Assessment of the Source Term in LWR in View of the Fukushima Accident

M. Becker*, C. H. M. Broeders, R. Dagan
Institute for Neutron Physics and Reactor Technology,
Karlsruhe Institute of Technology Campus North,
Hermann-von-Helmholtz-Platz 1,
76344 Eggenstein-Leopoldshafen

Abstract

The importance of a good estimation of the source term in nuclear reactors was once more emphasized by the Fukushima Daiichi accident. The need to know the partial inventory in the core at shutdown is highly important. In particular the highly-volatile isotopes like I-131, Cs-137 can cause a considerable biological damage to the thyroid and intestine respectively upon their release to the environment. In this study it is shown that for conventional LWR fueled reactors (PWR, BWR) the complexity of the whole core calculation can be reduced to a representative subassembly calculation, if one is interested in the equilibrium nuclide inventory. The dominating parameter here is only the total extracted energy. Other local parameters like void distribution are of second order importance. A demonstration of the source term evaluation was performed for the Japanese Fukushima Daiichi 3 and Daini 2 core, based on the available data. The relevant isotopes' activation was estimated during operation and after shutdown.

Introduction

The calculation of a core source term necessitates in general the coupling of the flux calculation with an appropriate burn up code to evaluate the nuclide inventory based on capture, fission and decay processes during operation state and after the shut down of the reactor. Evidently, the intricacy of such a procedure becomes larger with the size and type of the core, the number of fissionable nuclides involved and consequently the quality of the numerical tools used as well as the validity of the cross sections and fission yield libraries used. In this study, the problematic of the numerical procedure is reduced in view of the type of reactor under investigation. In the following it is shown that for the UOX fuel type the linear power rate has almost no impact on the criticality decrease as a function of the total extracted energy or total burn-up. This important fact can be used to predict the nuclide inventory.

The numerical tool used for the simulation is the reactor physics code KANEXT [1]. This system is highly modular, allowing for the usage of problem dependent specific available tools for each level of the simulation. For the current study the KANISN Sn

*Corresponding author: Maarten.Becker@kit.edu

transport code [7] was introduced to calculate the criticality and the flux of a three zones Wigner-Seitz pin cell. The microscopic multigroup transport library is based on the newest JEFF 3.1.1 evaluation in a 350 energy groups fine group structure. It contains an extended nuclide cross section set resulting from the NJOY treatment of the JEFF activation library, so that problem dependent flux weighted one group cross sections can be generated for nearly 800 isotopes. These replace – if available - the tabulated one group cross sections originating from ORIGEN formatted data files used in the BURNUP module [6]. As part of the modularity of the KANEXT system the fission yields of the validated (yet old) of the KORIGEN program ([2],[4],[5]) were inserted instead of the current one used in the JEFF 3.1.1. Further for the decay phase of the nuclides under investigation the KORIGEN code was used as a stand alone code.

Source Term Evaluation

The calculation of the fuel inventory during burn up can be complicated depending on the main fissionable isotopes in the core. For example in the case of thorium /uranium cycles the build up of the fissionable isotope U-233 is induced by the decay of Pa-233 with a half life of 26.96 days. Consequently, various linear power rates lead to different decrease path of the criticality as a function of the burn up, as can be seen in figure 1a. Contrarily, in an exemplary LWR pin cell, the decrease of the criticality does not depend on the linear power rate, but on the overall extracted energy. This effect can be explained by the small half-life of the Np-239 isotope to transmute to the Pu-239 isotope, which is then consumed in situ.

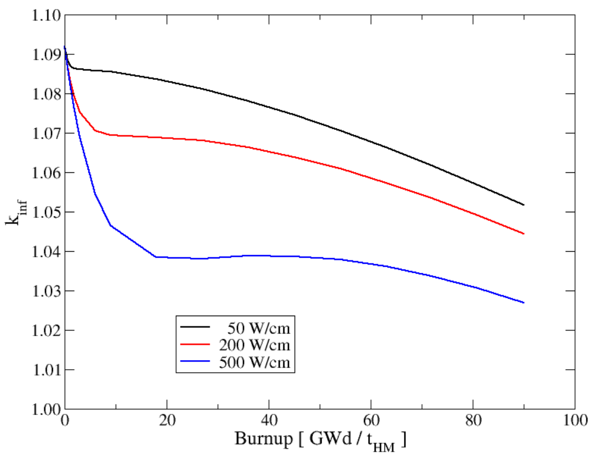

Figure 1a: Pb cooled Th/U cell

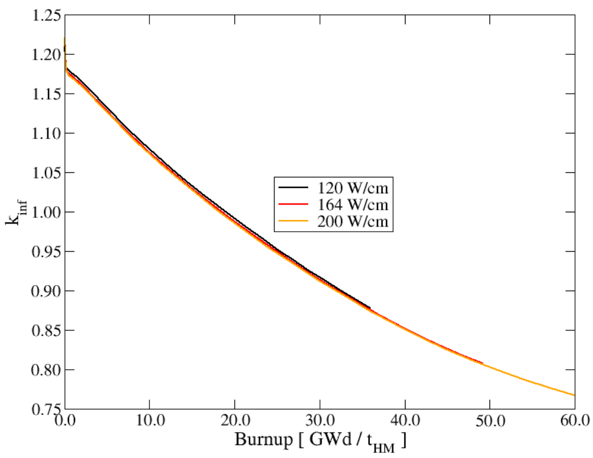

Figure 1b: Typical PWR cell with 4 % U-235

Figure 1: Influence of linear power rate on criticality for different fuel and reactor systems during burnup

Figures 2a und 2b underline the main dependence on the overall extracted energy from the inventory point of view. For the pin cell calculation of figure 1b the corresponding Plutonium-to-Uranium concentration ratio and the relevant fission product Cs-137 concentration are plotted for varied linear power rates.

For the same reason the Gadolinium control rods are not modeled. They are used to homogenize the power shape in the beginning of the cycle, but do not affect the nominal power of the plant. Thus, when looking for the global source term, it does not matter, where the power is produced. Contrary, for local distributions and effects, an accurate modeling of the Gadolinium rods is inevitable.

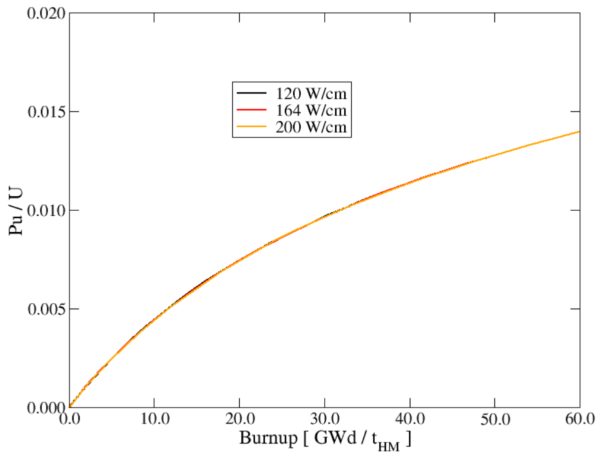

Figure 2a: Plutonium-to-Uranium ratio

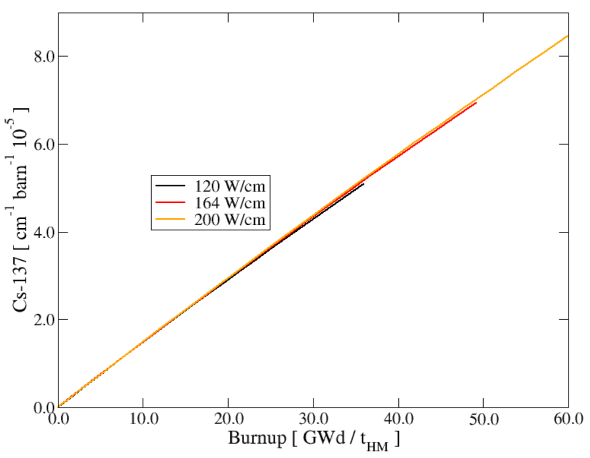

Figure 2b: Cs-137 number density

Figure 2: Evaluation of nuclide inventories in typical PWR cell

A reasonable good guess of the total source term may therefor be calculated, when the main parameters of the reactor under consideration are known. Table 1 summarizes the lattice parameters of a typical BWR fuel assembly with either 8 x 8 or 9 x 9 rod positions. These fuel specifications correspond to the Fukushima Daiichi 3 and Fukushima Daini 2 BWR power plants, respectively ([8],[9]). The focus has been however on the Fukushima Daiichi site, so that the global data is taken from the Fukushima Daiichi BWR 2 plant for both geometries [10]. In order to investigate the sensitivity of the result to the void in the upper BWR core, the water density was reduced to 0.45 g/cm^3 resembling 40 % of steam.

The global parameters allow for the calculation of a mean burnup at EOC of 31.4 GWd/tHM, nevertheless, the results in the simulation are achieved for 30.5 GWd/tHM.

The total radioactivity and the decay heat power of the core are shown in figure 3a for a time period of 42 days after emergency shutdown. It is not surprising in view of the main dependence on the extracted energy, that the behavior and the order of magnitude of the curves are comparable for the two lattices. The difference of less than 10% may have its reason in the spectral influence of the wider 8 x 8 lattice, for which problem dependent one group cross sections are calculated and collapsed in the KANEXT burn-up procedure. For the voided core, an enhanced radioactivity within 6 % is observed, which is considerably low for the interest of the study and mainly attributed to the evolution of the actinide concentrations.

Conclusion

The method presented provides a reasonable assessment of a source term and decay heat power of a LWR. The basic approach was to imply the global dependence of the inventory on the total extracted energy. The local linear power of the fuel assembly and other spectral aspects like void and Gadolinium are for this purpose only of minor importance, in accordance with [12].

The above mentioned procedure was applied to estimate the source term and decay heat power of a Fukushima Daiichi BWR 2 type reactor. The influence of different lattice types has been found to be negligible for this kind of study.

The absolute quantities are reasonable and provide in addition full isotopic details, which are needed for determination of potential emission paths and hazards to the environment.

Lattice parameter	Fuel assembly type	9x9	8x8
	Reference	JNES	OECD
	Lattice pitch (mm)	14.40	15.20
	Fuel pin radius (mm)	4.89	5.29
	Can thickness (mm)	0.71	0.86
	Can material	Zr	Zr
	Water density (g/cm3)	0.74	0.74
	Ratio to theoretical fuel density	0.93	0.95
	Fuel temperature (K)	1100	1100
	Can temperature (K)	560	560
	Coolant temperature (K)	560	560
	Fuel	UO2	UO2
	Fuel enrichment (%)	3.50	3.50
Global parameter	Discharge (EOL) burn-up (GWD/THIM)	50	50
	Mean core burn-up at EOC (GWD/THIM)	30.50	30.50
	Number of fuel batches	5	5
	System thermal power (MW)	2381	2381
	Power rating (W/cm)	158.3	195.20
	Fuel pin weight (g/cm)	5.52	6.90
	Core heavy metal weight (tonnes)	103.40	94.00
	Mean electric energy produced 2005-2009 (GWh_{el})	22717	22717
	Load factor	0.68	0.68

Table 1: Main parameters of the BWR study

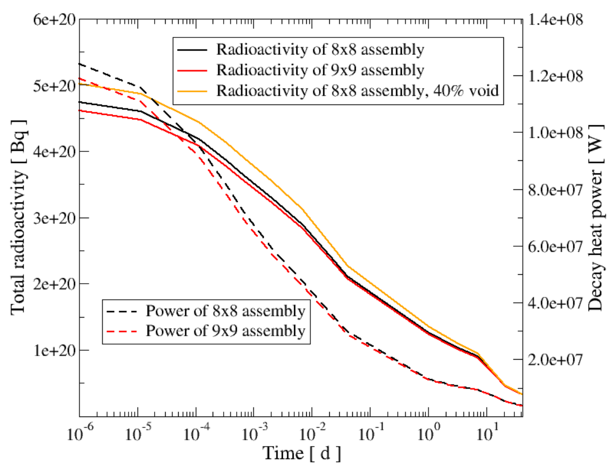

Figure 3a: Total radioactivity and decay heat power as a function of time for 2 lattices and the void case

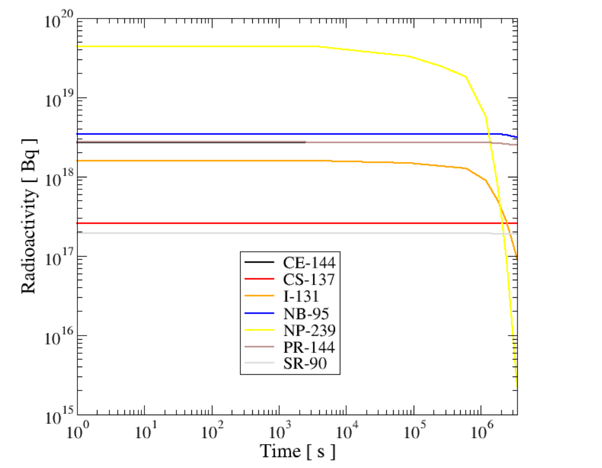

Figure 3b: Main isotopic contributors of the radioactivity after shutdown

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