber efficiency of the material used in the control rods, the higher the peak power in the assembly. The ranges are:

- case with 20 poison rods: power peak between 1.38 and 1.55 (with AICN and B_4C enr. + Hf)
- case with 32 poison rods: power peak between 1.48 and 1.65 (with AICN and B_4C enr. + Hf)

However, further core analysis are required, to check if the thermal-hydraulic limitations imposed are respected.

The preliminary results led to take into consideration, for the boron-free core model, all RCCA$_s$ (No. 45 clusters) positions allowed in the core, abandoning the RCCA passive scram system (9 positions) optionally foreseen in the reference MARS core.

VI. Conclusion

The reference MARS core concept allowed rather high load factor, but a "conventional" burn-up. With this study, CEA and the University of Rome "La Sapienza" proposed new core models, with the target to achieve higher fuel performance assuming only one type of assembly. Two new cores were studied:

- **Four-batches fuel (four-cycle loading strategy) with the same type of assembly in which 22 assemblies are loaded in sequential cycles, achieving a discharge burn-up of about 60 GWd/t.**
  All standard safety criteria are satisfied: no weak points were identified.

- **Once-trough fuel (single-cycle loading strategy): all assemblies are loaded and discharged together, are irradiated during one cycle, achieving a discharge burn-up of about 37 GWd/t.**

  The burnable poison utilization strategy has to be reviewed, to reduce the boron concentration during irradiation, because poisons presently used produce in the range of burn-up between 5 and 11 GWD/t positive values for moderator temperature coefficients and moderator power coefficients. With the exception of this point, all other characteristics are compatible with the MARS safety criteria.

- **The feasibility of a boron-free core needs to be fully demonstrated with dedicated studies; nevertheless some general characteristics and indications have been obtained in this work.**
  The reduction or the removal of soluble boron can lead to consider other aspects not fully investigated in this study:

  - reinforcement of the reactivity control
  - necessity of an alternative system for the core shutdown
  - modification of the assembly
  - increasing of the moderating ratio

  in order to decrease the control rod worth of each RCCA and thus to limit power perturbation in the core.

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