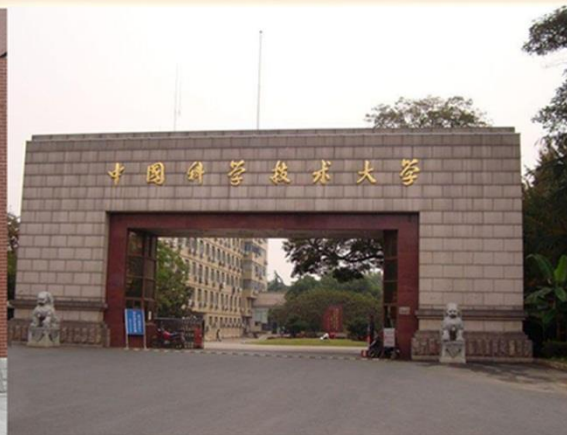




Institute of Nuclear Energy Safety Technology, CAS · FDS Team



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Validation of SuperMC with Fusion Shielding Benchmarks from SINBAD

Jun ZOU

Contributed by FDS Team

Institute of Nuclear Energy Safety Technology (INEST)

Chinese Academy of Sciences

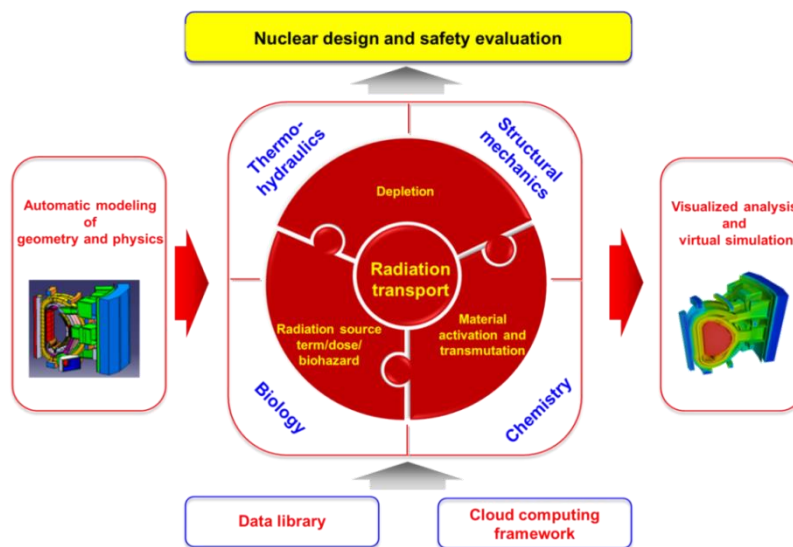
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SuperMC

Super Multi-functional Calculation Program for Nuclear Design and Safety Evaluation



Basic Function: Full-functional Neutronics Calculations

1. Radiation transport calculation

- **Multi-particles:** neutron (1e-11~150MeV), photon (1keV~1GeV), electron, proton and other charged particles.
- **Flexible source description:** general source, critical source, surface source, user-defined source
- **Physical parameters:** k_{eff} , surface/cell/mesh/detector flux, energy deposition, reaction rate, etc.
- **Adaptive variance reduction based on global weight window generator (GWWG)**
- **Various efficient parallel computation** MPI, OpenMP, Data decomposition parallel, etc.
- **Temperature-dependent cross section treatment:** thermal & resonance, On-line/OTF

2. Isotopes depletion calculation

- **Solving method:** Chebyshev Rational Approximation Method (CRAM), etc.
- **Inner-coupling:** beginning-of-step constant flux approximation (BOS), predictor-corrector (PC), improved semi-predictor-corrector (ISPC) method, etc.

3. Material activation and transmutation calculation

- **Computational modes:** point activation calculation, transport-activation coupling calculation. etc.
- **Activation properties** activity, decay heat, biological hazard, dose rate, clearance index, etc.

4. Shutdown dose rate calculation

- **Solving method:** Rigorous-Two-Step (R2S) method, Direct-one-step (D1S) method, Advanced D1S method

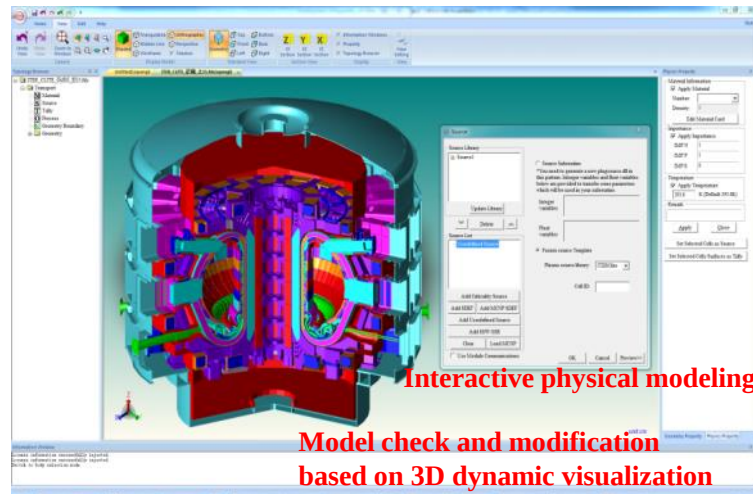
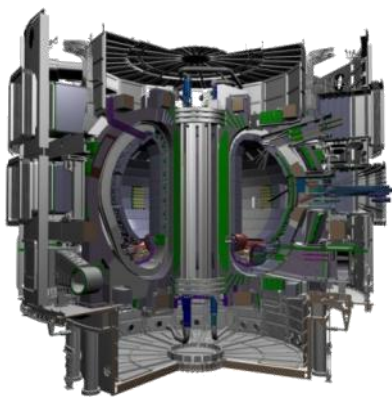
Feature 1: CAD-based Whole Process Accurate Modeling

■ Automatic modeling with CAD models

- Conversion between CAD/Image and MC simulation model, accurate description for **complex irregular geometry**
- Parameterized-based **high-fidelity (pin-by-pin level) whole reactor modeling**

■ Integrated interactive modeling

- Whole model interactive modeling (geometry material, source, tally, etc.), neutronics and thermo-hydraulics coupled modeling



SuperMC

(direct calculation)

Other Codes

(input file generation)

- MCNP
- TRIPOLI
- PHITS
- Geant4
- FLUKA



Feature 2: Feature-accelerated High-efficiency Calculation

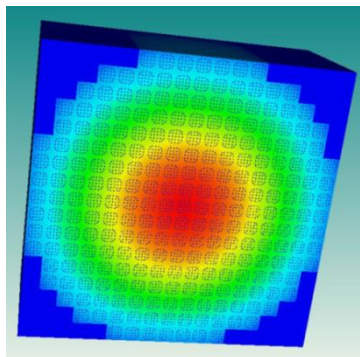
■ Radiation transport calculation acceleration methods

- 1. Location pre-judgment acceleration**
 - neighbor search , bounding box, optimal spatial subdivision method
- 2. Physics Pre-judgment acceleration**
 - Adaptive variance reduction based on weight window smoothing, Global weight window generator (GWWG), Uniform fission site method(UFS), GWWG coupled UFS
- 3. Hybrid MC and deterministic methods:**
 - Adaptive transaction region based region coupling, energy coupling, time coupling
- 4. Cell message based Multi-branches tree algorithm for massive tallies**
- 5. Other acceleration**
 - source convergence, union energy grid, etc.

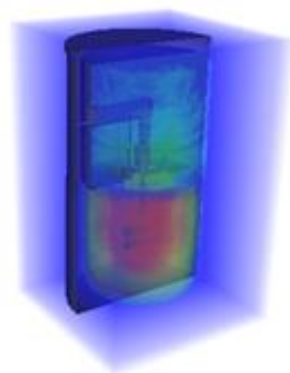
■ Burnup/activation/dose calculation acceleration methods

- 1. Nuclear data searching methods:**
 - union energy grid, bucket-sorting energy searching (reducing memory consume)
- 2. Dynamic construction method of transmutation chain based on depth-first Search**
- 3. Adaptive order reduction method for large scale matrix**

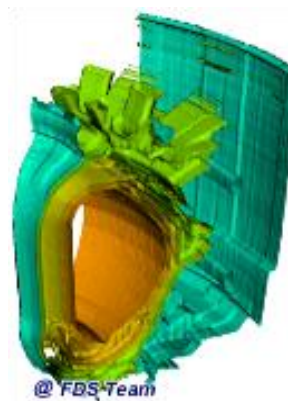
Feature 3: Intelligent Visualized Analysis



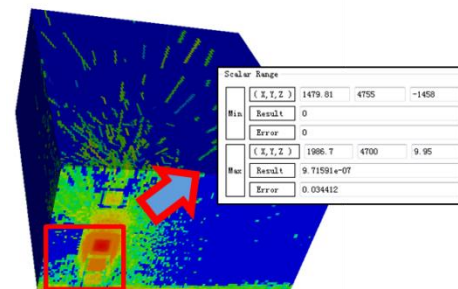
Surface rendering



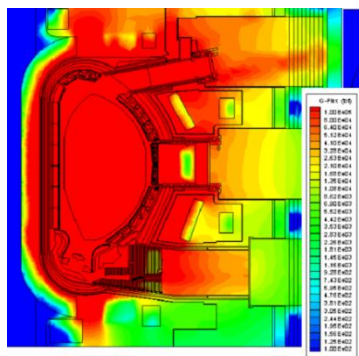
Volume rendering



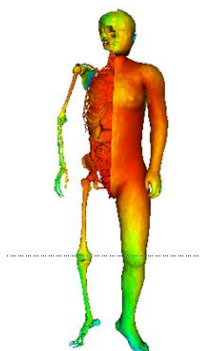
Iso-surface



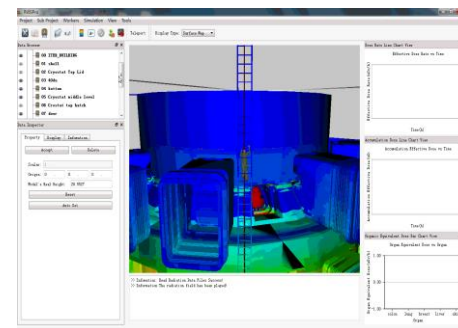
Data extract



Visualization mixed with geometries



Rad-Human

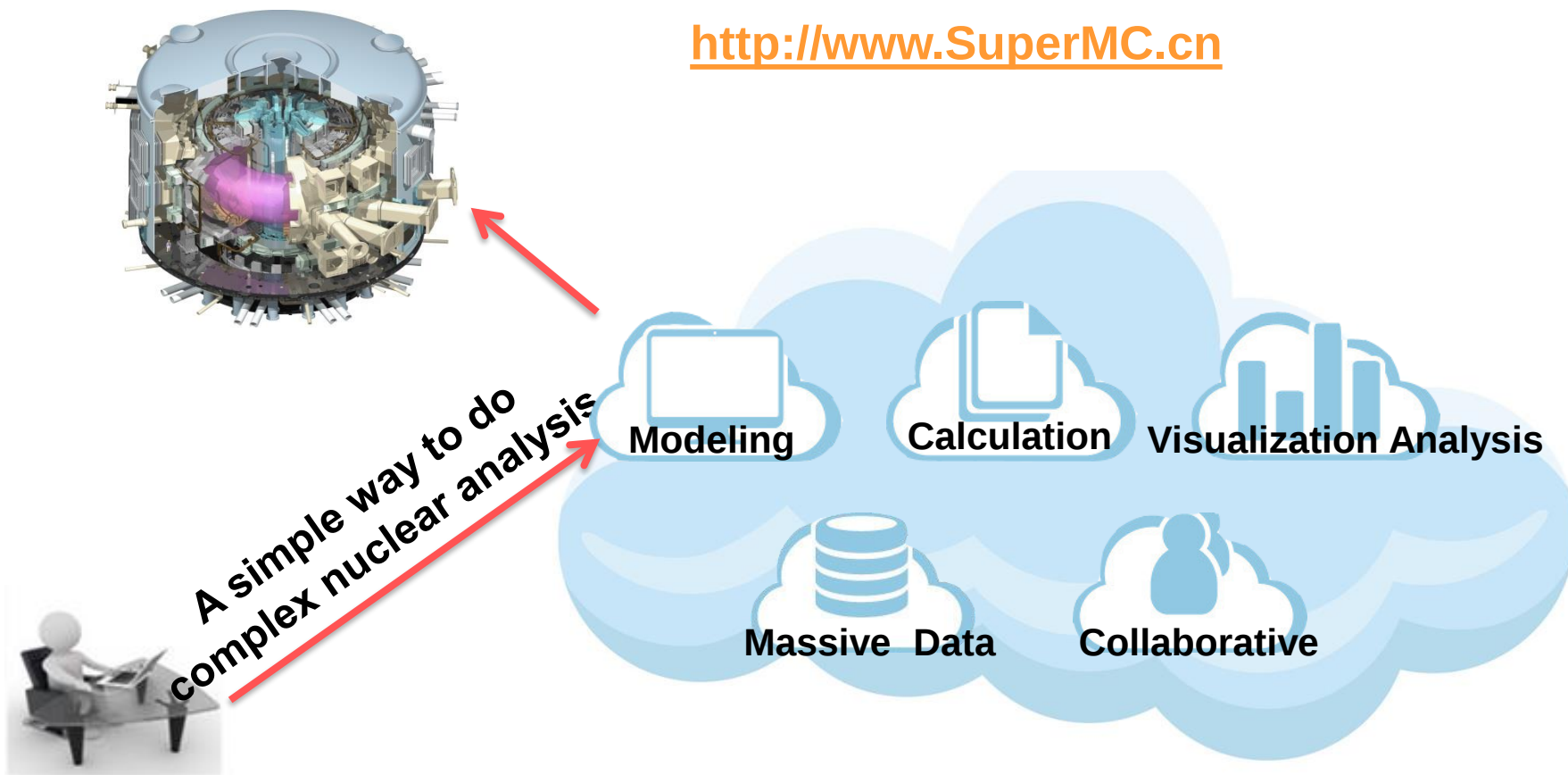


Virtual-reality based simulation

Visualization for multiple codes: SuperMC、MCNP、TORT、FISPACT ...

Feature 4: Collaborative Nuclear and Multi-physics Design Based on Cloud Computing

<http://www.SuperMC.cn>



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23 Fusion Neutronics Shielding Experiments

Fusion Experiment Platform	Experiment Cases	Measured Quantity
Osaka	aluminum, silicon, nickel and tungsten sphere	Neutron/photon leakage spectrum
FNS	graphite, oxygen, vanadium, tungsten, skyshine	Neutron/photon leakage spectrum, reaction rate
FNG	tungsten, iron, silicon carbide, FNG_ss, FNG_dose, FNG_str, etc	Neutron/photon leakage spectrum, reaction rate
IPPE	thorium	Neutron/photon leakage spectrum
Kant	beryllium	Neutron/photon leakage spectrum

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OKTAVIAN benchmark experiment

◆ AL

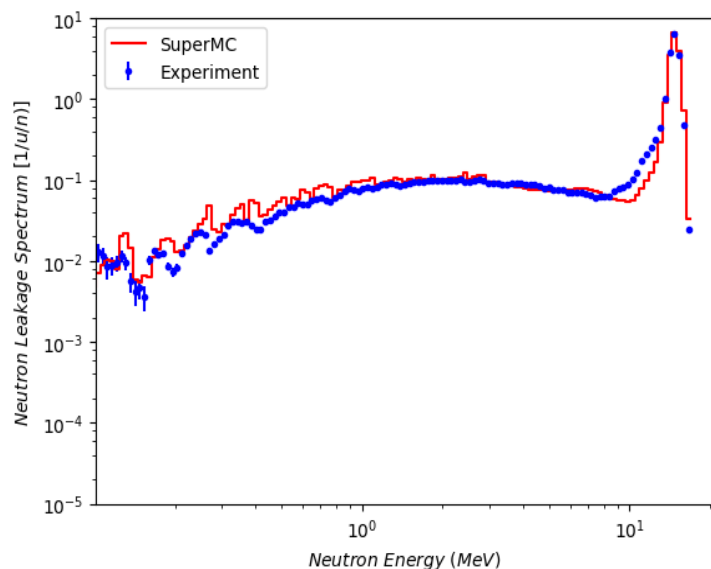
◆ Fe

◆ W

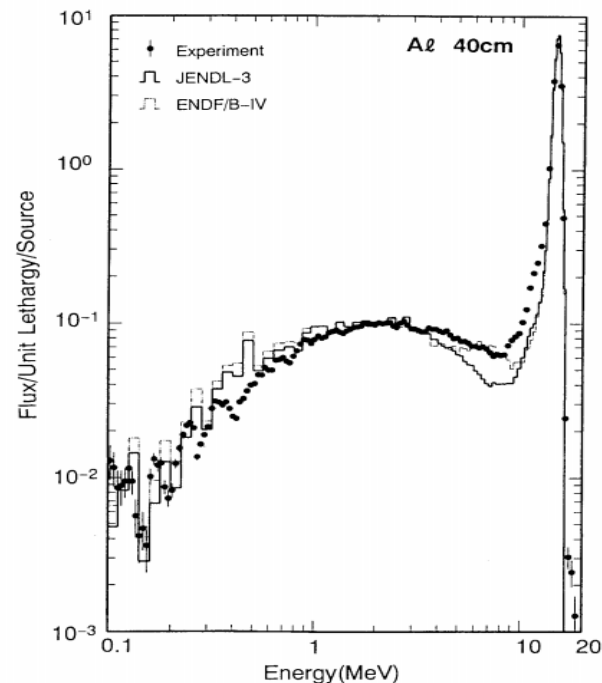
◆ Si

◆ Ni

Neutron leakage flux of Aluminum sphere



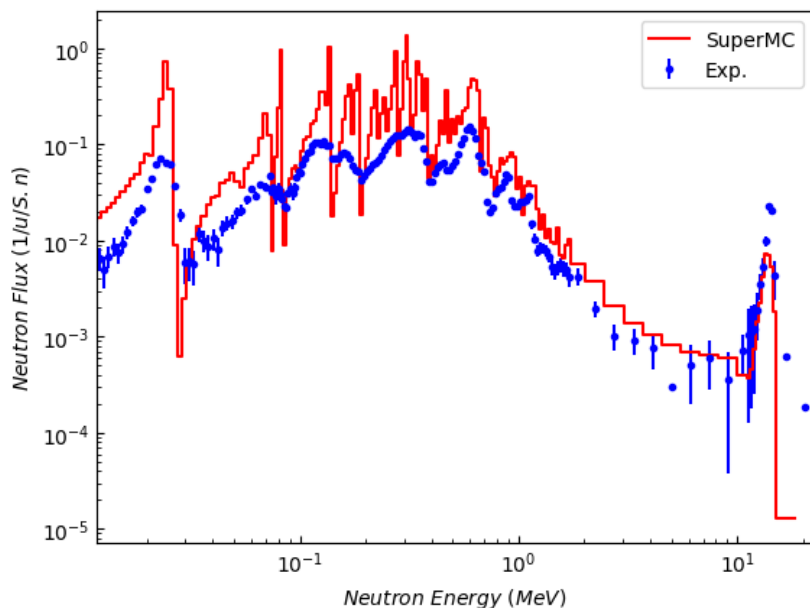
Neutron leakage flux of Aluminum sphere



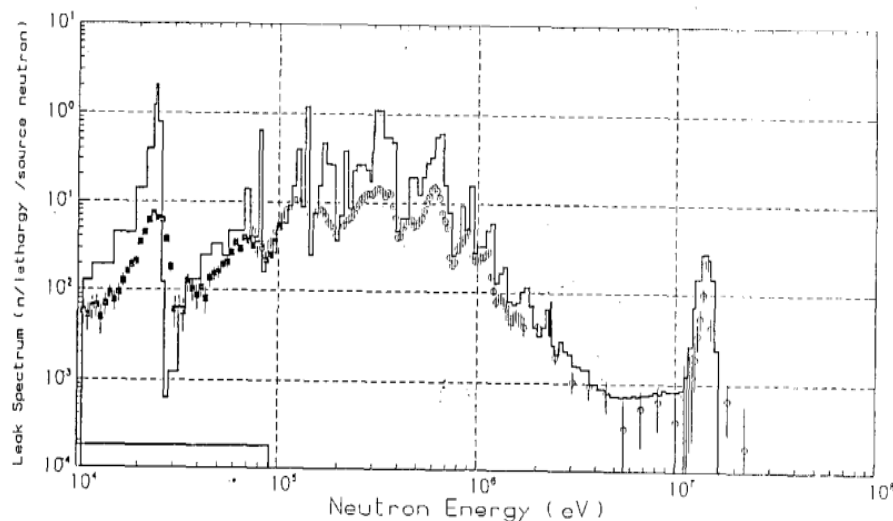
Neutron leakage flux of Aluminum sphere in JAEA report

- For the neutron leakage flux calculated by SuperMC comparing with experimental results, the average deviation was about 8%, and the maximum deviation was in the energy range about 10 MeV.
- In the report “JAERI-M 94-014” from JAEA, the maximum deviation was in the energy range about 10 MeV. The similar deviations between calculation and experimental results were shown in Figure 5 from the JAEA report.

Neutron leakage flux of Iron sphere



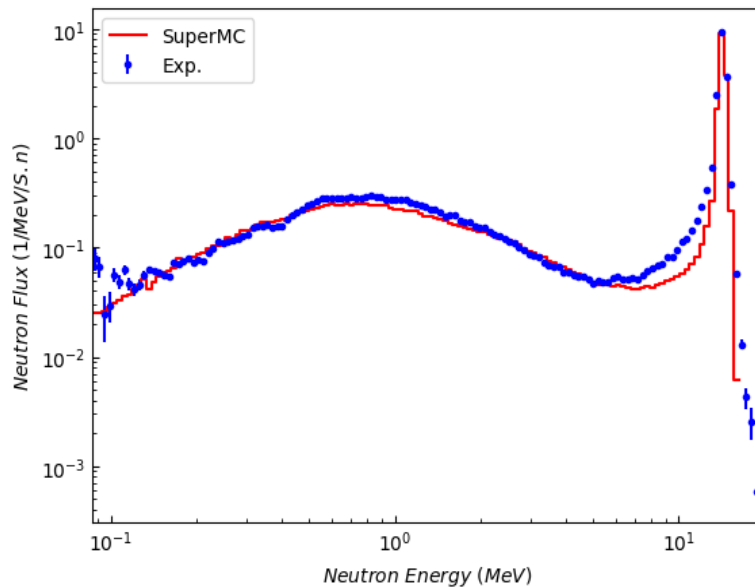
Iron sphere neutron leakage spectrum



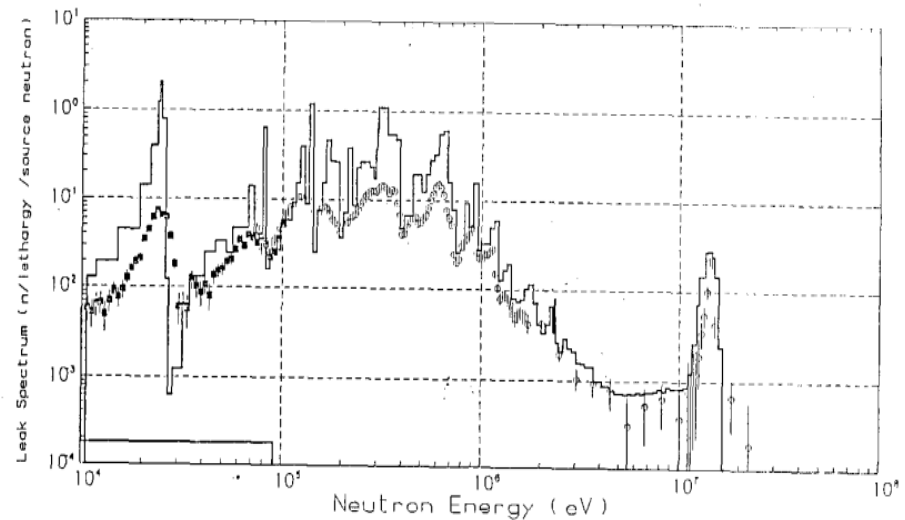
Iron sphere neutron leakage spectrum in JAEA report

- The average deviation between SuperMC calculation results and experimental results was about 15%. The maximum deviations between SuperMC results and experimental results were in the neutron energy range from 2 MeV to 10 MeV.
- Note: In the report “Neutron leakage spectra from a large iron sphere pulsed with 14 MeV neutrons”, the calculation results were lower than the measurement for this benchmark in the energy range between 2 to 10 MeV. The similar deviations between calculation and experimental results were shown in the right figure.

Neutron leakage flux of Tungsten sphere



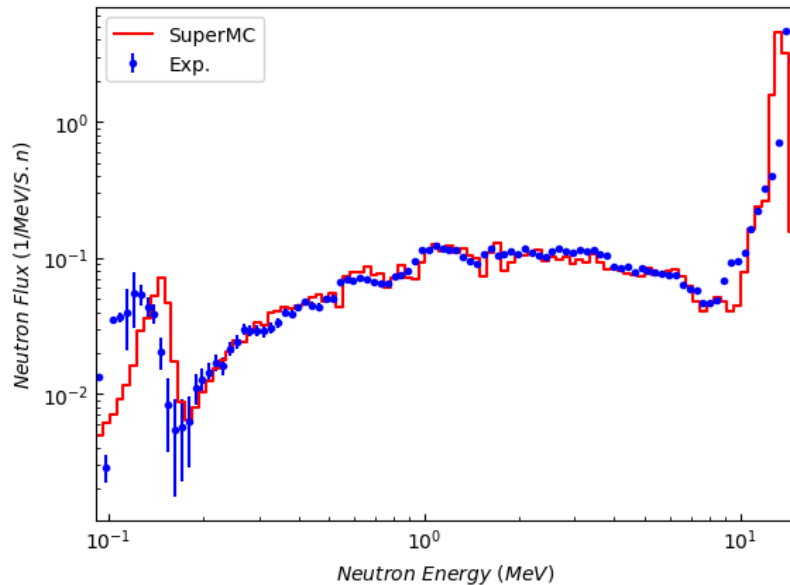
Tungsten sphere neutron leakage spectrum



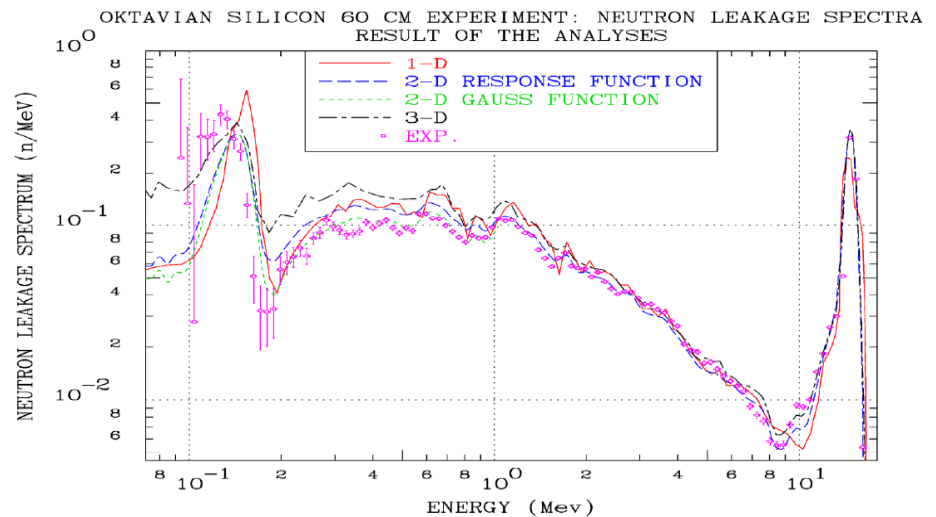
Tungsten sphere neutron leakage spectrum in JAERI report

- The calculation results showed consistent tendency with the experimental results, the average deviation between calculation results and experimental results was about 15%.
- Note: In the report “Collection of Experimental Data for Fusion Neutronics Benchmark, JAERI-M-94-014” from JAEA, the similar deviations between calculation and experimental results were shown in the right figure.

Neutron leakage flux of Silicon sphere



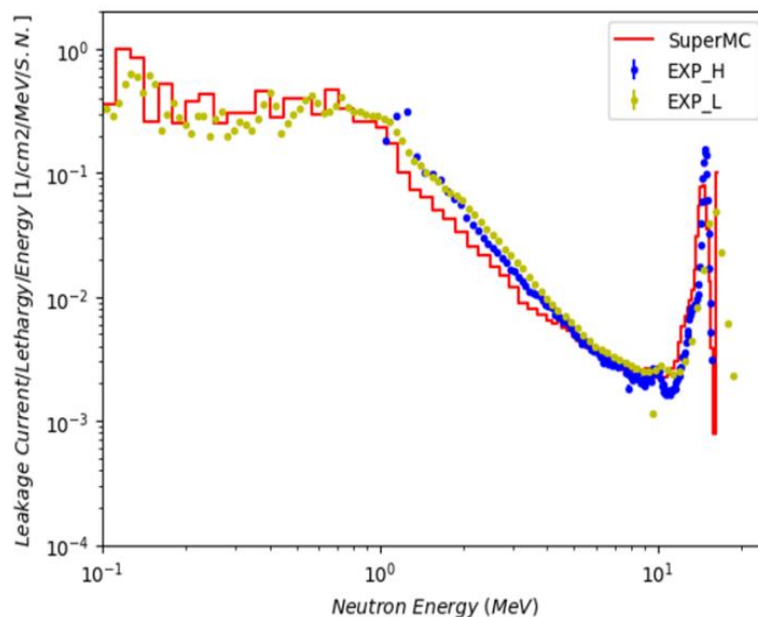
Silicon sphere neutron leakage spectrum



Silicon sphere neutron leakage spectrum in JAEA report

- The average deviation between calculation results and experimental results was about 12%. The maximum deviation between SuperMC results and experimental results was in the energy ranges around 0.1 MeV.
- Note: In the report “The quality assessment of the oktavian benchmark experiments”, the similar deviations between calculation and experimental results were shown in the right Figure.

Neutron leakage flux of Nickel sphere



Nickel sphere neutron leakage spectrum

- EXPH was the energy spectrum of high neutron energy region of experimental results, EXPL was energy spectrum of low neutron energy region of experimental results. As shown in this Figure, for the neutron leakage flux calculated by SuperMC comparing with experimental results, the average deviation was about 8%.

FNS benchmark experiment

◆ FNS_C

◆ FNS_O

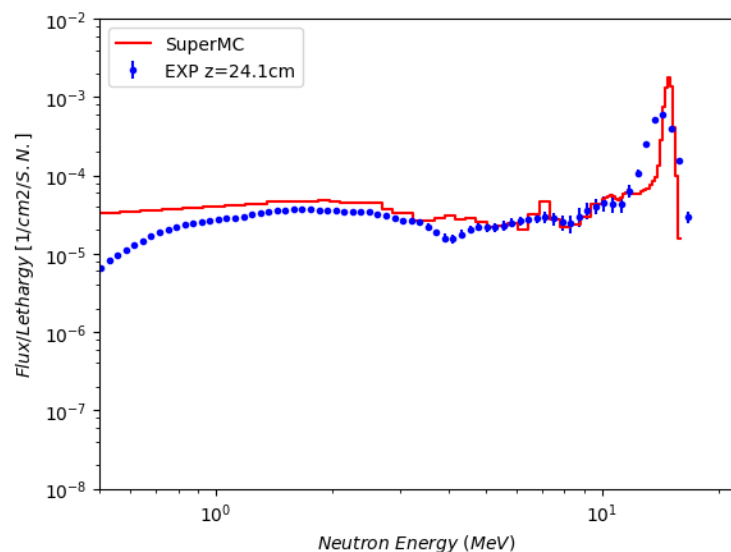
◆ FNS_SKY

◆ FNS_V

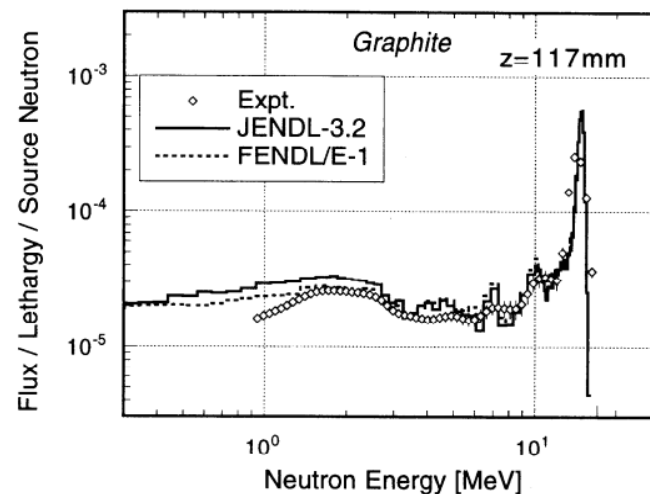
◆ FNS_W

◆ FNS_DUCT

Neutron leakage flux of FNS Graphite



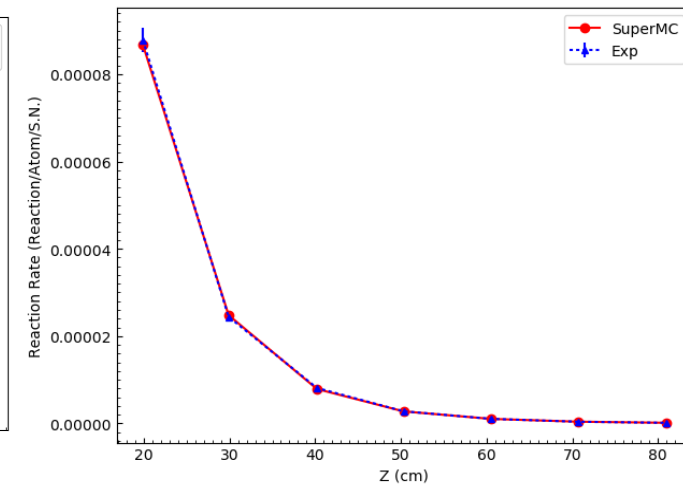
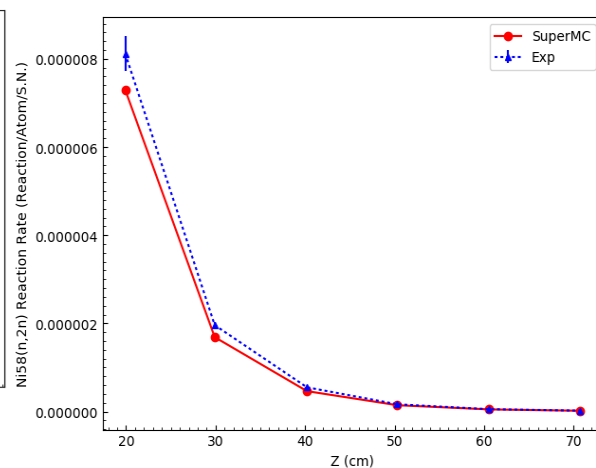
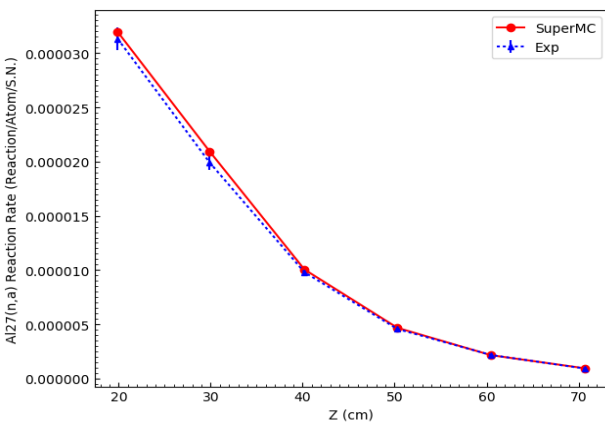
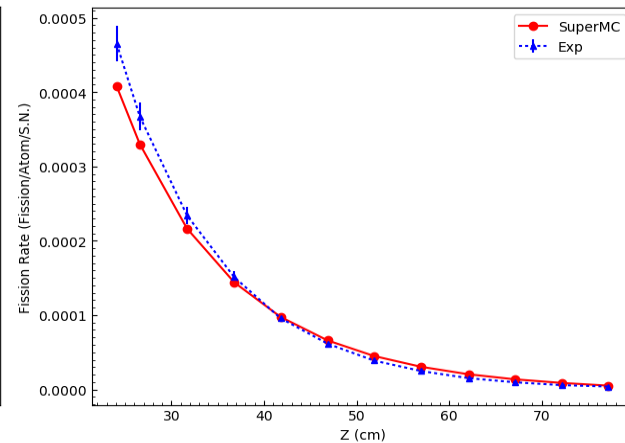
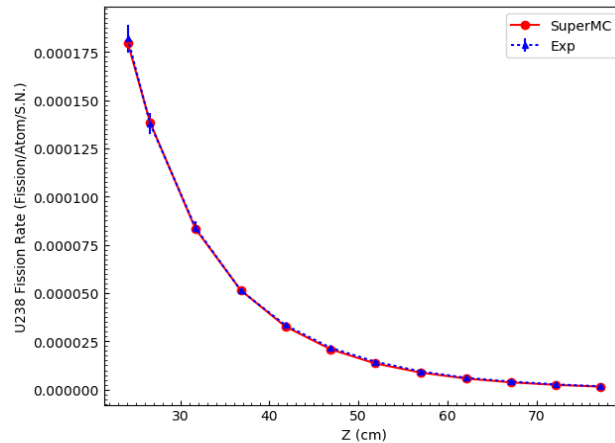
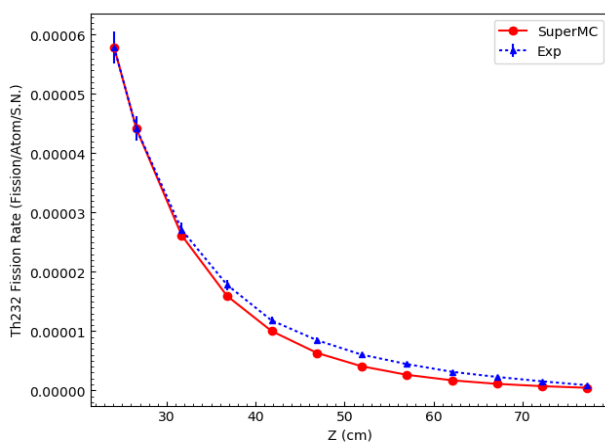
FNS graphite neutron leakage spectrum



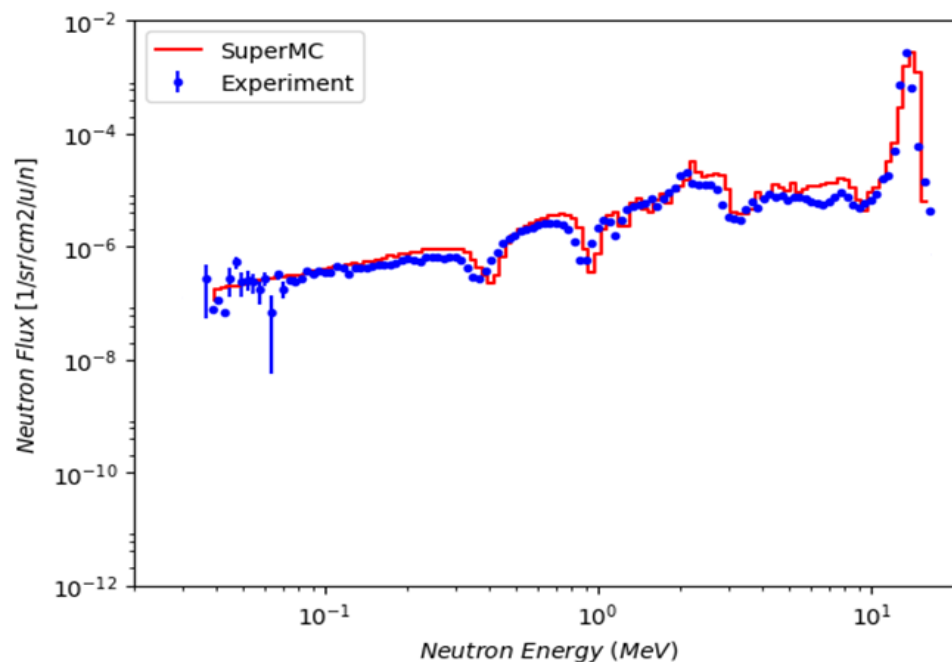
FNS graphite neutron leakage spectrum in JAEA report

- The average deviation was about 18%. The maximum deviation between SuperMC results and experimental results was in the energy ranges below 1 MeV.
- Note: In the report “Compilation of Benchmark Results for Fusion Related Nuclear Data—JAEA-Data/Code 98-024” from JAEA, the calculation results were 200% lower than the measurement for this benchmark in the energy range below 1 MeV. The similar deviations between calculation and experimental results were shown in the Figure from the JAEA report.

Reaction rates of FNS Graphite



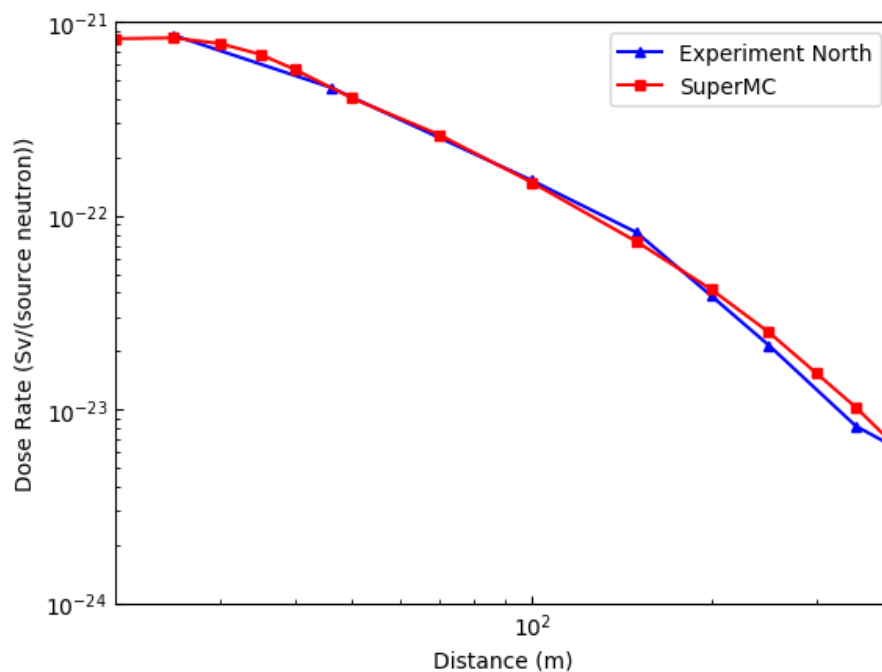
Neutron leakage flux of FNS Oxygen



FNS Oxygen neutron leakage spectrum

- Point detectors were set in SuperMC to calculate neutron flux at 5 places. The calculation results showed good consistent tendency with the experimental results. In the neutron energy range from 0.3 MeV to 0.8 MeV and 2 MeV to 8 MeV, the average deviation between the neutron flux calculated by SuperMC and experimental results was about 10%.

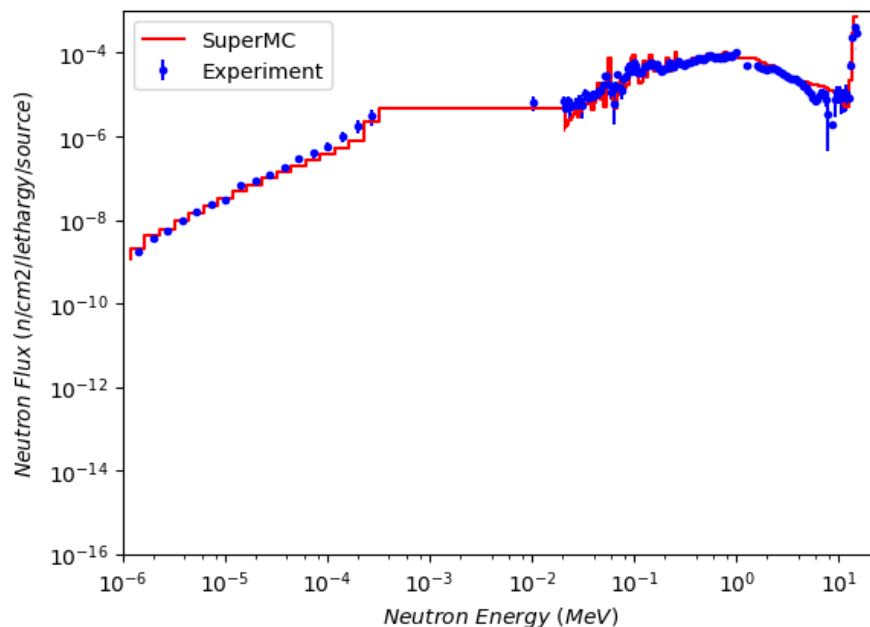
Neutron leakage flux of FNS Sky



Dose rate of FNS_SKY

- As shown in this Figure, for the dose rate calculated by SuperMC comparing with experimental results, the average deviation was about 8%.

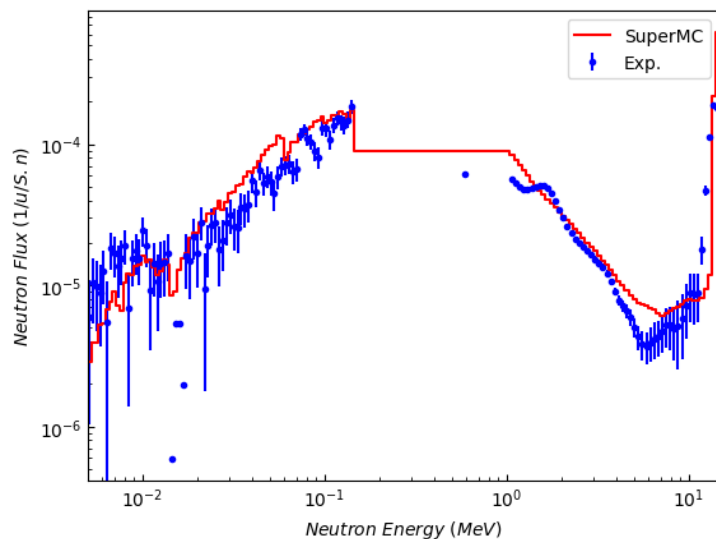
Neutron leakage flux of FNS Vanadium



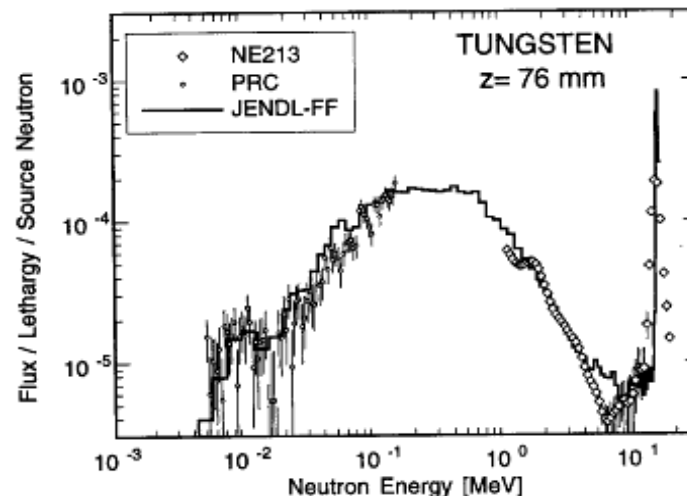
FNS Vanadium neutron leakage spectrum

- As shown in this Figure, for the neutron leakage flux calculated by SuperMC comparing with experimental results, which showed good consistent, the average deviation was about 8%.

Neutron leakage flux of FNS Tungsten



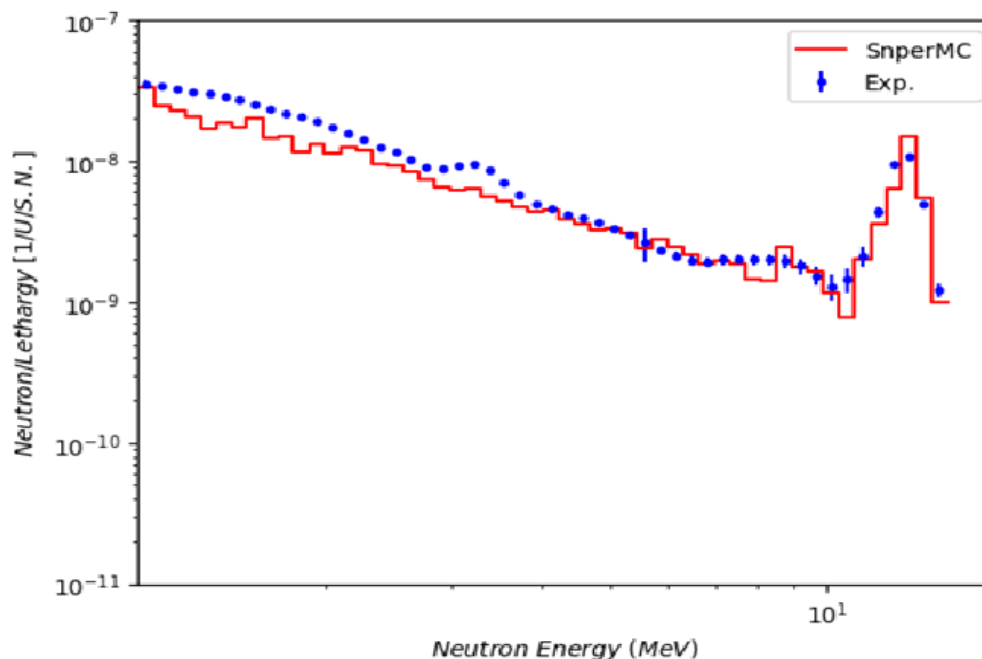
FNS Tungsten neutron leakage spectrum



FNS Tungsten neutron leakage spectrum in other report

- The comparison of neutron spectrum between calculation results and experimental results, which showed consistent tendency, except in the neutron energy range from 0.01 MeV to 0.03 MeV, the average deviations between calculation results and experimental results were about 10%, the maximum deviations between calculation results and experimental results were in the neutron energy range from 7 MeV to 11 MeV.
- Note: In the report “Data Collection of Fusion Neutronics Benchmark Experiment Conducted at FNS/JAERI- J98-021” from JAEA, the similar deviations between calculation and experimental results were shown in right Figure from the JAEA report.

Neutron leakage flux of FNS DUCT



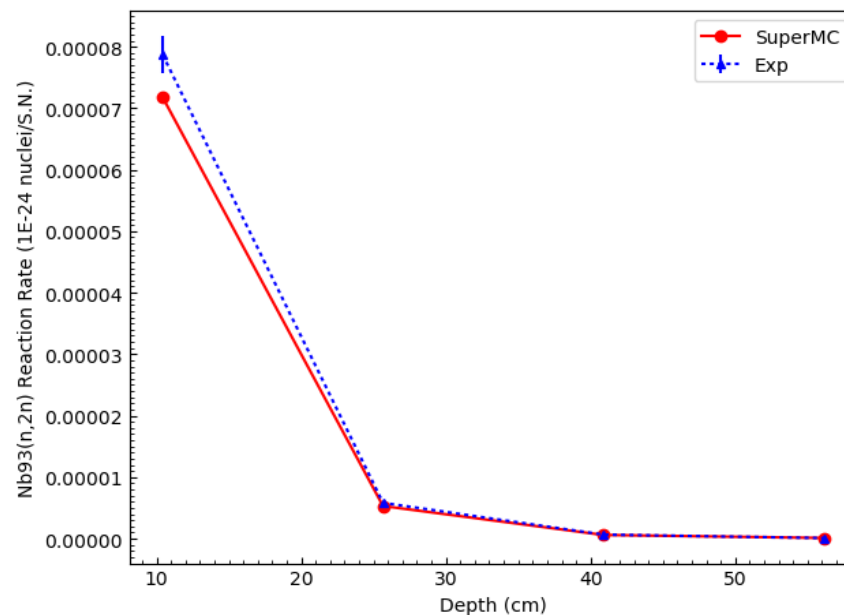
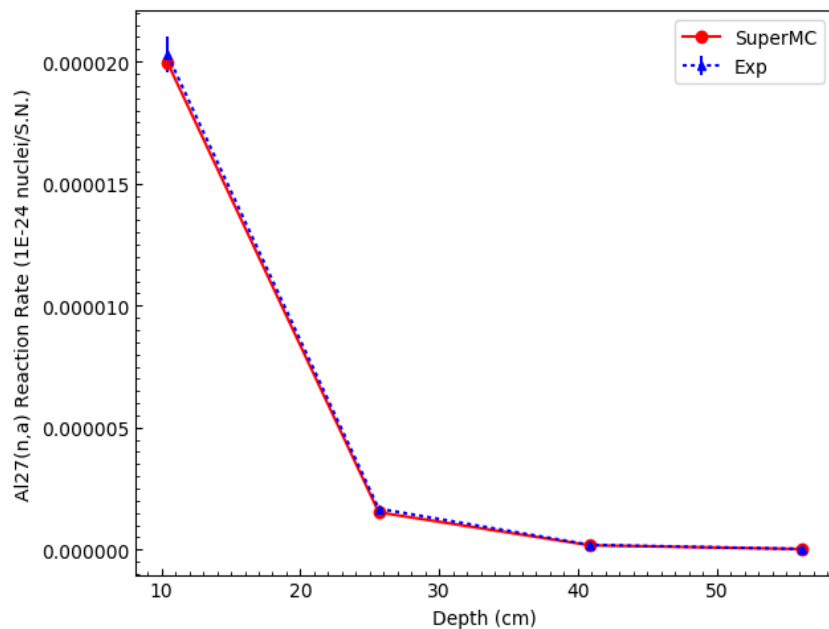
FNS DUCT neutron leakage spectrum

- As shown in this Figure, for the neutron spectrum calculated by SuperMC comparing with experimental results, the average deviation was about 12%. The maximum deviation between SuperMC and experiment was in energy region at 1 MeV~2 MeV and 2.5 MeV~3 MeV. The main reason for the deviation may be that the calculation was difficult to converge in position #5.

FNG benchmark experiment

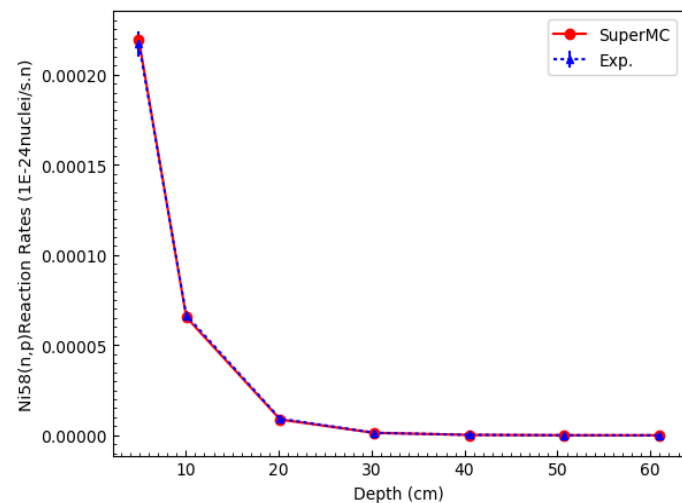
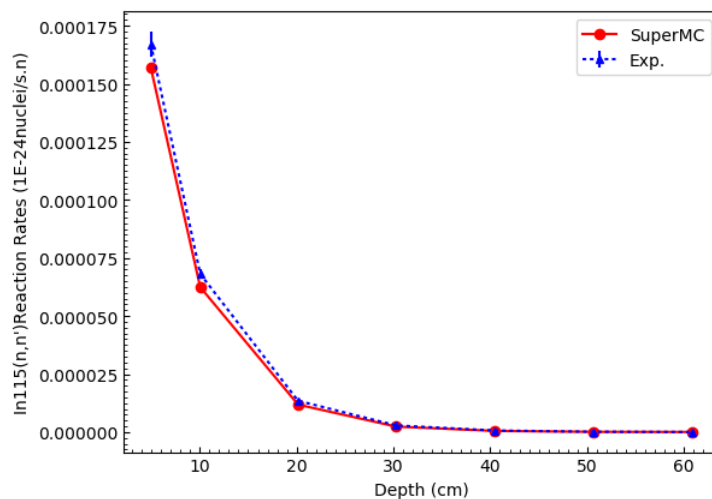
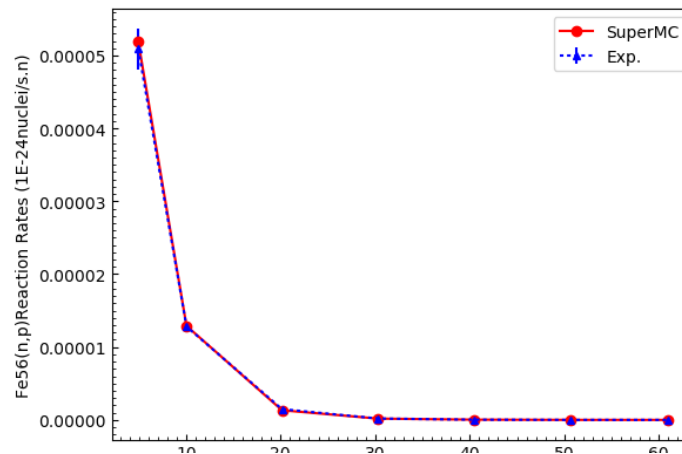
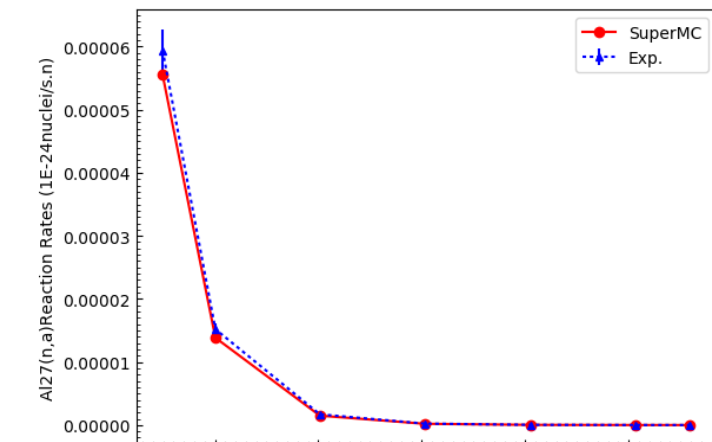
- ◆ FNG_SiC
- ◆ FNG_SS
- ◆ FNG_BLKT
- ◆ FNG_Dose
- ◆ FNG_Str
- ◆ FNG_W

Reaction Rate of FNS SiC



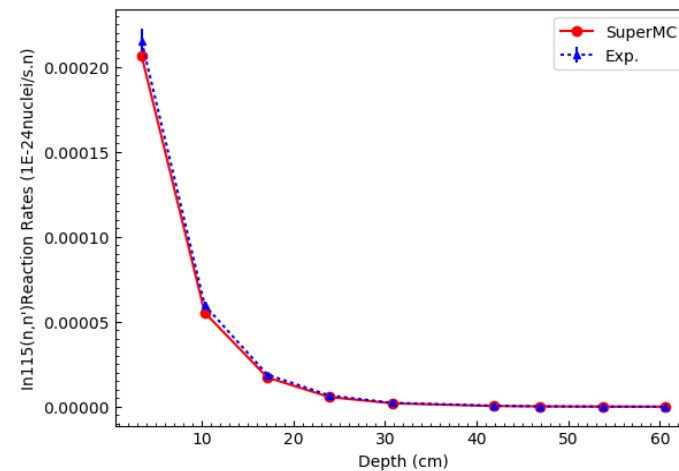
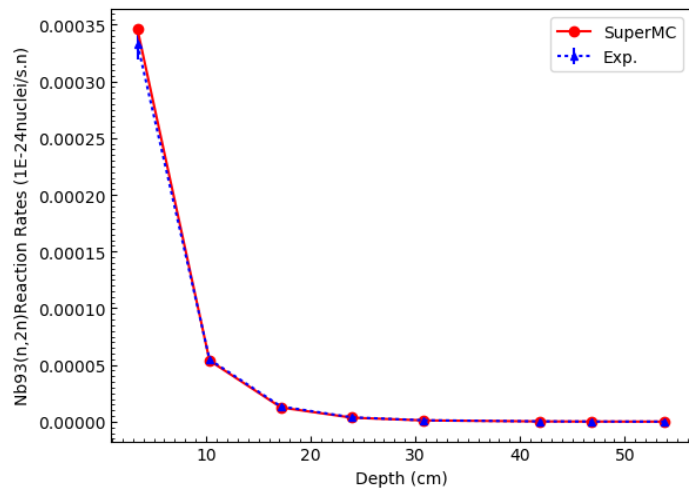
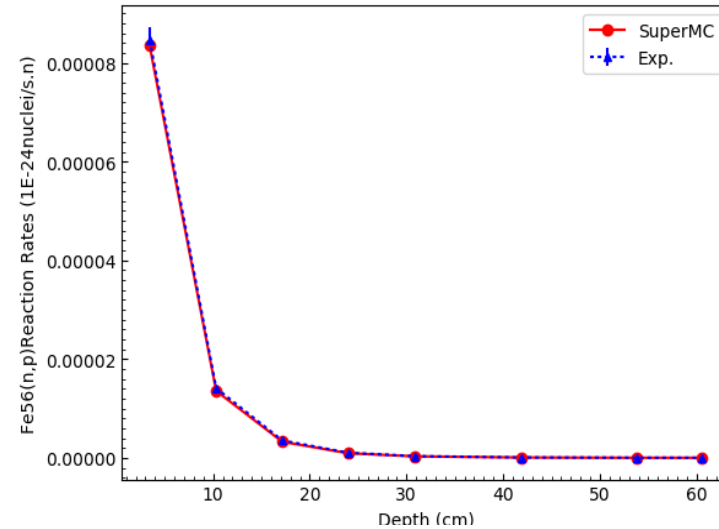
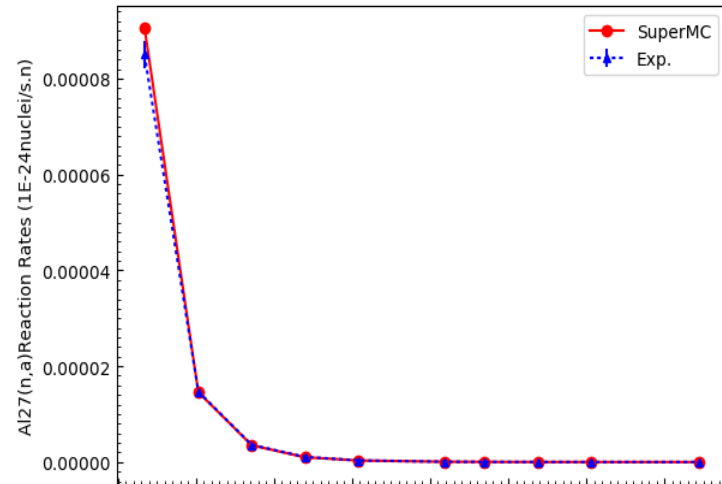
- As shown in this Figure, for the neutron spectrum calculated by SuperMC comparing with experimental results, the average deviation was about 12%. The maximum deviation between SuperMC and experiment was in energy region at 1 MeV~2 MeV and 2.5 MeV~3 MeV. The main reason for the deviation may be that the calculation was difficult to converge in position #5.

Reaction Rate of FNS SS



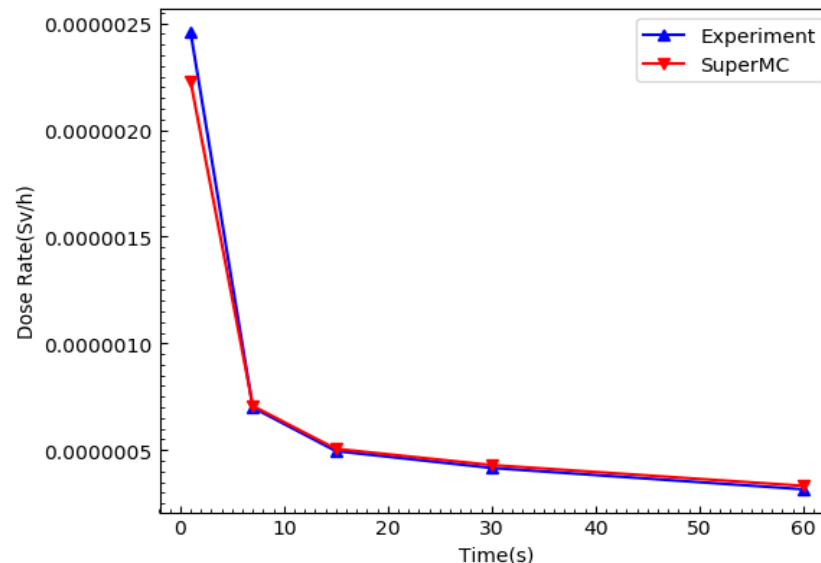
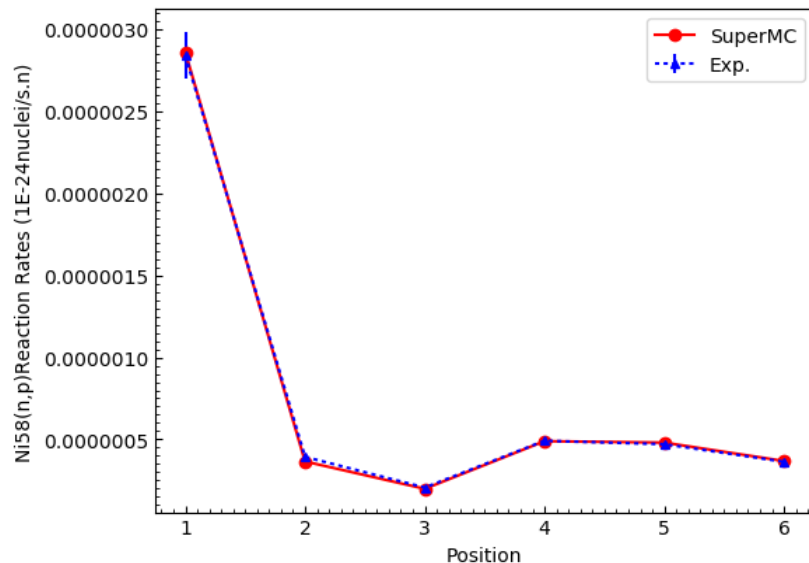
- As shown in this Figure, for the reaction rates calculated by SuperMC comparing with experimental results, the average deviation was about 5%.

Reaction Rate of FNS BLKT



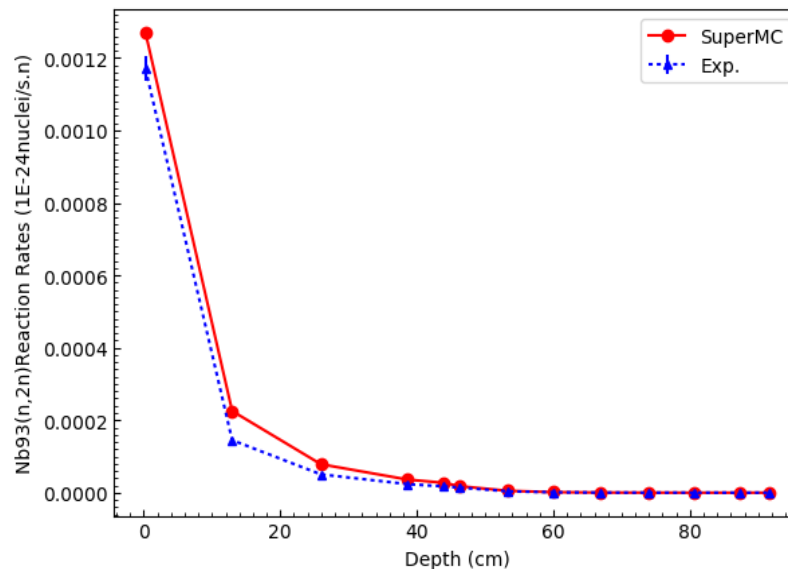
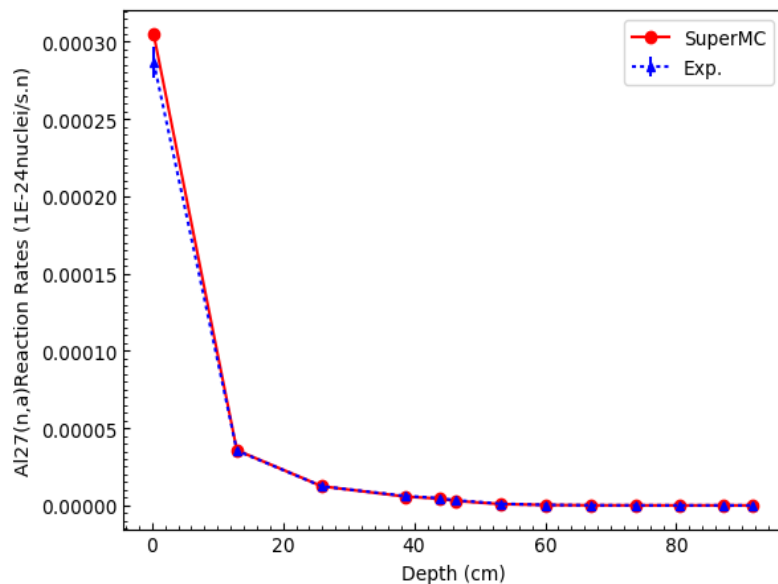
- For the reaction rates calculated by SuperMC comparing with experimental results, the average deviation was about 5%.

Reaction Rate of FNG_Dose



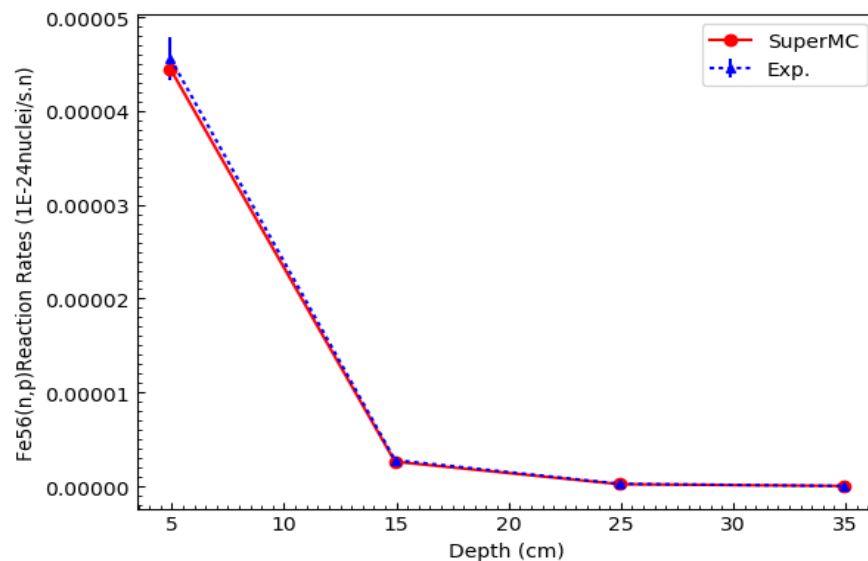
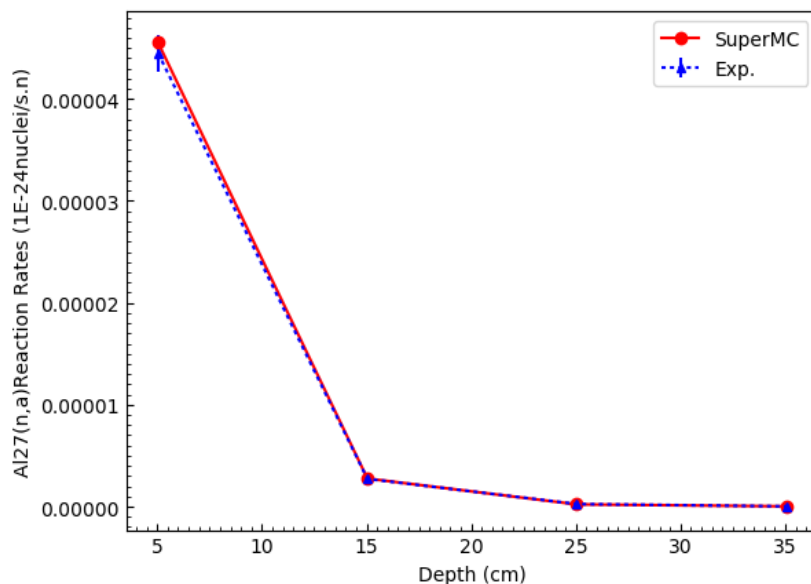
- For the reaction rates calculated by SuperMC comparing with experimental results, the average deviation was about 5%.
- For the dose rates calculated by SuperMC comparing with experimental results, in different cooling times, the average deviation was about 4.5%..

Reaction Rate of FNG_Str



- For the reaction rates calculated by SuperMC comparing with experimental results, the average deviation was about 5%.

Reaction Rate of FNG_Tungsten



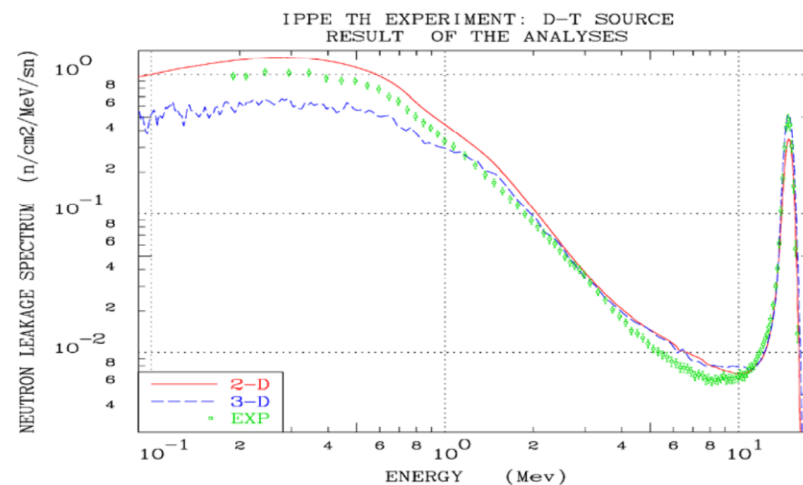
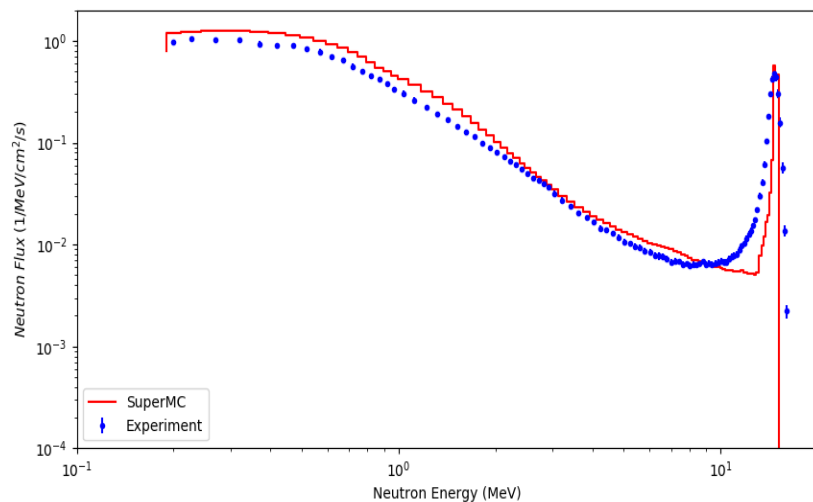
- For the reaction rates calculated by SuperMC comparing with experimental results, the average deviation was about 5%.

Other benchmark experiment

◆ IPPE_Th

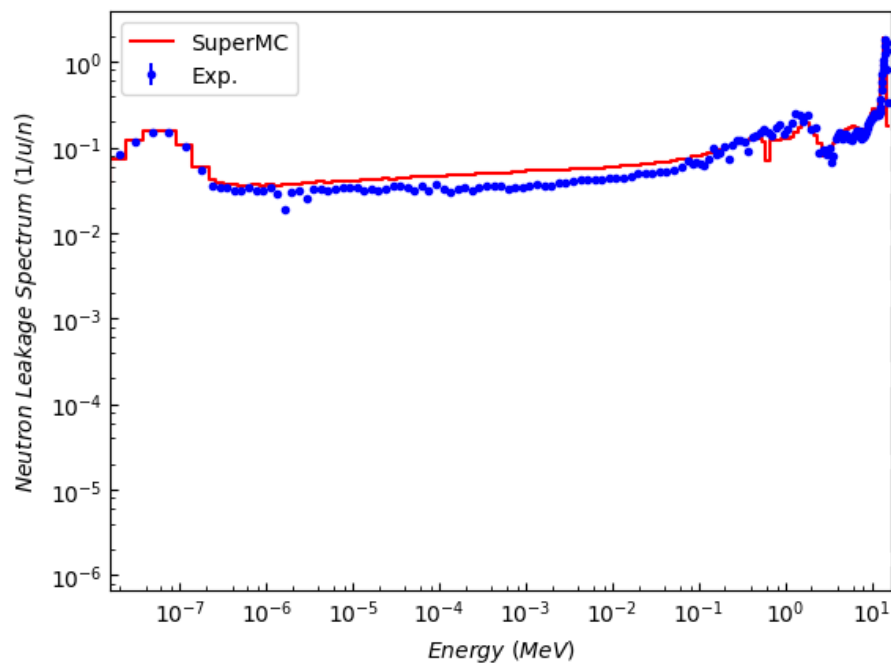
◆ KANT-Be

Neutron leakage flux of IPPE Th



- For the neutron leakage flux calculated by SuperMC comparing with experimental results, the average deviation was about 10%, and the maximum deviation was in the energy region from 10 MeV to 12 MeV.
- Note: In the report “THE QUALITY ASSESSMENT OF THE IPPE BENCHMARK EXPERIMENTS—IJS-DP-10217”, the deviation between calculation results and experimental results were about 30% in the energy ranges from 0.1 MeV to 1 MeV.

Neutron leakage flux of KANT-Be



- For the neutron leakage flux calculated by SuperMC comparing with experimental results, the average deviation was about 8%.

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Summary

- ◆ For the neutron/gamma flux, the average deviation between SuperMC calculation result and experimental result was less than 15% for most benchmark cases.
- ◆ For dosimetry reaction rate, the average deviation between SuperMC calculation results and experimental results was less than 5%.
- ◆ The global weight window, which is produced expediently by GWWG in SuperMC, can be efficient to reduce the statistical errors associated with computing the global or the multi-zones thick blankets in fusion devices (for example, in term of FOM, it achieved speed-up by ~145 times for case of FNS-DUCT).