Material Selection According to ALARA during Design Stages of EPR™

P. Jolivet, A. Tamba, F. Chahma – AREVA

Tour AREVA – 1 Place Jean Millier – 92084 Paris La Defense – France
E-mail: patrick.jolivet@areva.com, anne.tamba@areva.com, farah.chahma@areva.com

Summary

Material inventory of equipment under neutron flux and/or in contact with primary coolant is of great importance for radiation protection design, regarding elements which can be activated by neutrons in the core and contribute to Occupational Radiation Exposure (ORE) during maintenance. The amount of Cobalt-based hardfacing parts and the residual Cobalt content in components of the Reactor Coolant System (RCS) have to be justified according to the ALARA (As Low As Reasonably Achievable) approach applied at the design stage. This paper provides elements which demonstrate that the EPR™ design regarding material inventory will lead to a low ORE, in accordance with the ALARA approach.

1. Introduction

The ALARA approach has been applied on EPR™ since the beginning of the Basic Design phase in 1995, which means that radiation fields and worker doses were limited as far as reasonably achievable by also considering other social and economic factors. This approach was mandatory through the application of the ICRP recommendations, European Directive 96/29 and the requirements of the Customers on design and operation of new plants, which were gathered as on 1991 in the "European Utility Requirements" (EUR).

During maintenance operations in the radiation controlled area, personnel exposure is mainly caused by activated corrosion products in deposits, which constitute the major contribution to dose rates at the vicinity of radioactive systems and components. Therefore, material inventory of equipment under neutron flux and/or in contact with primary coolant is of great importance for radiation protection, regarding elements which can be activated by neutrons directly under flux or after being released inside primary coolant.

The designer has to justify that EPR™ material selection has been made according to an ALARA approach and to examine the opportunity of a further decrease in the inventory of activable species from several viewpoints: mechanical design, availability of substitution materials, procurements costs, industrial feasibility, ageing over 60 years and radiation protection impact in terms of dose savings. This paper presents an overview of material selection for the Reactor Coolant System (RCS) and shows how deep we can consider that dose reduction measures on EPR™ are ALARA.

2. Impact of Current EPR™ Material Inventory on Primary Circuit Contamination

During EPR™ Basic Design the designers had to answer to a not so simple question: "Where is it necessary to put an effort on material selection at the design stage to decrease doses according to the ALARA approach, and this for 60 years of plant operation[1]?"

By considering the plant experience of activity measurements and dose records on operating reference PWR plants together with estimations on EPR™ collective doses, one can estimate that approximately 75 to 80 % of the Occupational Radiation Exposure (ORE) will more or less be due to corrosion product deposits[2] and therefore, linked with the material selection. The main contributions by far to the radiation source term in those deposits are due to Cobalt nuclides.

[1] Decommissioning is addressed in one other ISOE 2010' paper by I. Terry

[2] 15 to 20 % of the ORE is due to water activity in fission and corrosion products and their retention areas (purification systems, effluent treatments and wastes). The balance to total dose (small fraction) is supposed to be due to Nitrogen-16 gamma radiation during RB accessibility at full power operation (water activation product of very short half-life).

Cobalt-58 mainly arises from the neutron activation of Nickel-58 (68% of natural Nickel), which is mostly released by the Steam Generator (SG) tubes made of Alloy 690TT (Ni-based), and to a lesser extent from the Nickel of stainless steels inside RPV and the loops. Cobalt-60 is formed by neutron activation of Cobalt-59, originating from various constituting materials: Cobalt-based hardfacing parts (Stellite™, Haynes), Cobalt as an impurity in SG tubes, stainless steel piping, etc.

$^{58}Ni + n \rightarrow {}^{58}Co + p$ (^{58}Co radioactive half-life: 71 days)

$^{59}Co + n \rightarrow {}^{60}Co + \gamma$ (^{60}Co radioactive half-life: 5.3 years)

2.1 Mechanisms Involved in the Contamination of EPR™ Primary and Auxiliary Circuits

The activity build-up in primary and auxiliary systems and components is a very global process and the contribution of one component in contact with the primary water to the measured dose rates cannot be easily estimated or derived by calculation. From Figure 1 (left part), it can be easily intuited that the driving parameters for the global plant contamination are:

- surfaces wetted by the RCS and or by sub-systems injecting water into the RCS,
- chemical composition of materials in activable elements,
- release rate of corrosion product species from the considered oxide surfaces under operating conditions and plant states (operation, shutdown),
- activation by the core,
- incorporation (build-up) of activated species in RCS and auxiliary system oxide surfaces.

Such phenomena involve many aspects of thermodynamics (metal, oxides, water), chemistry (speciation of nuclides, solubility in operating conditions), neutronics (neutron activation rates for several kinds of reactions), surface behavior (deposition, activity build-up)… which are difficult to model. Instead, the designers used plant experience which emphasizes that Cobalt-60 becomes the main contributor to dose rates after 5 to 6 operation cycles. During the first operation years Cobalt-58 dominates in the deposits. Given the geometry of the loops and the radioactive properties of both nuclides as well (decay period and gamma radiations), a ratio of 3 to 4 between Cobalt-58 and Cobalt-60 in deposits is needed to have an equal effect on dose rates (Figure 1, right part).

To save doses on the long term the ALARA analysis was first focused on the selection of materials which exhibit a low release rate and wear under operational conditions, and on Cobalt-60 precursors in RCS materials:

- Cobalt in Stellite™ hardfacing parts (through general corrosion and wear),
- Cobalt residual content in Nickel-based alloy of SG tubes (through general corrosion),
- Cobalt residual content in steels (through general corrosion).

The contributions of components to Cobalt-60 were considered in an integrated manner, as they are interdependent from each others. The material optimization regarding to the ALARA approach can only be done with a transverse view of all design options for the primary components.

2.2 Cobalt-60 Sources

Compared to existing French reference units major changes were implemented on the EPR™ to decrease by design potential radiation sources following an ALARA methodology of optimization. On the right-hand part of Figure 2, comparative global surfaces of Stellite™ are given between existing reference plants and the EPR™. It can be seen that the total Stellite™ surface has been drastically decreased compared to existing French units, in spite of a longer lifetime (60 years compared to 40 years) and more severe design transients. Stellite™ was totally suppressed where it could reasonably be avoided.

However, considering all EPR™ design features, the result of the iterative approach and validation steps over 15 years involving several disciplines (according to the ALARA methodology) has led to keep Stellite™ hardfacing parts inside the primary circuit at some locations, while minimizing the surface as far as possible especially for parts under neutron flux. For some cases, dose reduction in the range of uncertainty could not be a sufficient driving parameter compared to safety issues, lifetime, corrosion and wear, mechanical constraints under design loads, or because of the absence of qualified Cobalt-free materials for such applications.

- ***Cobalt in Stellite™ hardfacing parts of primary equipments and connected valves***

• *Reactor Coolant System valves*

Cobalt-free materials have been systematically chosen for implementation on EPR™ valves wetted by the primary coolant during normal operation. As a result of this ALARA measure, there is a remarkable reduction of Stellite™ global inventory compared to French reference plants and potentially-induced contamination in the EPR™ primary circuit.

• *RPV and RPV internals*

Radial guides are providing close centering of the RPV internals in the bottom of the core. This centering requires Stellite™ hardfacing according to mechanical and material constraints. However, an optimization was performed such as there are less centering keys in the EPR™ than in N4 plants. This resulted in a reduction by 30% in hardfacing surface, without jeopardizing functionality.

The Upper Core Plate (UCP) alignment is designed to provide a close circumferential centering. In faulted conditions, the guide pins also provide a lateral support to the UCP. This function also requires Cobalt hardfacing.

• *Control Rod Drive Mechanisms (CRDMs)*

The vertical movement obtained by the action of the CRDMs is said to be “step-by-step”. Each circumferential groove on the Drive Rod corresponds to one step. As millions of steps are to be performed during the 60 years of operation of the EPR™ CRDMs, the parts subject to friction and/or impact are possibly involved in a degradation process (mechanical damage: fatigue, wear) which may alter the correct behavior of the CRDMs. Because of safety concerns with this equipment, and also to secure the behavior during EPR™ lifetime of 60 years and avoid early replacements, a world-wide proven technology is used. The design of EPR™ CRDMs is the same as for KONVOI units. While maintaining comparable load follow and load regulation capabilities over 60 years, the total number of steps was also decreased compared to French units, due to a parallel optimization of the EPR™ core reactivity control modes.

CRDMs represent half of the total Stellite™ surface of the EPR™. Performance tests were performed, which showed that the EPR™ CRDM is able to bear the required millions steps, showing good results and even margins. The CRDM design is considered optimized, thus ensuring high mechanical properties, adequate life duration and hardness, and as good resistance to corrosion and wear as on KONVOI plants. The contribution to Cobalt-60 is thus assumed to be low for the EPR™, as those plants exhibit very low radiation fields although Stellite™ hardfacing is also present on CRDMs.

• *Main Coolant Pumps (MCP)*

As for the case of the French N4 primary pumps, auxiliary hydrodynamic bearing is designed to operate during the start-up and shutdown of the MCP, or during accident conditions (LOCA). This results in the absence of wear on the Stellite™ deposit during the normal operation of the MCP. No evidence of wear was pointed out during in-service inspections of existing MCP. As a consequence, the contribution of MCP to the EPR™ personnel dose is negligible and limited to the general corrosion of the deposit, if any. Possible release of small particles which could be the source of radiological "hot spots" in auxiliary piping is also considered as very improbable, since this would require abnormal conditions.

- ***Cobalt residual content in Nickel-based alloy (typically, the SG tubes)***

Because of the bigger size of EPR™ compared to existing units, the primary equipment surfaces of constituting materials are also bigger than on existing units (Figure 2 left part) and especially the SG tubes made of Alloy 690TT (Nickel-based material). As Cobalt often comes from Nickel impurities and due to the potential release of Nickel from SG tubes a particular effort was made in the equipment specification to decrease Cobalt residual content according to an ALARA approach.

An optimization between industrial feasibility (selection of raw materials) and procurement costs on one hand, and the potential effect on corrosion product source term on the other hand was found to be at 0.015% residual Cobalt on average per SG tube bundle. This is better than the RCC-M code (design and erection rules related to mechanical equipments of the Nuclear Island), which requires 0.018% on average per SG tube bundle.

- ***Cobalt residual content in steels***

The reduction of cobalt content in primary equipment materials under neutron flux (mainly the RPV internals) was also addressed at the very beginning of EPR™ Basic Design following ALARA methodology, as this was required in the EUR specifications. For this purpose, real Cobalt contents from chemical analyses on stainless steel parts were compared to the RCC-M specification of existing units to identify possible margins.

Optimization of margins between Cobalt specifications and industrial feasibility relies on a detailed analysis of the steel-maker capabilities to select raw materials. Indeed, recycled materials are used in the steel-making industry by all potential subcontractors for the melting of the final alloy. In addition to Nickel impurity, Cobalt may be present in all recycled materials as it is an alloying element used in some Nickel-based materials (super alloys) and special steels. The reduction of Cobalt content in primary components base materials thus requires an additional step of selection and control of recycled materials. Depending on the subcontractor (as well as addressed component, safety classification, elaboration process, required Cobalt content, procurement of recycled material), the impact on costs can drastically vary from one industrial context to one other.

Table 1 summarizes the optimization which has been found on the EPR™ due to Radiation Protection concerns in comparison to RCC-M requirements, and considering all above industrial and procurement restrictions. For RPV internals and primary loops, the EPR™ Cobalt specification is less than 0.06%, which is an improvement beyond the requirement of the RCC-M code (< 0.2% required, but < 0.1% expected).

- ***Contribution of all Cobalt-60 sources***

The remaining Stellite™ parts are decreased as much as possible in regions under neutron flux, given the mechanical and other constraints pointed out by component design teams. For all Stellite™ areas, an ALARA decision was made by comparing pros and contras. Among contras, the absence of qualified Cobalt-free material, the cost and collective dose associated with a material replacement before 60 years was often highlighted. Stellite™ was left at those only locations where it was not reasonably possible to remove it, as shown in the above examples. It was checked that optimized design will lead to smallest surfaces and/or negligible wear, such as the contribution of corresponding surfaces is expected to be low. Cobalt hardfacing was totally suppressed from the reactor coolant and connected auxiliary system valves.

Cobalt residual content in RCS constituting materials is also considered as “state-of-the-art” in most of the industrial contexts to decrease dose while limiting procurement costs. This is true for steels of the primary loop equipments and for the SG tubes in Alloy 690TT, for which a particular effort was made.

As a result, and in spite of a larger Stellite™ surface than on KONVOI plants (Figure 2, right-hand side), the global contribution of EPR™ material inventory to Cobalt-60 contamination in deposits is expected to be only approximately 40% over the 60 years plant life, which is in agreement with experience of French units in the first cycles only, as shown on Figure 1. The other contributions to deposit dose rates are addressed in the following sections.

2.3 Cobalt-58 Sources

Complementary to measures limiting long term effect of Cobalt-60 on ORE, design or operational provisions have also been implemented to mitigate Nickel-58 releases in the primary coolant during the first cycles of EPR™ operation, and especially the contribution to Cobalt-58 from SG tubes (Figure 2) made of Alloy 690TT with approximately 58% Nickel.

Particular attention was paid to the optimization of the primary water chemical specification during power operation, start-up and shutdown procedures. Moreover, an optimized pre-oxidation step of primary surfaces is foreseen during commissioning of the EPR™ to limit the release rate and thus, potential activation by neutrons of all released corrosion products.

Finally, radiation protection rules are systematically implemented in the component design to avoid retention areas and in the layout of rooms as well [1]. In EPR™ configuration the contribution of Cobalt-58 in deposits was estimated to represent approximately 50 % of the corresponding radiation field.

2.4 Other Potential Nuclide Sources in Deposits

There are also activated corrosion products from the other alloying elements (steels and Ni-based alloys), such as Chromium, Manganese and Iron. On existing units without pollutions, these nuclides usually account for additional 10% compared to the contribution of Cobalt-58 and Cobalt-60 to the deposit dose rates. Silver and Antimony are avoided by design in pumps and seals, then pollutions with Silver-110m and Antimony-122/124 are not expected on the EPR™ during normal operation. The only notable exception, also justified by mechanical designers, is the seal of the RPV head.

2.5 EPR™ Expected Dose Rates Due to Corrosion Product Deposits

As a result of this global material inventory and measures to mitigate corrosion product release, the assumed concentrations of both Cobalt nuclides in deposited activity are close to the ones of best existing plants and will lead to low dose rates at the vicinity of primary and auxiliary equipments. In a typical EPR™, dose rates due to deposits at 50 cm of the loops are expected in the same range as the measured values on KONVOI units, well below 0.2 mSv/h. With current knowledge of industrial feasibility and costs the existing material selection of EPR™ follows the ALARA approach.

3. Are Further Improvements in Material Inventory ALARA?

Continuous improvement is also an important aspect of the ALARA methodology. Further design changes to decrease all potential radiation sources have to be considered. To estimate whether or not a further reduction of the Cobalt-60 potential precursors follows an ALARA approach, a “decision-making” tool which was developed during Basic Design based on EPR™ characteristics and corrosion product release mechanisms (section 2.1), was run again. In the years 2000 to 2004, this tool had already allowed the above optimization of Stellite™ content compared to the EPR™ Basic Design. The tool was benchmarked against in-situ activity measurements on reference plants.

3.1 Cobalt-60 Potential Sources

Applying again the ALARA methodology, iteration was performed to try and decrease Cobalt inventory because of the rather high and long-term contribution of Cobalt-60 to ORE. A multi-discipline team was in charge of evaluating industrial feasibility, costs and expected savings on doses. Compared with the EPR™ current design and material inventory, changes due to other design options aiming at reducing Cobalt inventory were analyzed with regard to potential dose reduction. The “decision-making” tool based on component surfaces, release rates and dose considerations was used for this purpose.

Results are gathered in Table 2. It can be seen that the potential dose reduction compared to the design values or current objectives for EPR™ ORE (between 0.35 and 0.50 man-Sv/year on average) are rather low (some percents), given the very high level of uncertainty of such evaluations. At least, industrial risks for AREVA, additional drawbacks in terms of outage duration in case of early replacement, time schedule or procurement/ development costs were deemed to be too high in comparison.

3.2 Cobalt-58 Potential Sources

The SG tube material choice of Alloy 690TT is sometimes questioned, because of the potential amount of released Nickel with subsequent activation in Cobalt-58. The possibility to use Alloy 800 (Iron-based) like on existing reference German plants was analyzed with regard to corrosion resistance (stress corrosion cracking, intergranular attack) on primary and secondary sides. The industrial feasibility was also checked, as well as the consequence on manufacturing and time schedule for existing EPR™ projects. Corrosion aspects and world-wide experience with good behavior were in favor of Alloy 690TT in the integrated decision process.

With regard to radiation protection, it was emphasized that existing plants with Alloy 690TT as SG tube material could have a good behavior with regard to Nickel release and meet the design value of ORE, provided that the release rate of Nickel is controlled by adequate chemical specifications during start-up, power operation and shutdown. The SG tube manufacturing process will follow the “state-of-the-art”, thus avoiding the small grain layer which was formerly present on the inner surface of tubes due to manufacturing options and pollutions, and which was supposed to favor general corrosion of the base metal.

4. Conclusion

The current EPR™ design follows the ALARA approach and EPR™ units will exhibit low ORE values. Efforts on materials have to be complemented by radiation reduction measures in other fields like primary water chemistry. For some EPR™ projects, additional means to decrease potential doses could be implemented depending on customer requirements or local regulations. A case by case analysis of risks, sacrifices (cost, schedule…) and potential dose reduction has to be performed to validate their implementation, keeping in mind that the total corrosion products in deposits approximately account for 75 to 80 % of the total occupational radiation exposure of the EPR™ (40% due to Cobalt-60), given all other radiation sources. The situation has to be re-evaluated from time to time to check if things can be improved to prevent doses. Some changes might become more “reasonable” in a near future.

5. References

[1] I. Terry, P. Jolivet, ISOE Conference 2008, Turku, Finland

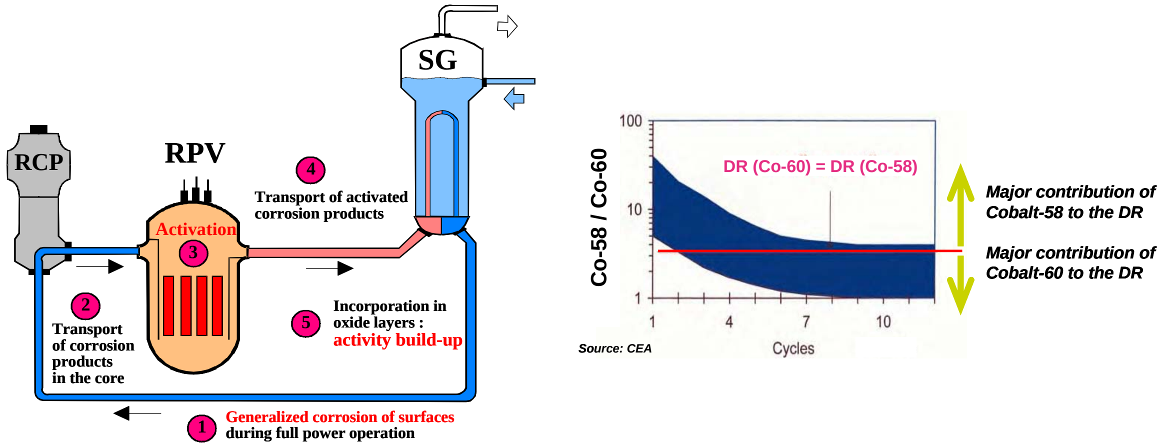
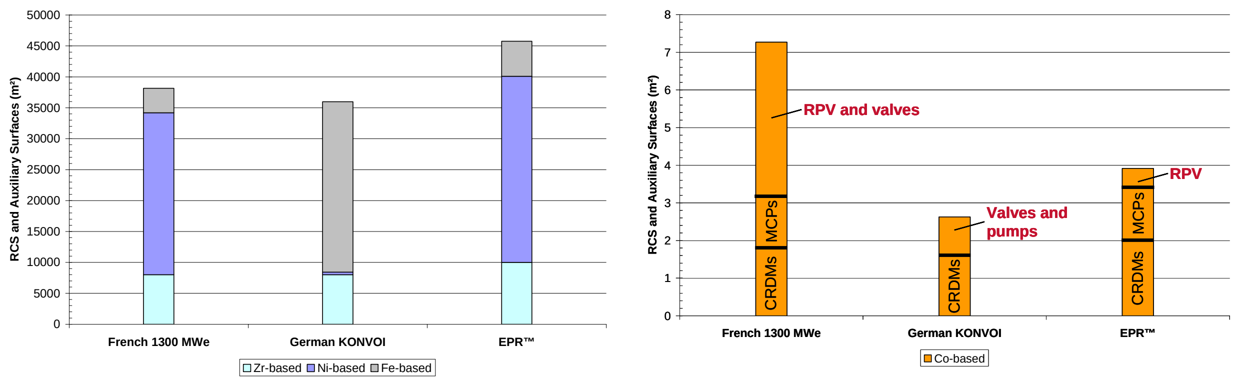


Figure 1: RCS Activity Build-Up and Feedback of Ageing Effect on Cobalt Nuclide Contributions



Ni-based: potential precursor of Co-58 and Co-60 (Co residual content) by general corrosion
Fe-based: potential precursor of Co-60 (Co residual content)

Co-based: potential precursors of Co-60 by general corrosion and wear/ degradation mechanisms
Co-based: no or negligible contribution to Co-60

Figure 2: Comparative Approximate Surfaces Wetted by Primary Coolant

Table 1: Cobalt Content Requirements in Stainless Steels In Contact With Primary Coolant

Equipment/ Material	RCC-M requirement (%)	EPR™ (%)
RPV internals	< 0.2 required, but < 0.1 expected	< 0.06
RPV and pressurizer stainless steel cladding	< 0.2	< 0.06
Main Coolant Lines and PZR surge line	< 0.2 required, but < 0.1 expected	< 0.06

Table 2: Dose Reduction Estimates by Further Decrease of Cobalt-60 Precursors in EPR™ Design

Design options	No Stellite™ for RPV internals bottom centering	No Stellite™ on UCP guide pins	No Stellite™ on CRDM Latch Tip	Lower cobalt content in base Steel materials (e.g. 0.03%)	No Stellite™ in Main Coolant Pumps
ORE reduction	-2 to -3%	-2 to -3%	-3 to -5%	-5 to -6%	negligible