# Experiment-calculated method for

# determination of prompt neutron

# lifetime in fast metal cores intended

# for verification of neutron transfer

# SIMULATION CODES

S.A. ANDREEV

Fеdеrаl State Unitary Enterprise “Russian Federal Nuclear

Center - Zababakhin All-Russia Research Institute of Technical

Physics”

Snezhinsk, Russia

Email: [s.a.andreev@bk.ru](mailto:s.a.andreev@bk.ru)

D.V. KHMELNITSKIY, S.S. BESOV

Fеdеrаl State Unitary Enterprise “Russian Federal Nuclear

Center - Zababakhin All-Russia Research Institute of Technical

Physics”

Snezhinsk, Russia

**Abstract**

The paper presents an experimentally-calculation method for determination of mean prompt neutron lifetime in multiplying systems being tested at RFNC–VNIIТF on the critical experiments facility FKBN-2. Further to determination of delayed critical state of the multiplying system a derivative was proposed to be calculated from the experimental relationship between prompt neutron decay constant and a gap between the upper and lower parts of the system. The quantity ∂α/∂H characterizes transient processes in the subcritical multiplying system and defines the mean prompt neutron lifetime in the system accurate to the factor . In turn, the factor may be calculated using the current Monte-Carlo neutron simulation software.

The experimental results for along with critical experiments data can be used for verification of computer codes and cross section data files.

The method was validated using the multiplying systems comprised of metallic uranium and plutonium in different mass ratio. The experiments were performed on the critical experiments facility FKBN-2 by the time-dependent correlation method. Benchmark analytical models of tested multiplying systems were created and critical and correlation experiments with different cross section data files were numerically simulated using the Monte-Carlo method within PRIZMA code.

## INTRODUCTION

At present one of the principle methods to test neutron constant accuracy is a comparison of results of neutronic calculations and precision (benchmark) experiments carried out on critical experiments facilities. In this regard the significant results were obtained, i.e., extensive data were collected; the international precision data directory for critical systems IHECSBE has been compiled and regularly updated [1]. But to test the correctness of simulated nonstationary prompt processes in fissile material (FM) systems the critical experiment results are insufficient. It is required to measure a physical quantity which characterizes time behavior of neutron flux density in multiplying systems (MS). The papers [2, 3] propose such a quantity being a derivative of prompt-neutron decay constant in some parameter directly relating to system reactivity. As to experiments carried out on the critical experiments facility FKBN at RFNC-VNIITF a gap between MS parts is considered as such a parameter.

The paper presents the experimentally-calculation method for determination of prompt neutron lifetime in subcritical MS, based on calculations using experimental results, and application of this method to test current cross section data files on fast multiplying systems with metallic uranium and plutonium.

## Experimentally-calculation method for determination of prompt neutron lifetime in multiplying systems

For MS, in the experiment as well as in calculations using modern precision codes two quantities are measured with high accuracy, i.e., delayed critical state and prompt neutron decay constant which defines exponential neutron decay in the subcritical MS with time.

The quantity α is typically measured for systems close to the critical state. In this case the accuracy of calculation depends on computational accuracy of system subcriticality, and therefore the effective multiplication factor .

The parameter characterizing the time behavior of prompt neutrons is their mean lifetime or mean generation time

|  |  |
| --- | --- |
| , | (1) |

where is the effective prompt-neutron multiplication factor, is reactivity. But is not measured directly during the experiment, then it is essential to find such a quantity which is, firstly, determined from experimental results, and secondly, relates to prompt neutron lifetime in MS, and the difference between its calculated and experimental values defines the calculation accuracy of .

To choose a quantity satisfying the above requirements, let us consider the subcritical MS. Using the available reactivity controller we shall slightly «disturb» its initial state. In a first approximation a change in spatial-energy distribution of neutron flux density can be neglected and the mean generation time can be considered constant

|  |  |
| --- | --- |
| , | (2) |

Within this approach the precision nonstationary experiments were set up on the critical experiments facility FKBN-2 [2−4]. The remote measurement of H gap between the upper and lower MS parts enables its subcriticallity level to be varied. Thus, by subsequent decrease of the gap and control of the neutron multiplication factor Q, and using extrapolation to zero of the relation Q-1(Н), the prompt critical state of MS and the associated critical gap are determined. Then the value of α is measured for several system states with different Н, and the relation is determined in its zone of linearity. The relation angle according to the expression (1)

|  |  |
| --- | --- |
| , | (3) |

accurate to the factor defines the mean prompt neutron lifetime in the tested MS. There is no way to determine the factor from measurement results. But it can be calculated for the tested MS using the Monte-Carlo precision codes, with its calculation accuracy being dependent on calculation error (less than or equal to 0.5 %). The described approach makes feasible the experimentally-calculation method for determination of mean prompt neutron lifetime in MS

|  |  |
| --- | --- |
| , | (4) |

and allows the use of value to compare the calculation and experiment results, as the relation between its experimental and calculation values

|  |  |
| --- | --- |
| , | (5) |

characterizes the calculation accuracy of mean prompt neutron lifetime in multiplying systems.

Let’s estimate the difference of from the ‘true’ value of mean prompt neutron lifetime in MS

|  |  |
| --- | --- |
| , | (6) |

By the example of the specific MS comprised of ten plutonium disks, up and down which there are two disks made of highly enriched uranium [2], using calculations by PRIZMA code [5] the addend in the parentheses was estimated. According to calculation results

, and thus for weakly subcritical systems the addend in the parenthesis of the expression (6) is small and less than and the equality is true to high precision (the difference is ~1%).

The results of experiments run on the critical experiments facility FKBN-2 in the above set-up provide a possibility to determine another three MS characteristics:

– Rossi alpha constant , that is prompt neutron decay constant in delay criticality state;

– Linear gap weight (in the units of ) ;

– , -as a quantity, in which calculations the delayed neutron characteristics from cross section data files are not used.

## Experimental results

Using the proposed method the set of experiments was performed on the critical experiments facility FKBN-2 with compact MS made of metallic uranium and plutonium (Fig. 1). The tested systems were assembled from highly-enriched uranium discs of radius 10 cm, α–plutonium discs of radius 6 cm in thin-wall stainless steel cases, placed in aluminum centering rings of radius 10 cm, and δ–plutonium hemispheres. The system feature is a gradual, from assembly to assembly, change of the uranium-plutonium mass ratio by sequential replacement of uranium discs by plutonium parts: from uranium only assembly MS342 to plutonium only assembly MS305. Five MS (MS325, MS326, MS327, MS340, MS341) are analogous to the plutonium assembly MS305 as they have analogous lower parts and comprised of four interleaved hemispheres made of δ–plutonium; the upper parts are different and obtained by the replacement of some plutonium disks by uranium ones. If to introduce the design parameter ξPu, i.e. a plutonium fraction of total fissions in the system, as a characteristic of each assembly, then for the tested systems its value varies from 0 for MS342 to 1 for MS305. The composition of seven tested MS is given in Table 1. For each MS in critical experiments the gap corresponding to prompt critical state of the system was determined, and the benchmark model was constructed with estimated error of (2σ): for tested MS =1.000 ± 0.001.

In correlation experiments nonstationary neutron processes in tested multiplying systems were recorded using the hardware-software complex NMIS. In measurements streams of random events were recorded, i.e. time points corresponding to neutron and gamma-quanta interactions in the detectors. Based on the results of processed streams of random events different correlation functions with exponential decay defined by the prompt neutron decay constant, were calculated. From the determined values of α for several gaps in the vicinity of delayed critical system the factors were calculated from the linear relation by the least-square method (see Table 1).

|  |  |
| --- | --- |
|  | 1 ⎯ uranium discs; 2 ⎯ plutonium discs;   3 ⎯ aluminum centering rings;   4 ⎯ fixed diaphragm; 5 ⎯ plutonium hemispheres; 6 ⎯ aluminum cup on moving stock. |

Fig. 1 Experimental design on critical experiments facility FKBN-2

TABLE 1. MS CHARACTERISTICS: CONFIGURATION, VALUES FOR AND ∂Α/∂H. ERROR IS 2σ.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Characteristics | Assembly Identifier | | | | | |
| MS305 | MS325 | MS340 | MS326 | MS341 | MS342 |
| ξPu | 1 | 0.91 | 0.59 | 0.49 | 0.30 | 0 |
| U-discs | 0 | 1 | 4 | 5 | 7 | 11 |
| Pu-discs | 10 | 10 | 6 | 5 | 3 | 0 |
| Pu- hemispheres | 6 | 4 | 4 | 4 | 4 | 0 |
| ±2σ**,** μs-1⋅mm-1 | 1.48  ±0.04 | 1.504  ±0.013 | 1.70  ±0.02 | 1.619  ±0.021 | 1.06  ±0.03 | 0.977  ±0.006 |

## Calculation results

The numerical simulation of critical and time-dependent correlation experiments was performed under PRIZMA code with cross sections taken from different data files: ENDF\B-VII.1, JENDL‑4.0, JEFF‑3.2. The simulation results of critical and correlation experiments, including computational-experimental values of mean prompt neutron lifetime are given in Tables 2, 3, and Fig. 2, 3. Uranium-plutonium assemblies in Table  2 and on graph 2 are ordered from left to right according to an increase in uranium fission fraction.

TABLE 2. CALCULATED VALUES OF FOR DIFFERENT CROSS SECTION DATA FILES. CALCULATION ERROR IS 2σ < 10-4.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Data file | Assembly Identifier | | | | | |
| MS-305 | MS-325 | MS-340 | MS-326 | MS-341 | MS-342 |
| ENDF\B-VII.1 | 0.9972 | 0.9961 | 0.9960 | 0.9977 | 0.9989 | 0.9995 |
| JENDL-4.0 | 0.9950 | 0.9937 | 0.9938 | 0.9955 | 0.9966 | 0.9964 |
| JEFF-3.2 | 0.9970 | 0.9963 | 0.9963 | 0.9977 | 0.9978 | 0.9961 |



MS-305 MS-325 MS-340 MS-326 MS-341 MS-342

ENDF\B-VII.1

JENDL-4.0

JEFF-3.2

Benchmark

**Assembly identifier**

**K\_eff**

*Fig. 2 Calculated values for . The error 2σ is for the benchmark model.*

According to the data in Table 2, the difference in the values between calculation and experiment does not exceed 0.6%. The experimental values of are observed to match within the given error only with ENDF\B-VII.1 calculation for purely uranium MS-342. As for the other multiplying systems, the higher the plutonium fission fraction, the larger the difference between calculated and experimental values of . Note, that underestimation of by 0.3% observed for purely plutonium MS-305 in ENDF\B-VII.1 and JEFF-3.2 calculations is inconsistent with the result obtained in calculation with MCNP for Jezebel assembly [6], while underestimation of by 0.3% for the uranium assembly MS-342 in calculations with JENDL‑4.0 and JEFF‑3.2 codes agrees with the calculation result for HMF-1 [7].

TABLE 3. CALCULATION RESULTS FOR CRITICAL SYSTEMS. THE INDICATED ERROR IS 2σ.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Data file | Characteristics | Assembly Identifier | | | | | |
| MS-305 | MS-325 | MS-340 | MS-326 | MS-341 | MS-342 |
| ENDF-BVII | ∂α/∂H,  μs-1mm-1,  2σ | 1.501  0.012 | 1.496  0.024 | 1.679  0.014 | 1.581  0.012 | 1.071  0.008 | 0.974  0.004 |
| χ**,**  2σ | 0.986  0.028 | 1.005  0.018 | 1.013  0.014 | 1.024  0.015 | 0.990  0.029 | 1.003  0.007 |
| ∂ρp/∂H·103, mm-1,  2σ | 4.55  0.11 | 4.93  0.05 | 6.34  0.09 | 6.50  0.09 | 5.20  0.08 | 5.89  0.07 |
| , ns  2σ | 3.08  0.16 | 3.28  0.06 | 3.73  0.10 | 4.01  0.11 | 4.91  0.21 | 6.03  0.11 |
| JENDL-4 | ∂α/∂H,  μs-1mm-1,  2σ | 1.508  0.009 | 1.513  0.020 | 1.675  0.011 | 1.571  0.010 | 1.064  0.008 | 0.964  0.004 |
| χ**,**  2σ | 0.982  0.027 | 0.994  0.016 | 1.015  0.014 | 1.031  0.015 | 0.996  0.029 | 1.013  0.008 |
| ∂ρp/∂H·103, mm-1,  2σ | 4.60  0.07 | 4.95  0.06 | 6.54  0.11 | 6.43  0.10 | 5.15  0.06 | 5.85  0.06 |
| , ns  2σ | 3.11  0.13 | 3.29  0.07 | 3.85  0.11 | 3.97  0.11 | 4.86  0.19 | 5.99  0.10 |
| JEFF-3.2 | ∂α/∂H,  μs-1mm-1,  2σ | 1.559  0.011 | 1.576  0.021 | 1.727  0.016 | 1.607  0.010 | 1.071  0.009 | 0.947  0.005 |
| χ**,**  2σ | 0.949  0.026 | 0.954  0.015 | 0.985  0.015 | 1.007  0.015 | 0.990  0.029 | 1.032  0.008 |
| ∂ρp/∂H·103, mm-1,  2σ | 4.56  0.08 | 4.96  0.06 | 6.56  0.11 | 6.57  0.10 | 5.21  0.07 | 5.91  0.08 |
| , ns  2σ | 3.08  0.14 | 3.30  0.07 | 3.86  0.10 | 4.06  0.12 | 4.92  0.21 | 6.05  0.12 |



MS-305 MS-325 MS-340 MS-326 MS-341 MS-342

ENDF\B-VII.1

JENDL-4.0

JEFF-3.2

Assembly identifier

*Fig 3 Values χ for different .MS the indicated error is 2σ.*

The experimentally measured derivative , practically for all tested MS within the measurement accuracy is described in calculations using ENDF\B-VII.1 and JENDL-4.0 codes. This is evidence of the correct reproduction in calculations with these data files of mean prompt neutron lifetime in fast uranium-plutonium systems. Some overestimation of calculated angle values when using JEFF-3.2 for MS with plutonium parts predominating (MS-305, 325, 340) can be explained by underestimated, as compared to ENDF\B-VII.1 and JENDL-4.0, Pu-239 inelastic scattering cross-section, resulting in neutron spectrum hardening and expected lifetime reduction.

CONCLUSION

To test neutron cross section data files, as applied to simulation of nonstationary neutron processes in multiplying systems, the experimentally calculation method for determination of mean prompt neutron lifetime was proposed. Within the proposed method:

– Based on measurement results for the states in the vicinity of delayed criticality the derivative is determined;

– Using the factor calculated by precision codes the prompt neutron lifetime is calculated.

The application of the method for cross section testing was demonstrated by the example of seven uranium-plutonium assemblies. For each system critical and time-dependent correlation measurements were performed and the benchmark model was constructed. In calculations by Monte-Carlo method under PRIZMA code it was shown that using ENDF\B-VII.1 and JENDL-4.0 data files it is possible to describe reliably (within the measurement accuracy) the neutron lifetime for fast uranium-plutonium systems. In calculations of MS with plutonium parts predominating, the use of JEFF-3.2 lead to underestimation of lifetime up to 5%.

The findings suggest the need for investigations to create data files on nonstationary experiments with multiplication systems for verification of neutronic calculation data.

References

1. International Handbook of Evaluated Criticality Safety Benchmark Experiments. NEA/NSC/DOC (95)03, (2016).
2. BESOV S.S., ERSHOVA L.S., KOSTENKO I.I., LUKIN A.V., SAMOILOVA L.Yu., SOKOLOV Yu.A., KHMELNITSKIY D.V. Neutron Cross-section Verification Based on Nonstationary Experiments with Multiplying Systems. — Atomnaya Energia, Vol. 110, Issue 4, (2011) 231—236.
3. BESOV S.S., ERSHOVA L.S., KOSTENKO I.I., LUKIN A.V., SOKOLOV Yu.A., KHATUNTSEV K.E., KHMELNITSKIY D.V. Estimated Accuracy of Prompt Neutron Lifetime in Metallic Plutonium System. — Atomnaya Energia, Vol. 114, Issue 3, (2013) 165—168.
4. BESOV S.S., ERSHOVA L.S., LUKIN A.V., SOKOLOV Yu.A., KHMELNITSKIY D.V. Determination of Prompt Neutron Lifetime in Fast Metal Cores by Constant Differentiation Method. — VANT. Ser. Physics of Nuclear Reactors, Issue 3, (2014) 94−105.
5. ARNAUTOVA M.A., KANDIEV Ya.Z., LUKHMINSKIY B.E.,MALYSHKIN G.N. Monte-Carlo Simulation in Nuclear Geophysics. In Comparison of the PRIZMA Monte-Carlo Program and Benchmark Experiments// Nucl. Geophysics, v. 7, № 3, (1993) 407-418.
6. DOUGLAS O'DELL R., BARE SPHERE OF PLUTONIUM-239 METAL (4.5 at.%. 240Pu, 1.02 wt.% Ga). Identification Number PU-MET-FAST-001. International Handbook of Evaluated Criticality Safety Benchmark Experiments.Plutonium Systems. NEA Nuclear Science Committee. Volume I, (2012).
7. VAN DER MARCK S.C., Benchmarking ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1.1 with MCNP6 // Nuclear Data Sheets, 113 (2012), 2935-3005.