ICNC 2019 - 11th International conference on Nuclear Criticality Safety
September 15-20, 2019 – Paris, France

RECENT DEVELOPMENTS TO THE MONK MONTE CARLO CODE FOR CRITICALITY SAFETY AND REACTOR PHYSICS ANALYSES

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ABSTRACT

Recent developments to the MONK® Monte Carlo neutronics code and its associated nuclear data libraries and the Visual Workshop integrated development environment are described. Improved physical modelling of bound thermal scattering and scattering at epithermal resonances, together with new nuclear data libraries containing low temperature data, improve the accuracy with which the effects of temperature on criticality can be assessed. Enhanced tallying capabilities include the implementation of a continuous energy adjoint flux estimator, thermal power flux normalization and power distribution output, and a new solid sphere tally body. The MONK validation database has been improved with the addition of a significant number of Tier 2 benchmarks and validation at elevated temperatures. Optimization, uncertainty quantification and validation tools in Visual Workshop are also described.

KEY WORDS

MONK, Monte Carlo, Criticality.

1. INTRODUCTION

MONK® is a powerful 3D Monte Carlo code for nuclear criticality safety and reactor physics analyses, forming part of the ANSWERS® [1] codes suite. ANSWERS codes are widely used in over thirty countries around the world, and on a range of reactor types including: AGR, BWR, CANDU, MAGNOX, RBMK, PBMR, PWR, VVER and many experimental reactors. The codes have already been applied to some of the future reactor technologies (e.g. high temperature and fast breeder reactors in the Generation IV programme) that are being developed not only for electricity generation but also for other applications. MONK's advanced geometry modelling and detailed continuous energy collision treatment provides realistic 3D models for an accurate simulation of neutronic behaviour. MONK's superhistory powering algorithm [2] provides robust and reliable estimates of the neutron multiplication factor and other parameters of interest, even for highly decoupled systems.

MONK has both continuous energy and multigroup capabilities, and is supplied with nuclear data libraries in both the BINGO continuous energy format and the WIMS 172 group format, based on evaluations including recent JEFF, ENDF/B and CENDL libraries. The BINGO continuous energy collision processor and data libraries support run-time Doppler broadening [3] for accurate temperature representation, which is important when modelling thermal feedback. An internally coupled depletion solver allows MONK to calculate microscopic burnup using either continuous energy or multigroup data.

MONK features an easy to use, flexible and powerful geometry package comprising two components: Fractal Geometry, which allows detailed geometries to be constructed hierarchically from simple components; and Hole Geometry (using Woodcock tracking [4]) which is used extensively in MONK to provide a wide range of more complicated fine geometric details and to expedite the specification of commonly-occurring replicating items. The two components can be mixed freely to define the required geometry in the most

efficient way. Additionally MONK is able to import the model geometry directly from CAD files and track neutrons directly in the CAD geometry without conversion or approximation.

The unified tally module in MONK provides a flexible means for defining tally bodies and meshes in a way that is decoupled from the underlying model geometry. Any number of independent scoring bodies may be used, they may overlap, and each may have its own defined scoring energy group scheme. Optionally the events scored within each mesh may be further broken down by material. Many of the recent features of MONK are based on unified tally meshes, including the Shannon entropy module, the fission matrix module, the mesh-based burnup capability, and the AT-in-UT (action tallies in unified tally) module, which tallies reaction rates in a mesh, optionally subdivided by material and nuclide. The mesh-based burn-up option uses unified tally meshes to define both a burnup (BU) mesh which automates the process of producing unique materials in each depleteable zone, and a thermal hydraulics (TH) mesh for externally coupling to TH codes. Fission heating powers can be computed in the TH mesh, and modified material temperatures and densities can be returned to MONK from a TH code using the same mesh.

The current QA-release version of MONK is MONK10B, which was released in 2017 after an extensive period of enhancements over the previous versions [5][6]. This is available for both Windows and Linux platforms. MONK supports MPI (message passing interface) parallelization using Open MPI, with a master-slave algorithm. Future releases are also planned to support hybrid MPI / OpenMP (Open Multi-Processing) parallelization or some other form of shared memory parallelism.

MONK has a proven track record of application to the whole of the nuclear fuel cycle and is well established in the UK criticality community as the *de facto* standard Monte Carlo criticality code. It has been in continuous development and use since the 1960s and is developed, distributed, licensed and actively supported by the ANSWERS Software Service [1], part of Wood.

2. PHYSICS

The BINGO collision processor and nuclear data library feature run-time Doppler broadening, enabling materials to be modelled at any temperature above the base temperature of the BINGO libraries, previously 293.6 K. Recent developments have produced a prototype BINGO library with a base temperature of 193.0 K, including bound thermal scattering data for hydrogen in liquid water down to 273.15 K, and hydrogen and oxygen in ice, allowing calculations to be performed at temperatures significantly below room temperature. A stochastic method has recently been implemented for temperature interpolation of bound thermal scattering data. The Doppler broadening rejection correction method [7] has also been implemented to improve treatment of scattering near epithermal resonances.

a. Stochastic interpolation of bound thermal scattering data

In the BINGO collision processor in MONK, any material may be set to any temperature T_{broad} above the base temperature of the BINGO library (this was 293.6 K for previous BINGO libraries but has been extended down to 200 K for the next library releases). If T_{broad} is within 0.5 K of a BINGO library temperature then the Doppler broadened nuclear cross-sections are obtained directly from the library file, otherwise run-time Doppler broadening is employed to determine the Doppler broadened cross-section at temperature T_{broad}.

The $S(\alpha,\beta)$ data needed to calculate secondary parameters for bound thermal scattering are stored in the BINGO library at a small number of fixed temperatures, and there is no straightforward way of interpolating these data analytically. The ENDF-6 Formats Manual [8] states, "Experience has shown that temperature interpolation of $S(\alpha,\beta)$ data is unreliable. It is recommended that cross-sections be computed for the given moderator temperatures only. Data for other temperatures should be obtained by interpolation between the cross-sections." This recommendation is followed in the BINGO collision processor and the inelastic scattering cross-section is interpolated between the temperatures at which the $S(\alpha,\beta)$ data are given. However, this simple interpolation is not applicable to the calculation of secondary energy and angle, and the BINGO collision processor therefore uses the $S(\alpha,\beta)$ data at the closest tabulated temperature. In certain cases, this can result in a significant change in reactivity for a small change in temperature, particularly where the temperature is near the mid-point between one $S(\alpha,\beta)$ temperature and the next. To address this issue, a

stochastic interpolation method [9] has been implemented which randomly selects one of the bounding temperatures at each collision with probability determined by where the actual temperature lies in the range.

A single pincell integration test has been used to demonstrate the effect of the stochastic interpolation method. This test case consists of a single 3.82 wt% enriched UO_2 unclad fuel rod of radius 0.48 cm, in the centre of a water-filled box with x and y dimensions of 1.2 cm. Reflecting boundary conditions are applied on all faces to represent an infinite array of fuel rods with a pitch of 1.2 cm. The hydrogen is modelled as ^{1}H bound in water and the oxygen is modelled as ^{16}O. The fuel temperature in this model is fixed at 500.0 K and the water temperature is varied between 293.6 K (the base temperature of a standard BINGO library) and 1100.0 K (which is greater than the maximum $S(\alpha,\beta)$ tabulated temperature for water in the JEFF3.2 BINGO library used. Calculations are performed at each of the eleven tabulated $S(\alpha,\beta)$ temperatures and additionally at points 0.1 K above and below the mid-points between each library temperature in order to demonstrate the step change in k_∞ at the mid-points. A final point at 1100.0 K is used to demonstrate the behaviour at temperatures above the maximum $S(\alpha,\beta)$ tabulated temperature. A corresponding point below the minimum temperature of 293.6 K is not permitted since it is below the base temperature of the BINGO library.

It is important to note that the water density is kept fixed at 0.99 g/cc for all temperatures in this integration test to allow the effect of the bound thermal scattering model to be decoupled from any effects of changing moderator density. While this is clearly non-physical, it is common for criticality safety analysts to model the moderator at the maximum expected or maximum theoretical density in order to maximize the reactivity, thereby ensuring that the criticality safety criterion is conservatively satisfied.

All MONK calculations were run with a target standard deviation of 0.0002 with the JEFF3.2 BINGO library, using a development version of MONK11A. The calculations were run in parallel using the Open MPI version of MONK running on 16 cores of a Linux HPC.

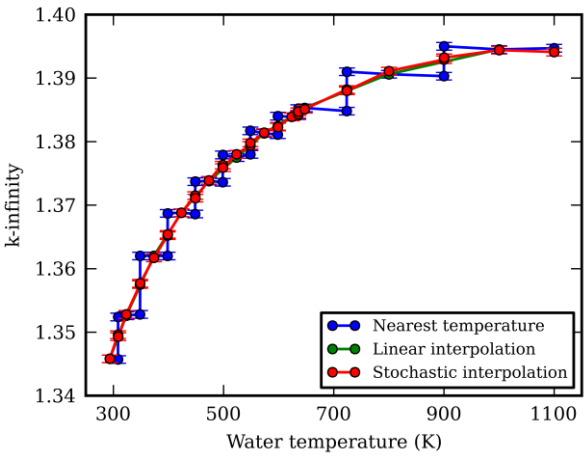

Figure 1. Results of the pincell test, comparing methods (error bars indicate ±3 standard deviations).

The results from the pincell test case are plotted in Figure 1. This shows the results of using the current nearest temperature treatment together with the results obtained using the stochastic interpolation methodology described in here. In addition to these two sets of results, Figure 1 also shows the results obtained by linearly interpolating between results obtained at tabulated $S(\alpha,\beta)$ temperatures only, i.e. points between tabulated temperatures are obtained by linearly interpolating between the results calculated at the two bounding tabulated temperatures. The results obtained using the nearest temperature approach show the expected step changes at the mid-points between tabulated temperatures where the collision processor switches from the data at the lower bounding temperature to the data at the upper bounding temperature. These step changes are non-physical and are an artefact of using the nearest temperature data without interpolation. The results obtained using the stochastic interpolation method completely eliminate the step changes seen in the results based on nearest temperature values and are statistically equivalent to the linear interpolation approach without requiring any post-processing. The nearest temperature and stochastic interpolation methods agree, to within the

stochastic uncertainty, at the tabulated temperatures, and the stochastic interpolation method correctly interpolates at intermediate temperatures, giving confidence that the method behaves as intended.

These results indicate that, for this model, using the nearest temperature approach can underestimate the multiplication by up to 470 pcm for temperatures just below the mid-point, and overestimate the multiplication by up to 380 pcm for temperatures just above the mid-point. The combined standard deviation from the pairs of calculations from which these differences are obtained is about 28 pcm.

b. Doppler broadening rejection correction

At epithermal energies, and at thermal energies for nuclides for which $S(\alpha,\beta)$ are not available, a monatomic free gas model is used to determine the energy and direction of neutrons scattering from nuclei. While the effect of thermal excitation of the nucleus is accounted for by Doppler broadening of the integral cross-sections it is common to use the so-called *asymptotic kernel*, which assumes that the double differential cross-section is constant over the energy range associated with the relative motions of the neutron and target nucleus. However, for heavy nuclides with significant resonances in the scattering and capture cross-sections at low energies it can be important to calculate the secondary energy more accurately and for this reason the Doppler broadening rejection correction [7] has been implemented in the scattering kernel in MONK. This implementation is available in MONK10B, but requires the user to supply elastic scattering cross-section data at zero Kelvin. The next releases of the BINGO libraries will include these 0 K cross-section data and MONK11A will read these data directly from the BINGO library. Using this more accurate representation of the scattering kernel can increase the upscatter into epithermal resonances, which can increase the capture if there is also a significant capture resonance. The net effect can reduce the reactivity of an infinite array of LWR pincells by around 300 pcm at high temperatures.

3. TALLYING

a. Continuous energy adjoint flux estimator

The adjoint flux, or importance function, finds uses in sensitivity and perturbation calculations and in calculating the kinetics parameters: effective generation time and effective delayed neutron fraction. Its calculation in continuous energy Monte Carlo codes has been challenging because of the need to transpose the scattering matrix. Using the iterated fission probability method [10], the adjoint flux can now be calculated in a continuous energy MONK calculation and tallied in any group scheme in a user-defined scoring mesh [11].

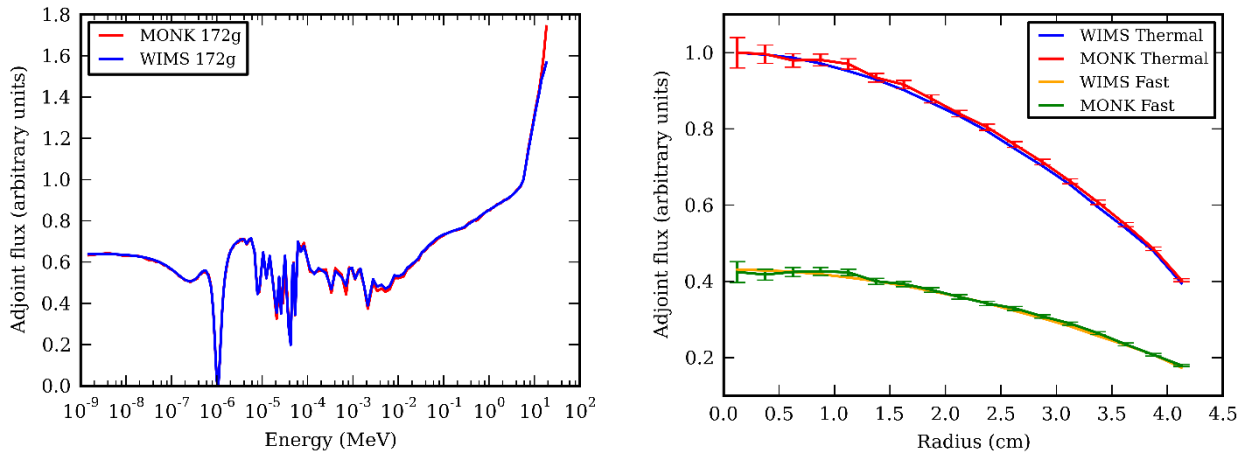

Figure 2. MONK and WIMS results for the adjoint flux in a cylinderized Jezebel benchmark.

Example adjoint flux results for a cylinderized version of the Jezebel bare plutonium (95.2 at% ^{239}Pu) sphere (PU-MET-FAST-001) [12] are shown in Figure 2. These graphs show the energy dependence of the adjoint flux scored in the WIMS 172 energy group scheme and the radial dependence of the adjoint flux in one fast group (WIMS group 20, 1.0026 MeV to 1.1080 MeV) and one thermal group (WIMS group 168, 0.010 eV to

0.015 eV). Very good agreement can be seen between the MONK continuous energy adjoint flux estimator and the WIMS calculation, demonstrating the correct implementation of the continuous energy adjoint in MONK.

b. Thermal power flux normalization and power distribution

The option to normalize the neutron flux to a given total thermal power has been added to the unified tally module. A further development allows the tallying of the power distribution, normalized to the total thermal power, in a unified tally mesh.

c. Unified tally solid sphere body

The unified tally module described in Section 1 features a number of 2D and 3D tally bodies, which may be overlaid over the underlying model geometry, and which may optionally be subdivided in more or more dimensions to define tally meshes. One of the available tally bodies is the sphere, which in previous versions of MONK has been available only as a spherical surface in which the surface-crossing neutron fluxes and currents could be tallied. The latest developments add a solid sphere body in which it is possible to tally the track length and collision density estimators of the neutron flux, and the AT-in-UT event counts.

4. INPUT AND GEOMETRY

a. Atomic mass parameters

The MONK input is free format, keyword driven and easy to read. It has powerful features for defining and using parameters, evaluating algebraic formulae, and looping over parameters with lists of values, allowing sophisticated multivariate parameter surveys to be carried out from a single input file.

Often the atomic masses of isotopes and elements are needed when defining material compositions using MONK's input formulae. To aid model QA and improve user convenience, special atomic mass parameters have been provided to allow the atomic mass data for isotopes and elements, which are present in the material database file, to be accessed from within the MONK input file. This removes the need for users to enter atomic masses manually, with the risk of introducing errors, and ensures that values are consistent with those used internally in the code.

b. Improved Random Hole

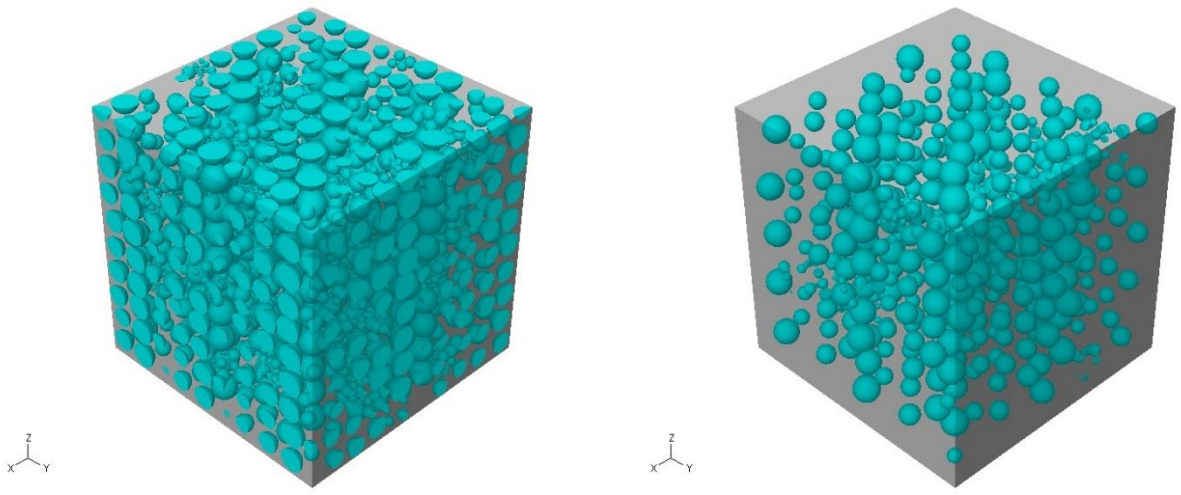

Figure 3. Examples of the Random Hole: original packing structure (left); and new packing structure, with truncated spheres removed (right).

One of the Hole Geometry options in MONK is the Random Hole, which models a pseudo-random arrangement of spheres with a pseudo-random distribution of sizes. It is one of several Hole geometries in MONK which are stochastic in nature, but this one is unique in handling the random nature of the medium in real time during the Monte Carlo tracking rather than pre-processing the geometry at the start of the calculation. Enhancements to this capability for MONK11A address some of the limitations of the current approach by including: an increased packing fraction limit; an alternative arrangement of spheres which demonstrably reduces streaming planes; options for the user to influence the random number generation should the arrangement of spheres appear non-random; and the ability to influence the realism of the model by being able to prevent the truncation of spheres at the boundary of the containing volume. Figure 3 shows an example in which the effect of removing spheres which are truncated by the bounding box is demonstrated.

5. NUCLEAR DATA

MONK11A will be released with BINGO and WIMS format nuclear data libraries based on the latest JEFF and ENDF/B evaluations: JEFF3.3 and ENDF/B-VIII.0. Important features of the new BINGO library include lowering of the base temperature from 293.6 K to 200.0 K, to allow calculations to be carried out at temperatures significantly below room temperature, and the inclusion of bound thermal scattering data for hydrogen and oxygen in ice. These new data libraries will allow MONK to carry out direct calculations to meet the IAEA transport regulations requirement that fissile material shall be transported so as to maintain subcriticality during routine, normal and accident conditions of transport, including the effects of changes in ambient temperature between -40°C and +38°C [13].

Work currently ongoing to prepare these latest nuclear data libraries follows on from the earlier work referred to in Section 2, which developed a prototype BINGO library based on JEFF3.1.2 data with a base temperature of 193.0 K and prototype bound thermal scattering data for hydrogen in ice. This prototype library has been used to perform direct MONK calculations for AGR fuel flasks at low temperatures, the results of which were shown to agree well with result based on extrapolation from calculations at higher temperatures [14].

6. SENSITIVITY AND UNCERTAINTY QUANTIFICATION

MONK features a first-order sensitivity capability, which uses differential operator sampling in combination with limited weight recycling and superhistory powering in order to estimate sensitivity coefficients without the need for calculating the adjoint. The user can request sensitivity coefficients for any combinations of reactions and nuclides, but the option exists to request a "standard" set of combinations for six reaction types: elastic scatter; inelastic scatter; fission; capture; (n,2n) and $\overline{\nu}$ [1], for all nuclides in the model. MONK can also combine the sensitivity coefficients with covariance data to determine the total uncertainty in the k_{eff} estimators to nuclear data. Recent developments to these capabilities have been carried out, primarily to improve run time performance.

The standard set of sensitivity coefficients is calculated for each of the experiments in the MONK validation database, and the similarity between these coefficients in an application case and the same coefficients in the validation benchmarks can be used to assess the suitability of particular validation benchmarks for a given application case. This is discussed further in Section 8.

7. VALIDATION

a. Introduction

The validation database for MONK comprises critical experiments covering uranium, plutonium and mixed systems over a wide range of moderation and reflection conditions. The experiments selected are regarded as being representative of systems that are widely encountered in the nuclear industry, particularly with respect to chemical plant operations, transportation and storage. From each experiment, a selection of the most important configurations has been modelled for inclusion in the database. At the time of the MONK10B release

[1] $\overline{\nu}$ is the average number of neutrons per fission. While this is clearly not a "reaction" *per se*, it is included in the list of reactions because MONK can calculate sensitivity to $\overline{\nu}$, as well as to reaction cross-sections.

in 2017 there were 801 experimental configurations in the database (excluding a small number which are normally omitted due to concerns over the analyses of the experiments). For each of these, MONK10B calculations were carried out using eight different nuclear data libraries (BINGO format: JEF2.2, JEFF3.1.2, JEFF3.2, ENDF/B-VII.1 and CENDL3.1; and DICE format: JEF2.2, ENDF/B-VI.3 and JENDL3.2). For each combination of experimental configuration and data library, results from four independent MONK calculations were combined to achieve a standard error on k_{eff} of 0.0005, using 5000 superhistories per stage, up 10 generations per superhistory and 20 settling stages. All of the results are provided to users in the MONK User Guide [15].

In addition to a summary of the benchmark and results published in the MONK User Guide, each experiment in the MONK validation database has an accompanying validation report describing the detailed specification of the benchmark, an analysis of the results and comparisons with other codes. A rigorous, independent peer review process is followed before a new benchmark is accepted into the MONK validation database, giving users considerable confidence in the quality of the validation evidence available to them. Therefore, while it might be relatively simple to model additional benchmarks in MONK, it requires significant time and resources to add them formally to the validation database.

b. Tier 2 Validation

For this reason, a new *Tier 2* validation database has been created, allowing the amount of available validation evidence for MONK to be expanded more rapidly. The Tier 2 validation cases have not yet been through the full peer review process required of the Tier 1 validation set, but have been self-checked to a level consistent with the example calculations in the ICSBEP Handbook [12] and can provide very useful additional validation evidence. Those Tier 2 validation benchmarks which are most applicable to current user validation requirements will be targeted for elevation to Tier 1 status.

To date 1065 Tier 2 validation cases have been added, all of which were taken from the ICSBEP Handbook [12], more than doubling the number of available validation benchmarks and taking the total to 1866. The calculation/experiment results for the Tier 1 and Tier 2 validation benchmarks are shown in Figure 4.

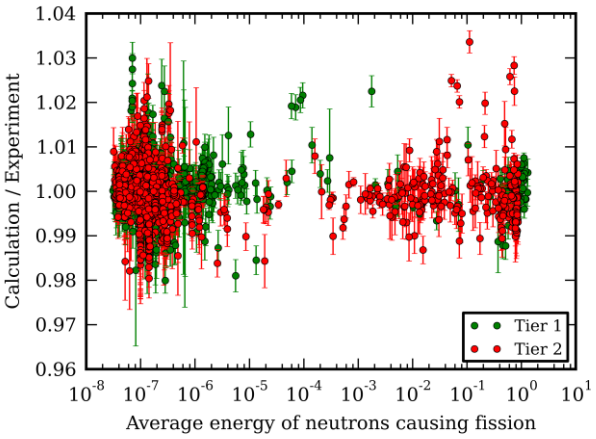

Figure 4. Calculation/Experiment results for Tier 1 and Tier 2 benchmarks plotted against the logarithmic average energy of neutrons causing fission. Error bars show the combined experimental and calculation uncertainties.

c. Validation at temperatures other than room temperature

The vast majority of validation evidence available for MONK and other Monte Carlo neutronics codes is based on room temperature benchmarks. The ability to model materials at any temperature in MONK has improved greatly over recent years, and at the same time interest in modelling the effects of temperature on criticality

has also grown. There is however a paucity of validation evidence available at temperatures other than room temperature. Efforts are therefore underway to improve the availability of validation evidence at a range of temperatures, and to include such evidence in the MONK validation database.

To this end three experiments comprising six configurations with temperatures up to 522 K were recently added to the Tier 1 validation set from the KRITZ-2 series of experiments (KRITZ-LWR-RESR-001 to KRITZ-LWR-RESR-003) [16], increasing the number of Tier 1 validation cases to 807. In addition, MONK results have been contributed to the draft KRITZ-1 benchmark KRITZ-LWR-RESR-004, which is currently in preparation for the IRPHe Handbook [16]. MONK results have also been contributed to the Working Party on Nuclear Criticality Safety Sub Group 3 code comparison benchmark [17] which assesses the effect of temperatures in the range 233 K (including ice) to 588 K on the neutron multiplication in PWR fuel assemblies.

8. VISUAL WORKSHOP

Visual Workshop is the ANSWERS product designed to prepare and verify models, launch jobs and visualize results. It is intended to be an integrated development environment for all of the ANSWERS codes, including MONK. A key feature of Visual Workshop's 2D and 3D ray trace model views is that they are generated using the same source code as is used in the ANSWERS Monte Carlo codes, giving a very high degree of confidence that the model displayed is exactly the model in which neutrons are tracked in MONK.

The current version of Visual Workshop is version 3C, released in 2017. The next version, Visual Workshop 4A, includes: developments to support new features in the latest versions of the physics codes; enhanced uncertainty quantification functionality; integration with high performance computing (HPC) resources (including the ability to submit jobs to an HPC queue); and internal upgrades to improve stability, improve the handling of large and complex models, and to convert to a fully 64-bit application.

Visual Workshop 4A will include a number of features which support the latest developments in MONK11A, including: support for the solid sphere body in unified tally; display of AT-in-UT event counts using the new fractional and density scoring options; display of stagewise flux entropy results; parser support for atomic mass parameters; optimization and uncertainty quantification tools; a tool for viewing MONK validation data; and a similarity index tool.

a. Similarity index tool

The similarity index tool in Visual Workshop compares the vectors of sensitivity coefficients produced by MONK with the standard combinations described in Section 6 for the application case and a selected set of validation cases. The tool produces an ordered list of validation benchmarks, ranked by the similarity of their sensitivity vectors to that of the application case, thus assisting the criticality analyst in selecting suitable validation benchmarks.

b. MONK validation database viewer

Visual Workshop 4A also includes a tool for searching the MONK validation database and viewing the experimental descriptions and the MONK benchmark results. This tool currently allows users to browse all of the experiments in the database, or to filter them by fissile material and form, or by MONK category number. MONK determines the category number during each calculation, based on a number of parameters describing the neutronic behaviour of the system. Validation cases having the same, or closely related, MONK category as the application case may be considered suitable validation benchmarks.

c. Optimization tool

The Visual Workshop optimization tool can be used to determine the values of one or more MONK input parameters which give a user-specified target value for a given result, such as the final estimate of k_{eff}, extracted from the MONK output files. The user specifies: the target result and its value, with the accuracy to which the optimization is required to achieve this value; the MONK input parameter(s) to vary, together with upper and lower limits; the maximum number of MONK executions; and the optimization algorithm

(Bisection, Brent-Dekker, Illinois, Muller, Pegasus, Regula-Falsi, Ridder or Secant). The tool then automatically runs MONK calculations in which the input parameters are varied according the selected algorithm until either the target result is achieved or the maximum number of executions is reached. An HTML optimization report is then automatically generated. This tool efficiently automates a task which criticality safety analysts routinely carry out using brute force methods or prior operational experience.

d. Uncertainty tool

The Visual Workshop uncertainty tool provides methods for quantifying the effects of one or more uncertain parameters in the MONK input file. The parameters are sampled from one of a number of available probability distributions (normal, truncated normal, uniform or beta) with user-supplied parameters. Several different sampling algorithms are available, including Monte Carlo, Latin hypercube, stratified, one and two sided tolerance calculations or linear sensitivity analysis. Alternatively tabulated parameter data may be supplied. The tool then runs the required number of MONK calculations using the sampled parameter values and produces an HTML report including the statistics of the requested result(s), such as the minimum and maximum values of k_{eff}, and the mean and standard deviation. The tool can also produce graphs of the requested results against the values of the sampled parameters. One example use of this tool is in quantifying the uncertainty due to manufacturing tolerances.

9. CONCLUSIONS

The ANSWERS Software Service continually develops the MONK Monte Carlo code for nuclear criticality safety and reactor physics analyses to meet the requirements of its users and to maintain state of the art capabilities. Recent developments to the collision processing and nuclear data libraries have largely concentrated on improving the modelling of temperature dependence, including; the implementation of a stochastic method for interpolating bound thermal scattering data; improvements to the scattering kernel; and the provision of low temperature nuclear data, including bound thermal scattering data for ice. The results tallying capabilities have been enhanced with the addition of a continuous energy adjoint flux estimator, thermal power normalization and power distributions, and a solid sphere tally body. Input enhancements include the provision of atomic mass parameters, and geometry enhancements include an improved method for modelling random distributions of spheres. The MONK validation database has been expanded significantly with the addition of 1065 Tier 2 validation cases, and some elevated temperature Tier 1 benchmarks, with further validation benchmarks at temperatures both above and below room temperature in preparation. The accompanying Visual Workshop integrated development environment has also been enhanced to support the latest features of MONK and to include tools to assist the criticality analyst. These include the similarity index for identifying benchmarks with similar sensitivities to nuclear data, the MONK validation database viewer to provide convenient access to validation benchmark descriptions and results, an optimization tool, and an uncertainty quantification tool. The developments described here are expected to be available in the next releases of MONK (Version 11A) and Visual Workshop (version 4C).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of EDF Energy, the UK Office for Nuclear Regulation, Rolls-Royce and the UK Ministry of Defence.

REFERENCES

[1] http://www.answerssoftwareservice.com

[2] R. J. Brissenden and A. R. Garlick, "Biases in the Estimation of k_{eff} and its Error by Monte Carlo Methods", *Annals of Nuclear Energy*, **13**, pp. 63-83 (1986).

[3] C. Dean, R. Perry, R. Neal and A. Kyrieleis, "Validation of Run-Time Doppler Broadening in MONK with JEFF3.1", *Journal of the Korean Physical Society*, **59**, pp. 1162-1165 (2011).

[4] E. Woodcock, T. Murphy, P. Hemmings and S. Longworth, "Techniques used in the GEM Code for Monte Carlo Neutronics Calculations", *Proceedings of Conference on the Applications of Computing Methods to Reactor Problems*, ANL-7050, pp. 557-579 (1965).

[5] S. D. Richards, C. M. J. Baker, P. Cowan, N. Davies and G. P. Dobson, "MONK and MCBEND: Current Status and Recent Developments", *Annals of Nuclear Energy*, **82**, pp. 63-73 (2015).

[6] S. D. Richards, M. Shepherd, A. Bird, D. Long, C. Murphy and T. Fry, "Recent Developments to MONK for Criticality Safety and Burnup Credit Applications", *Proceedings of International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering, Jeju, South Korea* (2017).

[7] B. Becker, R. Dagan and G. Lohnert, "Proof and Implementation of the Stochastic Fomula for Ideal Gas, Energy Dependent Scattering Kernel", *Annals of Nuclear Energy*, **36**, pp. 470-474 (2009).

[8] M. Herman and A. Trkov, "ENDF-6 Formats Manual – Data Formats and Procedures for the Evaluated Nuclear Data Files ENDF/B-VI and ENDF/B-VII", National Nuclear Data Center, CSEWG Document ENDF-102, Report BNL-90365-2009 Rev. 1, Brookhaven National Laboratory (2009).

[9] S. D. Richards, "Stochastic Interpolation of Bound Thermal Scattering Data in MONK", submitted to *Annals of Nuclear Energy* (2019).

[10] G. Truchet, P. Leconte, Y. Peneliau, A. Santamarina and F. Malvagi, "Continuous-Energy Adjoint Flux and Perturbation Calculation using the Iterated Fission Probability Method in Monte Carlo Code TRIPOLI-4 and Underlying Applications", *Proceedings of the Joint International Conference on Supercomputing in Nuclear Applications and Monte Carlo, Paris, France* (2013).

[11] F. Tantillo and S. D. Richards, "Adjoint Neutron Flux Estimator Implementation and Verification in the Continuous Energy Monte Carlo Code MONK", submitted to *Nuclear Engineering and Design* (2019).

[12] "International Handbook of Evaluated Criticality Safety Benchmark Experiments", NEA-1486/16, NEA Nuclear Science Committee (2018).

[13] "Regulations for the Safe Transport of Radioactive Material – Specific Safety Requirements", SSR-6 (Rev. 1), IAEA (2018).

[14] J. D. Watson, J. S. Martin, M. Henderson and D. Putley, "Assessing the Effects of Low Temperatures on k-effective for AGR Spent Fuel Transport Packages", *Proceedings of the International Conference on Nuclear Criticality Safety, Paris, France,* [This conference] (2019).

[15] "MONK – A Monte Carlo Program for Nuclear Criticality Safety and Reactor Physics Analyses. User Guide for Version 10B", ANSWERS/MONK/REPORT/013, Answers Software Service (2017).

[16] "International Handbook of Evaluated Reactor Physics Benchmark Experiments", NEA-1765/13, NEA Nuclear Science Committee (2018).

[17] S. Gan and A. R. Wilson, "Benchmark Specification: The effect of Temperature on the Neutron Multiplication Factor for PWR Fuel Assemblies", NEA-WPNCS Benchmark (2019).