UPDATE ON FRAMATOME'S ADVANCED SOLUTIONS AS A SERVICE SUPPORT TO REACTOR LIFETIME EXTENSION

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ABSTRACT

Nowadays, nuclear plant utilities which want to extend their plant lifetime operation, face challenges with the potential saturation of their spent fuel pool and design constraints on the accumulated vessel neutronic fluence. Framatome offers solutions by providing calculation tools and engineering services to meet customer needs. During the 2017 WRFPM (Water Reactor Fuel Performance Meeting) in Jeju Island, South Korea, were presented some of the solutions brought by Framatome: the management of the spent fuel pool and the reactor vessel fluence calculation. This paper provides further elements on the validation of the fluence calculation solution. The fully intuitive tool allows verifying the history of accumulated vessel fluence, designing solutions to reach reactor lifetime extension utilities goals, and tracking cycle by cycle the evolution of the vessel fluence.

1. Introduction

1.1 Context

In its 2017 reports [1], the IAEA accounted for more than 440 nuclear power reactors around the world. For a part of this aging fleet, the nuclear plant utilities are willing to extend their plant lifetime operation. Continuing operation also means that utilities face challenges with the potential saturation of their spent fuel pool and design constraints on the accumulated vessel neutron fluence.

To handle the spent fuel pool storage risk of saturation, Framatome provides various services such as dry cask storage and clean-up of pool elements. For the risk of reaching reactor vessel design limits, Framatome also provides hardware solutions to reduce the neutron fluence accumulation such as shielding fuel assemblies (SFA) and absorber rods.

During the 2017 WRFPM (Water Reactor Fuel Performance Meeting) in Jeju Island, South Korea, some of the software solutions [2] were presented: management of the spent fuel pool and vessel neutron fluence calculation. These software solutions are intertwined with the implementation of hardware solutions: the advanced code systems enable use of new optimized design.

The Framatome software solutions are based on the new code system named ARCADIA being implemented. ARCADIA [3] is an advanced 3D coupled neutronics/thermal-hydraulic/thermal-mechanical code system applied to Light Water Reactor (LWR) fuel assembly and core design calculations as well as for transient safety analysis.

Concerning the spent fuel pool manager available with ARCADIA and adaptable to other systems, it is directly connected to the definition of the core and uses the core calculation results to feed the characteristics of the fuel assemblies in the pool. This makes it more precise and agile than the classic conservative approach.

This paper focuses on the advancement on the new vessel neutron fluence tool answering the needs of utility customers in terms of lifetime extension.

1.2 Framatome solutions for vessel fluence tracking and prediction

The vessel fluence calculation tool is based on the methodology of the vessel adjoint flux evaluation. The computation of the adjoint flux is made once with MCNP [4] for all the rods in the core and multiplied by the 3D neutrons distribution evaluated by a core simulator (cf. Figure 1). Thanks to its flexibility, the tool can be adapted to various core simulators. It has already been adapted to the current code system SCIENCE and the new ARCADIA code system. This makes the vessel neutron fluence calculation quick once the MCNP model is defined. Therefore iterations during fuel management optimization are possible.

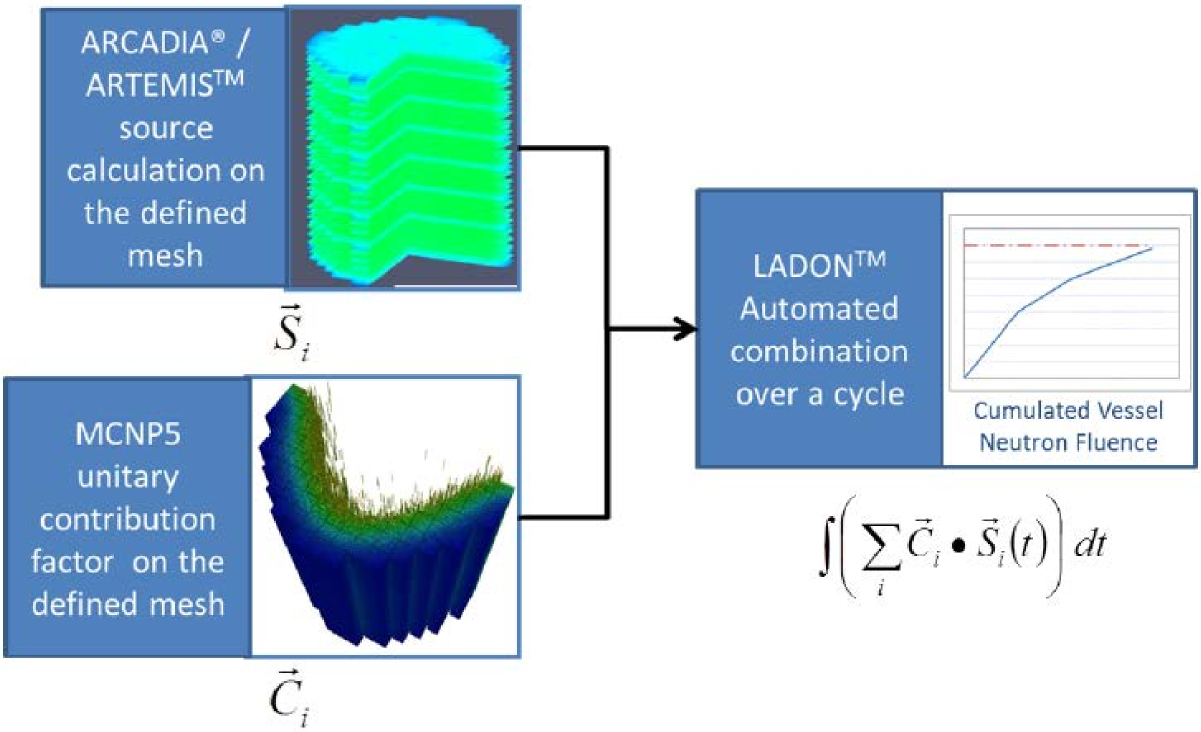

Fig 1. Vessel fluence methodology process

2. Validation of the tool

To validate the approach, the tool was applied for a sample plant for past cycles and compared to licensed calculated data (these licensed calculated data are not using the same solver, cross section libraries and methodology). The adequacy of the tool is estimated by comparing the calculated fluence of the tool versus the reference calculated fluence (Eq. 1).

$$Tool\_vs\_Ref = \frac{Fluence_{tool}}{Fluence_{licensed}} - 1 \quad \text{- Equation 1}$$

The synthesis is presented in the Table 1. Overall the best estimated (unbiased) ARCADIA and SCIENCE calculations are slightly under-conservative (respectively -3% and -5%) compared to calculated integrated peak fluence data on the vessel wall of the sample unit. These slight discrepancies have to be compared to the current 20% uncertainty bias used for industrial fluence evaluation. So the comparisons show very good agreement between the prediction tool and the reference calculated data, well within the usual method uncertainty on fluence calculation.

Integrated fluence over cycles	Licensed calculated fluence [n/cm2]	ARCADIA fluence [n/cm2]	Tool vs Ref [%]	SCIENCE fluence [n/cm2]	Tool vs Ref [%]
1 to 4	7.600e+18	7.344e+18	-3.36	7.164e+18	-5.74
1 to 7	1.310e+19	1.274e+19	-2.75	1.229e+19	-6.18
10 to 14	6.600e+18	6.396e+18	-3.10	6.337e+18	-3.99
1 to 16	2.590e+19	2.503e+19	-3.36	2.443e+19	-5.67
1 to 11	1.910e+19	1.853e+19	-2.97	1.804e+19	-5.57

Tab 1: Reactor vessel fluence - ARCADIA and SCIENCE benchmarks

The evolution of the vessel neutron fluence over many cycles was extrapolated following the recent fuel management until reaching the vessel neutron fluence criteria. This provides an anticipated end of life design limit for the plant as shown in Figure 2.

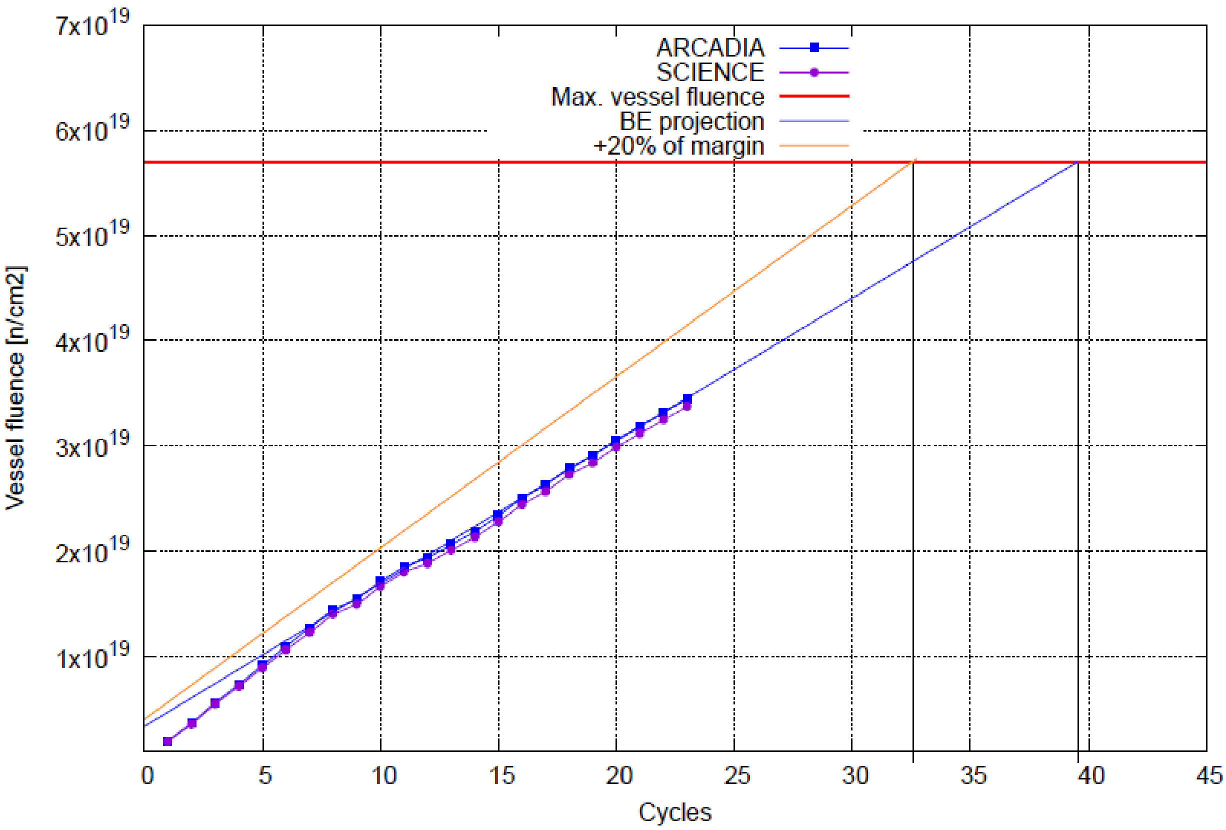

Fig 2. Vessel neutron fluence projection with ARCADIA and SCIENCE

Once the vessel neutron fluence model either developed with SCIENCE or ARCADIA is validated, it can be used for different applications.

3. Application of the tool

The fluence tool is adapted to both SCIENCE and ARCADIA, and can be adapted to other core simulators. Once the model is validated compared to MCNP reference calculations and/or benchmarked against capsule measurements, the tool is applied for the three following cases:

- Analysis of vessel neutron fluence reduction solution
- Tracking of accumulated vessel neutron fluence
- Optimization of cycle core design to minimize vessel neutron fluence

These applications are detailed in the following sections.

3.1 Analysis of vessel neutron fluence reduction solutions

The accumulated vessel neutron fluence depends on the type of reactor, the fabrication materials and the historical operation of the reactor. Therefore each reactor can have a different limiting neutron fluence criterion:

- For some reactors, the limiting fluence can be on the main vessel material with specific radial location. In that case, Framatome provides the following hardware solutions
    - o Absorber rods placed in the fuel assemblies in the periphery of the core. These absorber rods are made of usual absorber materials such as Hafnium. Framatome has also developed innovative absorber material with better performance and at cheaper cost. The absorber rods provide limited shielding factors to neutron fluence, since the neutron sources in the concerned assemblies are reduced and not suppressed totally.
    - o Shielding fuel assemblies placed in the periphery of the core. These SFA contains rows of inert rods and rows of fuel rods. The inert rods are usually made of stainless steel. The interest of inert rods is to suppress the production of high energy neutron that may travel to the reactor vessel in addition to absorbing incoming neutrons. Shielding fuel assemblies provides higher shielding factor than do absorbers inserted into guide tube locations. This factor can be adjusted based on the number of rows of inert rods in the assembly.
- For some reactors, the limiting fluence is located at a specific axial core height, related to vessel welding material. In that case, Framatome provides customized solution with specific shielding fuel assemblies. For this specific application, SFA are customized to a defined axial distribution of fuel rods that have a stainless steel region and a fuel region within the same rod. This allows the SFA to protect a specific axial height of the vessel.

The fluence tool is well suited to perform the analysis to customize the solution to the utility specific need. Without this tool, one has to use the classic Monte Carlo approach which is time-consuming and does not allow much iteration. With the tool, the process is to define a weighting factor matrix for main representative configurations: reference core model without fluence reduction hardware; 2 core models with 2 hardware sample solutions.
Once the matrixes are established with MCNP calculation, one can use the tool to combine core simulator calculation results with the matrix data. This process is quick and allows iteration in the core definition.

Therefore with the fluence tool, one can customize specific solution which meets the fluence reduction need without minimal impact on core performance.

3.2 Tracking of vessel neutron fluence

An application of interest is the tracking of vessel neutron fluence accumulation over the cycles. This is needed to prove that the core can still operate. Thanks to its simplicity, the fluence tool can be integrated to the set of codes for the cycle reload analysis where the safety criteria are evaluated. The fluence tool is used in conjunction with the core simulator calculation during the cycle depletion to determine the accumulated fluence as an automated process in the cycle reload analysis report. This way, one can track the trend of accumulation of fluence compared to the reference trend that was planned to respect the limiting vessel neutron fluence criterion.

3.3 Optimization of cycle core design for vessel neutron fluence

A third application is the use of the fluence tool as part of the tools used to optimize a reload cycle design. During such activity, the core designer optimizes the core definition to meet the safety criteria. Thanks to the flexibility of the tool, the core design can also consider the vessel fluence as part of the design criteria. For example, the core designer can test various cases or fuel assembly placement or orientation in the core to minimize the vessel neutron fluence while still meeting the safety criteria.

Up to now, this evaluation could be a process via a rough evaluation of the fuel assembly burnup on the periphery of the core. Thanks to the tool, the core designer can have a more precise evaluation. This precision which was not necessary in the early cycles of the reactor is now of interest as the vessel neutron fluence may become a limiting criterion for some plants.

4. Conclusion

With the worldwide aging fleet of nuclear power reactors, utilities are facing new challenges to maintain the operability of the plants. Framatome provides services and hardware solutions to meet customer needs for over-crowded spent fuel pool storage and for vessel neutron fluence criterion. To facilitate the implementation of the solution, Framatome has also developed software solutions along with its new code chain named ARCADIA. This paper presents good validation results shown by the neutron fluence tool used for various key applications: customize hardware solution, track vessel neutron fluence and optimize core based on vessel neutron fluence.

5. References

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