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REACTOR CRITICALS AND SPENT FUEL SYSTEMS SIMILARITIES

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Abstract.

Many conservative assumptions for subcriticality assessment calculations have to be made in current calculations of spent fuel storage systems. This is due to a fact that there is no available database of benchmarks containing spent fuel or materials with isotopic composition like spent fuel. However one potential source of spent fuel system experiments is being omitted – there are hundreds of commercial reactors around the world containing spent fuel on some level of burnup. These reactors have to be tested for safety reasons in the beginning of each cycle and parameters of these test states are well known.

In this paper a possibility of using commercial reactor critical states for code validations and for subcriticality assessments of storage systems is discussed and potential approach for criticality safety analysis is given.

Keywords: Reactor criticals, spent fuel storage systems, calculation similarity, criticality safety analysis.

1. Introduction

Spent fuel storage systems subcriticality limit of $k_{eff} < 0.95$ is set in current Czech [1] and many other countries legislation. This limit is usually fulfilled, even though some adjustments and estimations not reflecting real state have to be used when creating storage models.

Firstly, due to a lack of credible benchmarks with spent fuel isotopes, currently there is low knowledge about spent fuel model calculations precision and therefore reliable calculations with fresh fuel are usually performed. This also means that calculated k_{eff}s are usually higher than reality, because by using of fresh fuel, falling trend of fuel reactivity with raising level of burnup is omitted.

Secondly, some conservative assumptions have to be used about neutron absorbers included in system. But if these would be too conservative, not all systems would fulfil the legislative limit.

Because of these adjustments, calculations for proving subcriticality of spent fuel storage system are performed on models, which are not perfectly alike to the reality of storages.

Subcriticality calculations of storage systems (and even criticality calculations of systems including spent fuel) would be more reliable, if a calculation code and process could be validated on spent fuel experiments. Luckily one possible source of experiments is available – physical and safety start-up tests from beginning of each cycle of commercial reactors in nuclear power plants. States from these tests has sufficiently known parameters to become benchmark experiments, including mainly exactly known $k_{eff} = 1$ (that is why these states are being referred as "reactor **criticals**") and precisely measured core parameters from instrumentation and control system.

As was said, there is potential for development of more trustworthy process for spent fuel systems calculations validation. But the first milestone is to verify that reactor criticals and spent fuel systems are sufficiently similar. This is what will be discussed in this paper.

2. Current approach to subcriticality assessment

As was already written in the introduction, spent fuel storage systems subcriticality assessments have to be performed based on calculations using fresh fuel isotopic composition and conservative assumptions. Brief summary of fresh fuel systems experiments available for code validations and generally used conservative adjustments will be given.

2.1. Generally available benchmarks for code validation

In an ideal case calculation codes should be validated using benchmarks of same type of systems calculations like the newly projected system it will be applied to. In reality this is impossible for spent fuel storage systems, because benchmarks with spent fuel composition are usually not described in available databases. Few artificially prepared experiments with spent fuel

isotopes were described, but these usually has only units of required isotopes and not in atomic density quantities which are typically present in real spent fuel. Therefore validation of calculation codes for any type of calculation is usually performed using fresh fuel experiments only. This approach is not ideal and in case of using it, calculations of models of different types should be penalized.

Main source of benchmarks cases with fresh fuel which can be used for validation of calculation codes is International Handbook of Evaluated Criticality Safety Benchmark Experiments (produced by ICSBEP) [2]. This database contains sets of various cases of different systems from just uranium sphere in moderator to simplified minicores (for example VVER reactors type largest available minicore is with 17 fuel assemblies). Isotopic composition for these benchmarks is fresh fuel and closest to real cores of nuclear reactors are systems with fresh MOX fuel, because of Pu included in it (from comparisons in [3]).

Summarized from previous text – benchmarks currently used for code validations are not similar to storage systems on sufficient level and therefore not appropriate for spent fuel systems calculations validation.

2.2. Conservative adjustment of models

Fresh fuel isotopic composition is used for currently performed spent fuel storage subcriticality assessment. For that case there are two main generally used adjustments:

- omitting of burnable absorbers,
- partial boron credit.

In newly produced fuel assemblies burnable absorbers (for VVER it is gadolinium in Gd_20_3 mixed to some pins in fuel assembly) are used for flattening of neutron flux profile in fuel assemblies during reactor operation. These absorbers reduces reactivity and therefore have to be removed from model. Technically after few cycles in reactor, their influence is negligible, but since fresh fuel is used in calculation, these absorbers have to be removed to stay conservative.

In spent fuel storage pools a boric acid is dissolved to reduce reactivity. Conservatively the boric acid should be completely removed from model, since it reduces reactivity. On the other side, with zero concentration of the boric acid and fresh fuel isotopic composition, k_{eff} of the pool loaded with currently used fuel assemblies from VVER–440 cycles from last years would not fulfil 0.95 k_{eff} limit, because of their initial enrichment. Rule of partial boron credit means utilization of 1/3 of a nominal boron concentration in storage models and was permitted by state supervisor. With that amount of boron in the pool system, currently used fuel with original enrichment 4.38 % meets limit requirements [4].

3. Theory of similarities

As was often said in previous text, fresh fuel and spent fuel systems are not similar, but it was not said, how similarity can be measured. This section will quantify similarity.

For purposes of this paper when talking about the similarity, the similarity of calculations between modelled systems is meant. When a model is prepared and calculations are performed, final k_{eff} is based on a geometry of model, an isotopic composition and nuclear data. When nuclear data changes (each time individual value from library), it affects k_{eff} – value describing size of this change is called "sensitivity" (of k_{eff} to variance of nuclear data). Set of this values describes computational behaving of calculation.

For similarity assessment sensitivities for each isotope, reaction and energy group are needed. Set of these sensitivity profiles is unique for each calculation and if compared with another systems profiles it gives information about how similar these two systems are.

SCALE code system [5] includes module TSUNAMI–IP, which is used for comparison of systems based on sensitivities. There are few similarity values produced by TSUNAMI–IP comparison, but only similarity coefficient c_k will be used in this paper, because it is most complex coefficient of all coefficients available.

c_k coefficient describes a total similarity between two systems. This value is normalized, therefore 1 means a total computational similarity, 0 means no similarity. Generally value of 0.95 is considered to be sufficient for similarity , but based on [6] $c_k > 0.8$ will be sufficient, if more than 25 experiments with this level of similarity will be available for a comparison and following (sub)criticality assessment (which will not be described in this paper). Experiments with $c_k < 0.7$ are considered to be "highly dissimilar" based on [7].

Main objective of using a similarity comparison and filtering of experiments dissimilar to newly projected system is that validation of code for final calculations of new system (here for example spent fuel system) should not be performed based on dissimilar experiments or benchmarks.

4. Reactor criticals states

Start–up tests on commercial reactors have to be performed in the beginning of each cycle after loading of new fuel. Timepoint in the beginning of cycle before powering up means that there is no X_e and other short term decay fission products in core, which would bring in additional uncertainty, because they decay during a shutdown when refuelling. During start–up tests, some of states are so called "hot zero power" (which implies, that power in core is considered to be negligible) and some of these start–up tests are critical ($k_{eff} = 1$, from there comes reactor "criticals") – these states (on Figure 1) can be used as experiments and were used in works described in this paper.

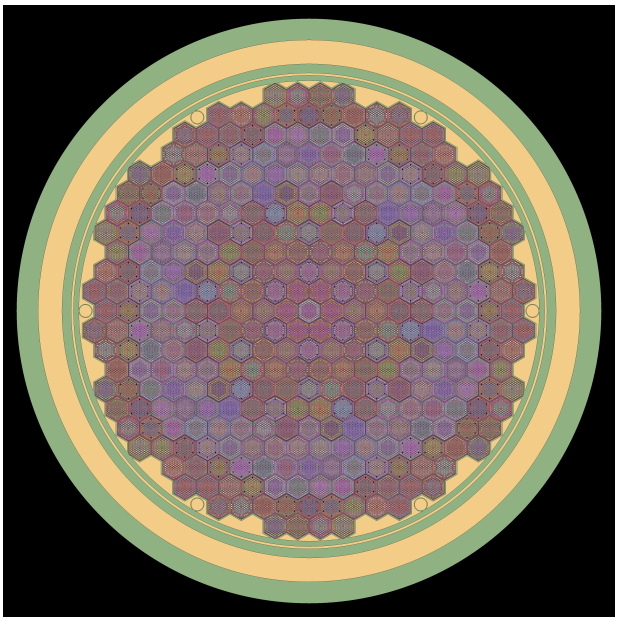

Figure 1. Reactor critical fullcore model

For reactor criticals all parameters of core are known from instrumentation and control systems. Therefore reactor criticals are experiments on reliability level of benchmarks, just with no detailed description in generally available database.

Data for reactor criticals models used for work described in this paper were taken from a database of operation histories of Czech commercial reactors in Dukovany and Temelin, which is stored in Department of Reactor Physics, NRI Rez near Prague. This database contains more than 120 reactor critical states from beginnings of cycles with average core burnups within 16 to 26 GWd/tU.

5. Spent fuel storage systems

Typical spent fuel storage systems are of two types – casks and pools. In this paper, a VVER–440 storage pool filled with Gd2MP with initial enrichment 4.38 % and a VVER–1000 cask CASTOR filled with TVSA–T c44E12 fuel are used for comparison. For calculations of both models are used states when spent fuel in various levels of burnup is loaded and model is filled with water with no boric acid. These states are used conservatively, because these are potentially most reactive states during lifecycle of storage's intended usage.

Visualisations of spent fuel storage models are showed in Figures 2 and 3.

6. Software used in calculations

Comparison calculations were performed in `TSUNAMI-IP` module of SCALE mentioned above, version used was 6.2.3. Sensitivities were calculated in Serpent 2.1.32, because during works it was found that SCALE code (namely `TSUNAMI-3D-K6`) was not

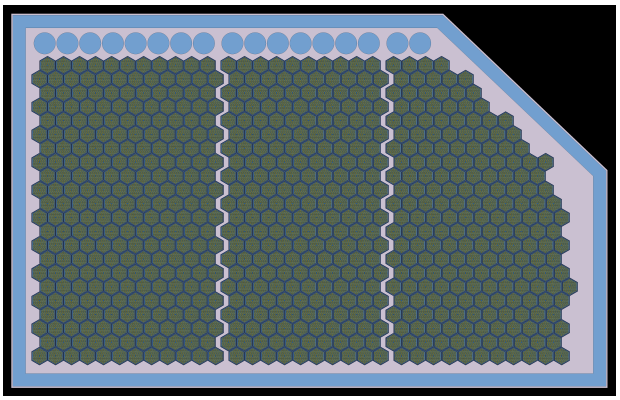

Figure 2. Spent fuel storage pool

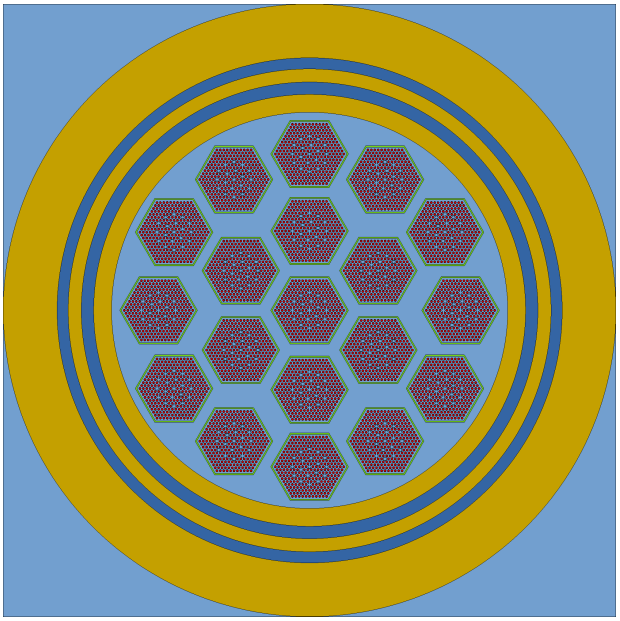

Figure 3. Spent fuel storage cask CASTOR

able to easily calculate such complex system as a fullcore model of a reactor core.

Calculations in Serpent 2 can produce sensitivity data, but they are written in format incompatible to SCALE. Therefore a software for preparation of sensitivities, which can read sensitivity data from Serpent 2 outputs and prepare sensitivity inputs for `TSUNAMI-IP` comparison calculations, had to be created.

7. Results of similarity comparison

For this work 19 reactor criticals states from various cycles of Dukovany and Temelin nuclear power plants start–up tests were taken for sensitivity calculation. Storage systems were prepared artificially, with exactly given burnups on various levels.

Similarity coefficients were calculated in `TSUNAMI-IP` and amounts of reactor criticals which are more similar to individual spent fuel storage systems than various c_k values can be seen in Tables 1 and 2.

Fuel burnup [GWd/tU]	**Pool** k_{eff}	**Required** $c_k >$ 0.8	0.9	0.95
10	0.890	19	18	16
15	0.862	19	19	16
20	0.836	19	19	19
25	0.814	19	19	19
45	0.720	19	6	0

TABLE 1. Amounts of reactor criticals with c_k similarity higher than 0.8, 0.9 and 0.95 to pool storage systems in various levels of burnup.

From Table 1 can be seen, that for the storage pool there are plenty of sufficiently similar available reactor criticals experiments. In future subcriticality assessments of spent fuel storage pool, it will be possible to validate calculation codes based on reactor criticals states.

Fuel burnup [GWd/tU]	**CASTOR** k_{eff}	**Required** $c_k >$ 0.7	0.75	0.8
5	0.801	5	1	0
15	0.796	9	4	0
25	0.744	13	6	0
45	0.649	10	4	2

TABLE 2. Amounts of reactor criticals with c_k similarity higher than 0.7, 0.75 and 0.8 to storage cask CASTOR systems in various levels of burnup

On the other side CASTOR (as can be seen from Table 2) has less sufficiently similar systems. That could be for example due to a pitch between fuel assemblies or support construction itself. Current results for these sets of CASTOR and reactor criticals models are not similar enough for reliable calculations for subcriticality assessment.

Anyhow by comparisons presented in this section is shown that calculating states from the reactor criticals database is possible and that they are more similar to spent fuel systems than usually used fresh fuel systems are.

8. CONCLUSIONS

As was described in the beginning of this paper, current approach to calculations of spent fuel systems is not considered to be optimal. Conservative assumptions have to be made, using these it is not automatic to fulfil legislative limits, and credit of burnup lowering reactivity is not used. Non-using of burnup credit is mainly due to fact, that there is a lack of spent fuel systems for validation. In this paper the lack is resolved by using reactor critical states from start–up tests of commercial nuclear reactors.

Similarities between reactor criticals and spent fuel storage systems were compared using `TSUNAMI-IP` module from SCALE code system. Based on this comparison it was shown that code validated using reactor criticals would be eligible for calculations of storage pools, but not so adequate for CASTOR cask calculations.

Even though similarities were high enough to storage pool only, possibility of validation of code for spent fuel systems calculation was proved when reactor criticals were used.

Generally it was shown and is suggested that codes can and should be validated based not only using fresh fuel benchmarks, but also using reactor criticals states.

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