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Original Article

Integral nuclear data validation using experimental spent nuclear fuel compositions

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ABSTRACT

Measurements of the isotopic contents of spent nuclear fuel provide experimental data that are a prerequisite for validating computer codes and nuclear data for many spent fuel applications. Under the auspices of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) and guidance of the Expert Group on Assay Data of Spent Nuclear Fuel of the NEA Working Party on Nuclear Criticality Safety, a new database of expanded spent fuel isotopic compositions has been compiled. The database, SFCOMPO 2.0, includes measured data for more than 750 fuel samples acquired from 44 different reactors and representing eight different reactor technologies. Measurements for more than 90 isotopes are included. This new database provides data essential for establishing the reliability of code systems for inventory predictions, but it also has broader potential application to nuclear data evaluation. The database, together with adjoint based sensitivity and uncertainty tools for transmutation systems developed to quantify the importance of nuclear data on nuclide concentrations, are described.

1. Introduction

Integral benchmark experiments provide global measures of data performance for applications and are a valuable resource for nuclear data testing and evaluation efforts. Integral testing of the US ENDF/B-VII.1 nuclear data library [1] and several international nuclear data libraries rely heavily on testing using critical benchmarks as compiled in the International Criticality Safety Benchmark Experiment Project (ICSBEP) Handbook [2]. Integral testing of ENDF/B-VII.1 included more than 2,000 critical benchmarks for compounds, metals, solutions, and other mixed systems in thermal, intermediate, and fast neutron energy spectra. The use of criticality experiments as a centerpiece of data-testing efforts in the United States reflects both the investment in nuclear data development by the criticality community and the availability of high-quality and well-documented ICSBEP benchmarks.

Under the auspices of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), physics benchmarks have been compiled and documented in the International Reactor Physics Benchmark Experiment (IRPhEP) Handbook [3] that exercise nuclear data in broader range of applications. As of 2014, the IRPhEP Handbook contained 136 evaluations and measurements of critical buckling, spectral characteristics, reactivity coefficients, kinetics, reaction rates, and power distribution measurements. Both the ICSBEP and IRPhEP benchmarks are applied to realistic applications, including uncertainty analysis and cross section adjustment, uncertainty evaluation for reactor core design methods, criticality safety problem validation, and cross section data testing [4]. However, an intrinsic limitation of both the ICSBEP and the IRPhEP benchmarks is that their focus, for the most part, is on static systems of unirradiated nuclear materials. Thus, many of these benchmarks exercise data for predominantly uranium and plutonium metals and compounds, moderators/reflectors materials, and absorber (criticality control) materials. There are relatively few benchmarks for irradiated nuclear materials.

Interim dry fuel storage research and licensing activities are increasing as spent fuel pools at nuclear plants in many countries are reaching capacity. In addition, geological repositories in Finland and Sweden are expected to be operational in the next decade. Recognizing the need for improved experimental benchmarks to support international activities in spent fuel management, the Expert Group on Assay Data for Spent Nuclear Fuel (EGADSNF), under the guidance of the Working Party on Nuclear Criticality Safety of the OECD/NEA, has developed and expanded a database of

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spent fuel isotope compositions obtained by destructive radiochemical analysis of irradiated fuel samples from commercial nuclear reactors. Under this initiative, the spent fuel database SFCOMPO 2.0, originally developed by the Japan Atomic Energy Research Institution [5], has been expanded from 246 samples to more than 750 samples from 44 reactors representing eight different international reactor technologies.

Because of the design complexities and uncertainties in the actual conditions of an operating reactor, applying these data to obtain realistic estimates of the accuracy of calculated results can be extremely difficult. In addition, there can be large uncertainties in the measurement data attributed to the complex radiochemical measurement processes not present in criticality and reactor physics experiments. Under the OECD/NEA, these data have been more completely documented and peer reviewed for accuracy by international experts. Although measurement accuracies and the quality and extent of documentation often fall short of the high standards set by the ICSBEP and IRPhEP benchmarks, these measurements nevertheless represent valuable validation tests and have been widely used to evaluate the performance characteristics of computer codes, models, and nuclear data used for calculating spent fuel compositions [6,7].

Because of the significant complexity of spent fuel measurements and past inconsistent documentation of reactor design, operating data, and the design and measurement uncertainties, these measurements have not been widely adopted for integral testing of nuclear data. France is an exception, where measurements of irradiated fuel compositions from the French Gravelines and Bugey reactors, and the Swiss Beznau reactor, were used in the development and validation of the European JEF-2.2 libraries [8]. More recently, additional assay measurements, including data made available in SFCOMPO, have been used in the validation of JEFF-3.1 [9,10].

Unlike the ICSBEP and IRPhEP benchmarks involving primarily steady-state systems, spent fuel experiments involve time-dependent isotope depletion and decay as defined by the transmutation equations. Therefore, identifying the relationships between computational bias and nuclear data is particularly challenging. Tools to help understand and quantify the complex relationships between nuclear data and measured compositions are therefore needed in order to better utilize databases such as SFCOMPO 2.0 for nuclear data testing and evaluation.

This paper describes the current status of the new SFCOMPO 2.0 database and benchmark development efforts, and it summarizes and demonstrates new nuclear data sensitivity and uncertainty analysis tools for depletion problems being developed and targeted for future release in the SCALE nuclear systems analysis code system [11].

2. SFCOMPO database

2.1. Database content

SFCOMPO 2.0 is a database of well-documented, peer-reviewed measurements of spent fuel assay data [12] that can be used by the nuclear community for validating computational systems and nuclear data in applications of reactor physics, nuclear fuel cycle, used fuel storage and disposal, as well as advanced fuels and reactor design concept evaluations. The measured assay data have been compiled and reviewed by international radiochemistry experts and modeling practitioners as coordinated through the activities of the OECD/NEA EGADSNF [13].

Since 2007, the database has been expanded beyond pressurized water reactor (PWR) and boiling water reactor (BWR) fuel types that were included in earlier versions. The database now includes eight different reactor designs: light water PWR, BWR, water–water energetic reactor (VVER)-440, and VVER-1000; heavy water CANDU (CANada Deuterium Uranium), graphite-moderated Magnox, advanced gas-cooled reactor, and RBMK (reaktor bolshoy moshchnosty kanalny, high-power channel reactor) reactor designs. Measurements have been acquired from 67 different fuel assemblies and 291 fuel rods. The updated database, SFCOMPO 2.0, contains more than 20,000 measurement entries, with associated uncertainties as reported by the measurement laboratories.

Each reactor design class includes a range of fuel assembly designs. The diversity of designs, coolants, moderators, enrichments, and fuel burnup values provides a wide range of neutron spectral conditions during irradiation that can be used to test the performance of nuclear data over different neutron energy regions. For example, the database includes spent fuel measurements for samples with enrichments from 0.71 wt.% (natural U) to 4.9 wt.%, and burnup values from 0.85 GWd/tU to more than 70 GWd/tU. Coolant and moderator materials include light water, heavy water, gas, and graphite. The reactors, country of origin, and the number of measured fuel samples available for each reactor are summarized in Table 1.

Table 1
Summary of SFCOMPO 2.0 database content.

Design	Reactor	Country	Samples
AGR	Hinkley—3	United Kingdom	21
	Hinkley—4	United Kingdom	36
	Hunterston B—1	United Kingdom	6
BWR	Cooper	United States	17
	Dodewaard	The Netherlands	5
	Forsmark—3	Sweden	2
	Fukushima Daiichi—3	Japan	36
	Fukushima Daini—1	Japan	13
	Fukushima Daini—2	Japan	44
	Garigliano—1	Italy	26
	Gundremmingen—1	Germany	18
	JPDR	Japan	30
	Monticello	Italy	30
	Quad Cities—1	United States	18
	Tsuruga—1	Japan	10
CANDU	Bruce—1	Canada	3
	NPD	Canada	27
	Pickering A—1	Canada	1
Magnox	Bradwell—1	United Kingdom	1
	Hunterston A—1	United Kingdom	3
PWR	Beznau—1	Switzerland	6
	Calvert Cliffs—1	United States	33
	Genkai—1	Japan	2
	Gösgen—1	Switzerland	4
	H. R. Robinson—2	United States	7
	Mihama—3	Japan	9
	Neckarwestheim—2	Germany	1
	Obrigheim—1	Germany	33
	Ohi—1	Japan	1
	Ohi—2	Japan	5
	Takahama—3	Japan	16
	Three Mile Island—1	United States	24
	Trino Vercellese—1	Italy	49
	Turkey Point—3	United States	18
	Vandellos—2	Spain	9
	Yankee	United States	78
RBMK	Leningrad—1	Russia	41
VVER-1000	Balakovo—2	Russia	3
	Balakovo—3	Russia	2
	Kalinin—1	Russia	5
	Novovoronezh—5	Russia	10
VVER-440	Kola—3	Russia	12
	Novovoronezh—3	Russia	7
	Novovoronezh—4	Russia	28

AGR, advanced gas-cooled reactor; BWR, boiling water reactor; CANDU, CANada Deuterium Uranium; PWR, pressurized water reactor; RBMK, reaktor bolshoy moshchnosty kanalny; SFCOMPO,; VVER, water–water energetic reactor.

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