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Experimental Needs for Criticality Safety Purposes

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Experimental Needs for Criticality Safety Purposes

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Foreword

The Working Party on Nuclear Criticality Safety (WPNCS) was established under the auspices of the Nuclear Energy Agency's (NEA) Nuclear Science Committee (NSC) to deal with technical and scientific issues relevant to criticality safety. It is interested in, among other areas, the static and transient configurations encountered in the nuclear fuel cycle, such as fuel fabrication, transport, separation processing and storage. The objective of the WPNCS is to guide, promote and co-ordinate high-priority activities of common interest to the international criticality safety community, to publish reports and handbooks and develop databases and tools to support the work of the community.

The goal of the WPNCS Subgroup on Experimental Needs for Criticality Safety Purposes (SG-5) was to highlight the needs of integral experiments and to identify the available experimental facilities where integral experiments could be performed.

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List of abbreviations and acronyms

ADS	Accelerator-driven system
ANS	American Nuclear Society (United States)
AOSTA	Activation of OSMOSE samples in TAPIRO
BA	Burnable absorber
BWR	Boiling water reactor
BUCCX	Burn-up credit critical experiments
CE	Calculation/Experimentation
CE	Combustion Engineering
CAAS	Criticality accident alarm systems
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (French Alternative Energies and Atomic Energy Commission)
CIELO	Collaborative International Evaluated Library Organisation
COGEMA	Compagnie générale des matières nucléaires (France)
CNRS	Centre national de la recherche scientifique (French National Centre for Scientific Research)
CURIE	Critical Unresolved Region Integral Experiment
CVR	Research Center Řež (Czech Republic)
DAF	Device assembly facility
DoE	Department of Energy (United States)
EDF	Électricité de France (France)
ENEA	National Agency for New Technologies, Energy and Sustainable Economic Development (Italy)
ENDF	Evaluated Nuclear Data File
EPFL	École Polytechnique Fédérale de Lausanne (Switzerland)
FA	Fuel assemblies
FPs	Fission products
Gd	Gadolinium
HEU	Highly enriched uranium
HF	Hydrogen fluoride
HTC	Haut taux de combustion (French)/high burn-up (English)
IAEA	International Atomic Energy Agency
ICNC	International Conference on Nuclear Criticality
ICSBEP	International Criticality Safety Benchmark Evaluation Project (NEA)

IPEN	Instituto de Pesquisas Energéticas e Nucleares (Brazil)
IPS	In-pile sections
IRPhE	International Reactor Physics Experiments Evaluation (NEA)
IRPhEP	International Reactor Physics Experiment Evaluation Project
IEU	Intermediate enriched uranium
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (Institute for Radiological Protection and Nuclear Safety, France)
JENDL	Japanese Evaluated Nuclear Data Library (Japan)
JHR	Jules Horowitz Material Testing Reactor (France)
KWU	Kraftwerk union
LEU	Low-enriched uranium
LACEF	Los Alamos Critical Experiment Facility (United States)
LANL	Los Alamos National Laboratory (United States)
LLNL	Lawrence Livermore National Laboratory (United States)
LWR	Light water reactor
MOX	Mixed oxide
MTR	Material testing reactor
MYRRHA	Multi-purpose HYbrid Research Reactor for High-tech Applications
NAGRA	National Cooperative for the Disposal of Radioactive Waste (Switzerland)
NASA	National Aeronautics and Space Administration (United States)
NCERC	National Criticality Experiments Research Centre (United States)
NCS	Nuclear criticality safety
NCSP	Nuclear Criticality Safety Program (United States)
NEA	Nuclear Energy Agency
NNSA	National Nuclear Security Administration (United States)
NNSS	Nevada National Security Site (United States)
NRC	Nuclear Regulatory Commission (United States)
NSC	Nuclear Science Committee (NEA)
NU	Natural uranium
NUCEF	NUclear fuel Cycle safety Engineering research Facility (Japan)
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory (United States)
OSMOSE	OScillation in Minerve of isOtopes in Eupraxic Spectra
PET	Positron emission tomography
PHWR	Pressurised heavy water moderated power reactor
PIRT	Phenomena identification and ranking tables

PMMA	Polymethyl methacrylate
PTFE	Polytetrafluoroethylene
PSI	Paul Scherrer Institute (Switzerland)
PWR	Pressurised water reactor
RMB	Brazilian Multipurpose Reactor
R&D	Research and development
RPV	Reactor pressure vessel
SCK CEN	Belgian Nuclear Research Centre (Belgium)
SDF	Sensitivity data files
SG-5	Subgroup on Experimental Needs for Criticality Safety Purposes
7uPCX	Seven percent critical experiment
SNL	Sandia National Laboratory (United States)
SNM	Special nuclear material
SNTP	Space nuclear thermal propulsion
SPRF	Sandia Pulsed Reactor Facility
SS	Stainless steel
STACY	Static Experiment Critical Facility (Japan)
TA-18	Los Alamos National Laboratory's Technical Area 18 (United States)
TAPIRO	TAratura PIla Rapida di potenza 0 (“Fast Pile Calibration at 0 Power” reactor, Italy)
TEPCO	Tokyo Electric Power Company (Japan)
TEX	Thermal/Epithermal eXperiments
TRG	Technical review group
TSL	Thermal Scattering Law
UK	United Kingdom
UKAEA	UK Atomic Energy Agency
US	United States
UOX	Uranium oxide
UZrH	Uranium zirconium hydride
VENUS	Vulcan Experimental NUclear Study
VVER	Water-water energetic reactor
WPNCS	Working Party on Nuclear Criticality Safety (NEA NSC)
ZED	Zero energy deuterium
ZPPR	Zero power plutonium reactor
ZPR	Zero power reactor

Executive summary

The goal of the Nuclear Energy Agency (NEA) Working Party on Nuclear Criticality Safety (WPNCS) Subgroup on Experimental Needs for Criticality Safety Purposes (SG-5) was to highlight the needs of integral experiments and to identify the available experimental facilities where integral experiments could be performed. Subcritical, critical and supercritical experiments were considered as they contribute to code and nuclear data validation and criticality accident study. Such experiments also play a role in the bias and uncertainty estimation for safety issues.

Experimental needs were solicited from international nuclear criticality safety (NCS) practitioners by means of a survey form, which was distributed to criticality safety practitioners and WPNCS members. A total of 28 survey forms were received by the SG-5, 4 more after closure of the group, and an additional 2 emails describing experimental needs. The surveys came from eight organisations and five countries (Canada, the Czech Republic, France, Japan and the United States); additional surveys were emitted by four organisations in two countries (United Kingdom and Switzerland). Needs were ranked by the members of the subgroup, with due consideration for the evaluation of the need, the current knowledge level and the number of forms, which mentioned a given need. With input from the surveys, the participants finalised the rankings during three meetings of the subgroup, in September 2019, August 2020 and May 2021. Submission of multiple forms for the same need was seen as an important indicator that the need should be higher priority, as it affected multiple organisations. After the discussions within the group, the needs were assigned a priority from 1 to 5, with 1 being the lowest priority and 5 the highest. The results of the ranking are provided below.

Table EX1. Experimental needs and priority ranking

Need	Priority ranking
Intermediate: ^{240}Pu and ^{238}U	5
Chlorine	5
Criticality safety training	5
Structural materials: Fe	4
Intermediate: ^{239}Pu and ^{235}U	4
Molybdenum	4
TSL: UZrH	4
TSL: Polyethylene at low temp	4
Solution reactor	4
Criticality studies and neutron source	4
Structural materials: Ta	3
Structural materials: Ni	3
Structural materials: Cr	3
Structural materials: Mn	3
Structural materials: Ni	3
Structural materials: F	3
TSL: HF	3
TSL: Lucite	3
Low temperature	3
High temperature	3
Slab fuels	2
Structural materials: Si	2
Structural materials: W	2
Structural materials: Nb	2
Structural materials: Al	1
Structural materials: Zr	1

The subgroup acknowledges that some of the needs might already be met through completed experimental programmes that have not yet been evaluated as criticality benchmarks. A section of the report was dedicated to describing existing proprietary experiments that might be used to meet some of the prioritised needs, including experiments from Valduc and Cadarache in France, the Vulcan Experimental NUclear Study (VENUS) in Belgium and the KRITZ facility in Sweden (see section 2.4).

An additional report section highlighted some of the many criticality experiment facilities available to perform some of the prioritised experiments (see section 2.5). These facilities each provide unique fuels, reflectors, moderators and capabilities, and the subsections highlighted the unique characteristics of each facility. The listing did not cover all criticality experiment facilities worldwide as some of the facilities could not be contacted or were unable to share information before the report was published. The facilities included in the report are: VENUS (Belgium), IPEN (Brazil), Zero Energy Deuterium (ZED-2) (Canada), LR-0 (Czech Republic), RSV TAPIRO (Italy), the Static Critical Facility (Japan), the National Criticality Experiments Research Centre (United States), Sandia Critical Experiments Facility (United States) and CROCUS (Switzerland). There are known facilities in Belarus, China, Japan and Russia that were not included in this report.

1. Introduction

Experimental Needs for Criticality Safety Purposes is the fifth expert subgroup (SG-5) convened under the auspices of the Nuclear Energy Agency (NEA) Working Party for Nuclear Criticality Safety (WPNCS). The aim of the subgroup was to highlight the criticality safety-related needs for integral experiments and to identify the available experimental facilities where integral experiments could be performed. Consideration was given to subcritical, critical and supercritical experiments that could be used to contribute to code and nuclear data validation, bias and uncertainty estimation, and criticality accident study.

The main tasks of SG-5 were to compile the needs for experiments in criticality safety, rank and document the needs based on priority, and document the existing international capabilities for experimental facilities that could address the needs.

2. Experimental needs

2.1. Presentation of the survey

A survey form was distributed in July 2019 to international nuclear criticality safety (NCS) practitioners to understand their experimental needs. The form is presented in Figure 1. It requested general information used to identify the respondent (name, nationality, employer) and a detailed description of the experimental need. The requested information included application details about isotopes/elements, specific reaction types and the energy spectra of interest. The respondent was asked to provide their judgement on the importance of the need to criticality safety (high/medium/low) and to provide feedback on the current level of knowledge of the data need (known/partially known/unknown). Respondents were also asked to describe the methodology used to identify the needs, whether it was a survey of existing integral data or based on sensitivity and uncertainty methods.

SG-5 received a total of 28 survey forms, with an additional two emails describing experimental needs. The surveys came from eight organisations and from five countries (Canada, Czech Republic, France, Japan and the United States). Four more surveys from two additional countries (Switzerland and United Kingdom) were distributed after closure of the group and are reported in the appendix. The needs highlighted in them are consistent with needs observed in other countries.

Figure 1. Survey form

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date:

Name:

Institution:

Country:

Email:

2. **Methodology used to highlight the needs:**

3. **Experimental needs:**

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other:* ....
Description of the Application	
Isotope/element/medium of interest	
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other:* ....
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	☐ Fast ☐ Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	☐ High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known ☐ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Source: NEA data, 2022.

2.2. Methodology for the ranking

The identified needs were ranked according to the consensus of the participants of the subgroup, with consideration for the evaluation of the need, the current knowledge level and the number of forms that mentioned a given need. With input from the surveys, the participants finalised the rankings during three meetings of the subgroup, in September 2019, August 2020 and May 2021. The submission of multiple forms for the same need was seen as an indicator that the need should be of a higher priority, as it affected multiple organisations. After discussions with the group, the needs were assigned a priority from 1 to 5, with 1 being the lowest priority and 5 the highest. Other ranking approaches were considered, including more formal methods such as the Phenomena Identification and Ranking Tables (PIRT) methodology. However, a calculational-based approach was not pursued due to the significant time and computational resources needed for such an effort and the fact that some of the experimental needs do not have quantifiable feedback to the calculations to allow for a meaningful comparison.

2.3. Identified needs with priority

2.3.1. Overall ranking

Table 1 shows the results of the subgroup ranking of the submitted experimental needs. A ranking of 5 denotes the highest priority while a ranking of 1 denotes the lowest priority. Additional details are provided for each experimental need in sections below the table, sorted according to ranking group.

Table 1. Experimental needs and priority ranking

Need	Priority ranking
Intermediate: ^{240}Pu and ^{238}U	5
Chlorine	5
Criticality safety training	5
Structural materials: Fe	4
Intermediate: ^{239}Pu and ^{235}U	4
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Criticality studies and neutron source	4
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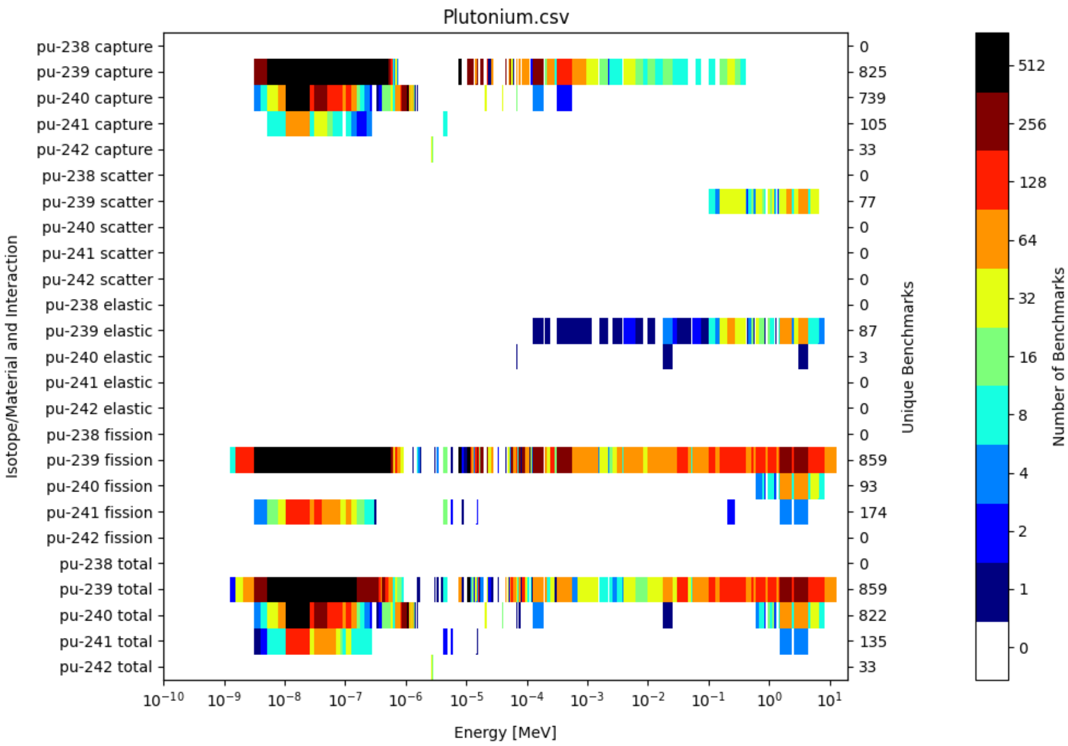
Structural materials: Cr	3
Structural materials: Mn	3
Structural materials: Ni	3
Structural materials: F	3
TSL: HF	3
TSL: Lucite	3
Low temperature	3
High temperature	3
Slab fuels	2
Structural materials: Si	2
Structural materials: W	2
Structural materials: Nb	2
Structural materials: Al	1
Structural materials: Zr	1

Source: NEA data, 2022.

For the majority of the needs, the level of knowledge was assessed through representation of relevant experimental benchmarks in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook (NEA, 2020), an extensive and well-documented collection of over 5 000 critical and subcritical configurations used in the field of nuclear criticality safety (NCS) as the main source of trusted computational models for radiation transport code validation. Distributed with the ICSBEP Handbook are Sensitivity Data Files (SDF) for 4 180 of the benchmark configurations, calculated using a combination of data libraries, MCNP and SCALE codes (Hill, 2014). k_{eff} sensitivities were calculated for each isotope and reaction type relative to a change in nuclear data reaction cross sections using a calculated adjoint flux. These sensitivities were used to make "heat maps" of the ICSBEP coverage of experiments sensitive to reaction cross sections per isotope over all neutron energy ranges (Thompson, Bahran and Hutchinson, 2018). Heat maps are presented for the relevant experimental needs in the following sections. Figure 2 shows an example heat map, for plutonium isotope reactions. The heat map is colour coded to indicate the total number of benchmarks that have at least 10^{-3} k-effective sensitivity to a 1% cross-section change at a given energy. Black and red areas of the graph, such as those for ^{239}Pu capture, fission, and total cross-section in the thermal region, indicate reactions and energy regions that have high benchmark coverage. White and blue areas of the graph indicate sparse coverage.

Figure 2. ICSBEP sensitivity heat map for plutonium isotopes



Source: NEA data, 2022.

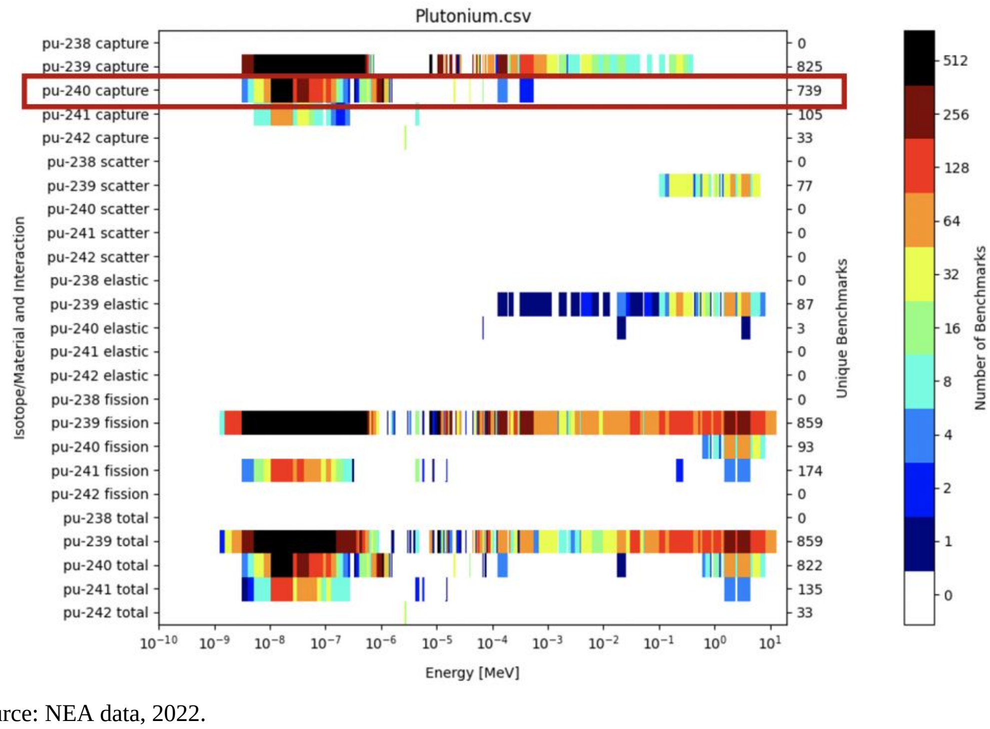
2.3.2. Priority 5 needs, highest priority

Experiments in intermediate energy spectra ^{240}Pu and ^{238}U

The International Criticality Safety Evaluation Project (ICSBEP) Handbook in general lacks benchmarks in the intermediate energy region, which spans from 0.625 eV to 100 keV, as the majority of cases in the handbook are for configurations where the neutron fission energy is mostly fast or mostly thermal. While additional intermediate experiments are needed for many isotopes, ^{240}Pu and ^{238}U experiments in this region are of particular interest to criticality safety. Regimes needed to be covered include UO_2 and UO_2-PuO_2 powders (U enrichment lower than 5 wt%, ^{240}Pu content of 20 wt%) with low moderation ratio and mixed oxide (MOX) fuel assemblies in dry storage or in transport casks.

^{240}Pu validation is important to criticality safety under reprocessing scenarios, as encountered, for example, in the French commercial nuclear programme during fuel fabrication, storage and transportation (^{240}Pu content in Pu higher than 15%). Nuclear fuel burnt in a reactor will breed ^{240}Pu, with longer burn-up time resulting in a higher fraction of the plutonium content becoming ^{240}Pu. While the 2020 edition of the handbook contains 793 plutonium configurations, experiments with intermediate fission spectra are sparse. The vast majority, 650, are thermal plutonium solution systems, with 530 of these cases being very thermal with a thermal fission fraction greater than 80%. There are also 121 fast metal cases, of which 82 have fast fission fractions greater than 80%. Since the majority (546) of the benchmarks contain plutonium with 6 wt% or less of the ^{240}Pu isotope, data validation and testing of ^{240}Pu cross sections is limited by the lack of sensitivity in most of the benchmarks. Figure 3 shows a heat map of the plutonium isotopic sensitivity, with the ^{240}Pu capture cross-section (the reaction with the most contribution to the total cross-section in intermediate energies) highlighted inside a red box. The graph shows the lack of sensitive benchmarks in ICSBEP to this reaction channel.

Figure 3. ICSBEP sensitivity heat map for plutonium isotopes, highlighting ^{240}Pu capture

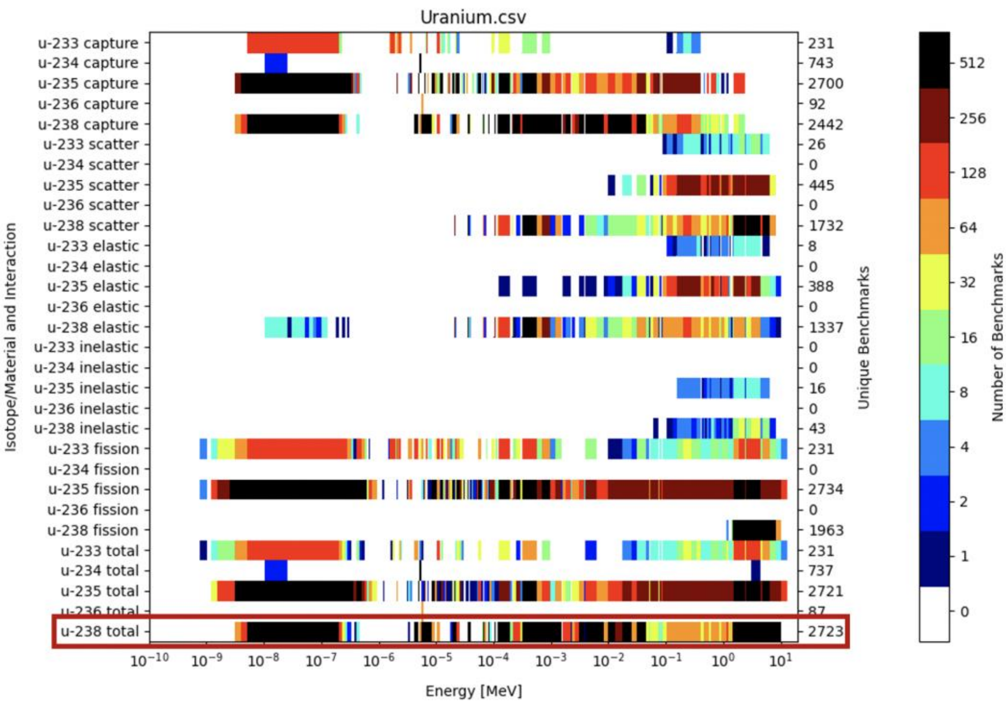


Source: NEA data, 2022.

^{238}U validation is important to criticality safety under fuel fabrication and reprocessing scenarios, as also encountered, for example, in the French commercial nuclear programme during fuel fabrication, storage and transportation, both for uranium and mixed oxide fuels. Much of the need stems from uranium or mixed oxide powder in an under-moderated (such as from damp powders) or dry state, which can lead to epithermal or intermediate energy systems that must be evaluated for criticality safety, which have high sensitivity to the ^{238}U capture cross-section. While the 2020 edition of the ICSBEP Handbook contains many low-enriched uranium experimental configurations sensitive to ^{238}U, the vast majority of the systems are thermal fission configurations, with only a few in the intermediate energy region. Additionally, there are needs for intermediate energy systems with a thick reflector composed of ^{238}U.

A journal article (Perfetti and Rearden, 2019) determined that ^{238}U capture data was a large contributor to the bias for a criticality safety application using TSURFER. The findings from another WPNCS Subgroup (SG-2), Blind Benchmark on MOX Damp Powders, also found that some of the configurations studied show a significant sensitivity to ^{238}U resonance capture cross sections.

Figure 4. ICSBEP sensitivity heat map for uranium isotopes, highlighting ^{238}U total cross-section

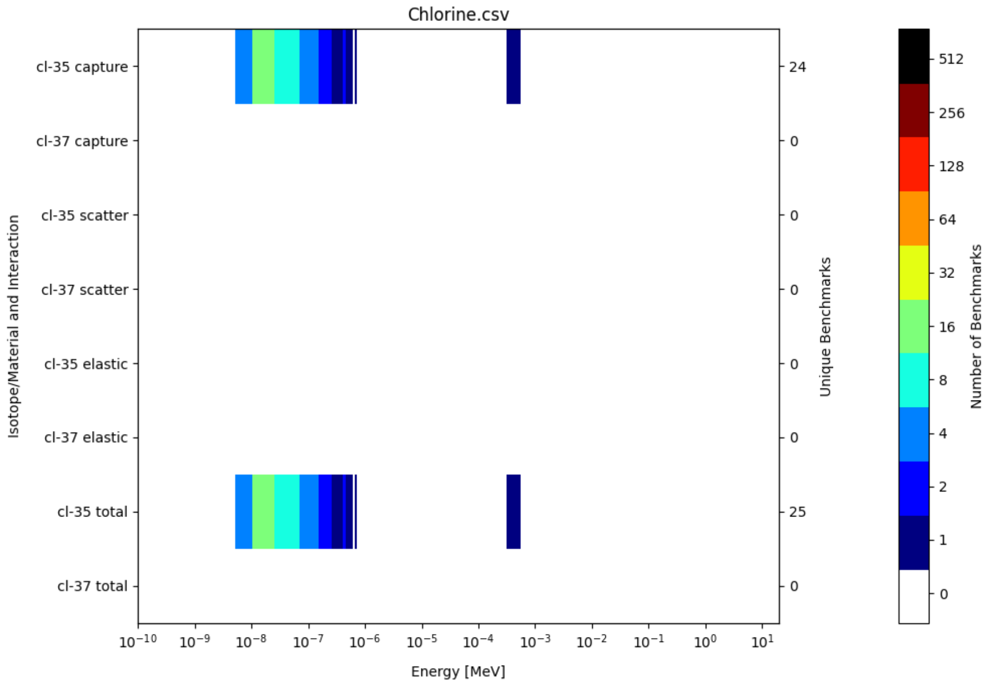


Source: NEA data, 2022.

Chlorine

Three experimental need forms were received for chlorine, covering fissile chloride solutions for aqueous reprocessing, salt used in pyroprocessing and the use of seawater as a poisoning solution in response to a nuclear reactor accident located near a coast. For criticality safety, there is a need for thermal and intermediate chlorine experiments to allow for credit to be taken for the neutron absorbing poisoning effect. There is also an overlap of needs with the advanced reactor community, as molten salt reactors are gaining favour due to their superior heat transfer properties and enhanced safety considerations, but quantifying the poisoning effect (specifically the ^{35}Cl (n,p) cross-section at neutron energies >100 keV) is important to designing a functional reactor (Batchelder, 2019; Bostelmann, Ilas, and Wieselquist, 2020). Experiments of interest are chlorine-reflected assemblies at all energy spectra and thermal and intermediate absorption experiments with dispersed chlorine. Figure 5 shows the chlorine heat map for ICSBEP.

Figure 5. ICSBEP sensitivity heat map for chlorine isotopes



Source: NEA data, 2022.

Criticality safety training

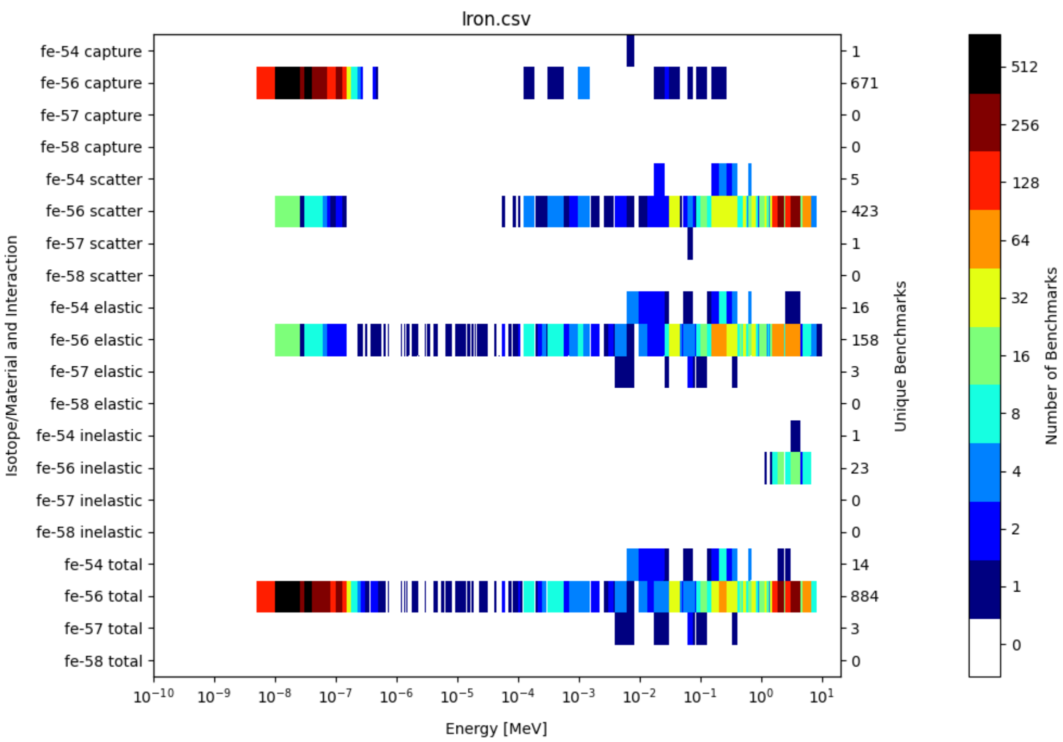
While not an explicit integral data need, there was a strong consensus in the subgroup that experimental facilities have another high-priority purpose for criticality safety: providing hands-on training in the parameters that affect criticality safety (mass, moderation, reflections, spacing, poisons, etc.). American Nuclear Society (ANS) Standard 8.26, the Criticality Safety Engineer Training and Qualification Program, requires hands-on experimental training for criticality safety engineer qualification; many other countries have similar training requirements. Unfortunately, with the closure of many experimental facilities, the availability of such courses to satisfy qualification requirements is significantly reduced. For example, no training course is currently offered in France that would satisfy this requirement.

2.3.3. Priority 4 needs

Structural materials: Fe

Iron is a commonly used structural material and is thus often analysed as part of a criticality safety evaluation. There are many critical benchmarks that contain iron, as shown in the plot in Figure 6. However, there are some applications of iron where adequate validation does not exist, mainly in the thermal and intermediate energy regions. The nuclear criticality safety evaluations supporting many US liquid waste processing operations currently credit the presence of neutron absorbers in large, geometrically unfavourable liquid waste storage tanks to preclude criticality (Kersting and Losey, 2018). These are not the traditional strong neutron absorbers used for reactor reactivity control (such as boron, gadolinium, etc.), but are instead weaker absorbers like iron that were disposed to the tanks along with the fissile material. As shown in in Figure 6, there are few benchmarks sensitive to the intermediate energy region. Iron cross sections were recently re-evaluated under the 2017 Collaborative International Evaluated Library Organisation (CIELO) pilot project, whose work used a set of 24 ICSBEP benchmarks based on adequate sensitivity, including 16 fast benchmarks, 6 thermal benchmarks, and two intermediate benchmarks (Herman et al., 2018).

Figure 6. ICSBEP sensitivity heat map for iron isotopes



Source: NEA data, 2022.

Experiments in intermediate energy spectra: ^{239}Pu and ^{235}U

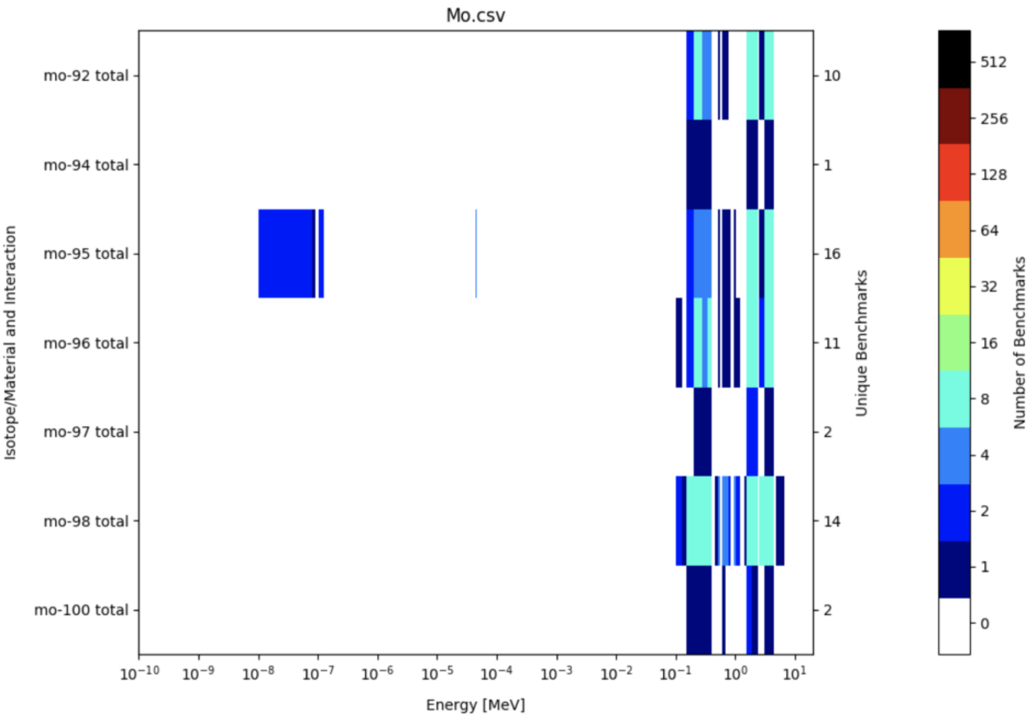
In general, the ICSBEP Handbook lacks benchmarks in the intermediate energy region, which spans from 0.625 eV to 100 keV, as the majority of cases in the handbook are for configurations where the neutron fission energy is mostly fast or mostly thermal. While additional intermediate experiments are needed for many isotopes, ^{239}Pu and ^{235}U are the most commonly encountered fissile species and experiments in this region are needed to ensure appropriate validation of cross sections for criticality safety.

Structural materials: Molybdenum

Molybdenum is a commonly used alloying agent for fuel that lacks adequate validation in the thermal and intermediate energy regions. Applications with experimental needs include fuel fabrication (UMo fuel for research reactors, space reactors and advanced fuel concepts, and accelerator targets), reprocessing (UPuMoZr fuel residues in reprocessing plant dissolvers), burn-up credit applications, medical isotope production and storage, mainly for capture in the thermal or intermediate (epithermal) energy ranges for 95 Mo. The US Nuclear Criticality Safety Program (NCSP) has also identified improving Mo nuclear data as a priority and has funded differential measurements and new resonance region evaluations of Mo. Mo is also a stable fission product (FP) and the ultimate goal of the NCSP is to take credit for Mo in transportation, fuel storage and reprocessing activities. A 2019 study analysing integral needs for 20% enriched U-Mo alloy reactor fuel determined that additional benchmarks were needed to provide validation for reactor simulations (Bess et al., 2019).

Few benchmarks are sensitive to Mo, as shown in the heat map in Figure 7 and Table 2, extracted from (Bess et al., 2019). A few fast energy experiments incorporating molybdenum reflection are available in ICSBEP, and the MIRTE 2 experiments (Leclaire et al., 2020) involving molybdenum are the best existing experiments in the thermal range. Experiments that involve molybdenum in sleeves or in foils and that use fuel rods that are well-characterised would be of interest.

Figure 7. ICSBEP sensitivity heat map for molybdenum isotopes



Source: NEA data, 2022.

Table 2. ICSBEP and IRPhEP benchmarks and calculated molybdenum sensitivites to k_{eff}

Evaluation ID	Fuel (wt.%)	Molybdenum Details	k_{eff} Sensitivity (| %Δk/%Σ |) Thermal (< 0.625 eV)	Total (0 - 20 MeV)
LEU-COMP-THERM-067	UO_2 (4.35 ^{235}U)	Mo Rods in Research Reactor	< 0.011	< 0.013
LEU-COMP-THERM-103	UMo (19.8 ^{235}U) UO_2 (4.35 ^{235}U)	UMo Plate Experiment in Research Reactor	Unavailable	Unavailable
HEU-COMP-INTER-005	UO_2 (90.11 ^{235}U)	Mo Pellets Between UO_2 Fuel	Unavailable	Unavailable
HEU-COMP-MIXED-003	UO_2 (95.92 ^{235}U)	Mo Tubes in Space Reactor Mockup	< 0.030	<0.044
HEU-COMP-MIXED-004	UO_2 (95.92 ^{235}U)	Mo Tubes in Space Reactor Mockup	< 0.030	<0.044
HEU-MET-FAST-005	UMo (90 ^{235}U)	Be & Mo Reflected Space Reactor Mockup	< 0.001	< 0.058
HEU-MET-FAST-084	U metal (93.3 ^{235}U)	Mo & Mo_2C Reflected Cylinder	0	< 0.036
HEU-MET-FAST-092	U metal (96 ^{235}U)	Mo Reflected Cylinder	0	< 0.029
HEU-MET-FAST-093	U metal (96 ^{235}U)	Mo Diluted Cylinder	0	< 0.031
HEU-MET-FAST-094	U metal (96 ^{235}U)	Be & Mo Diluted Cylinder	0	< 0.005
HEU-MET-MIXED-020	U metal (96 ^{235}U)	Mo & CH_2 Diluted Cylinder	< 0.025	< 0.031
PU-MET-FAST-044	Pu metal (5.1 ^{240}Pu)	Mo Reflected Sphere	< 0.004	< 0.018
MINERVE-FUND-RESR-001	UAl (90-93 ^{235}U)	^{95}Mo Pellet in Oscillation Measurement	Unavailable	Unavailable

Source: Table from Bess et al., 2019.

Thermal Scattering Law (TSL): UZrH

Uranium zirconium hydride (UZrH) is the fissile medium that is used in TRIGA® reactors. The TRIGA® reactor is the most widely used non-power nuclear reactor in the world. Sixty-six TRIGA® reactors have been constructed to date in twenty-four countries. These reactors are used in many diverse applications, including production of radioisotopes for medicine and industry, treatment of tumours, non-destructive testing, basic research on the properties of matter and education and training. The CERCA factory, currently performing an upgrade of the TRIGA® manufacturing facilities, is the only manufacturing site for this type of fuel.

The fuel elements consist of cylindrical elements of two types (standard or small diameters). The fissile material is UZrHx with an atomic ratio of H/Zr of approximately 1.6. The U concentration ranges between 8 wt% and 47 wt% with an enrichment of 20 wt%.

UZrH must have adequate validation for criticality safety in other operations, such as during transportation of fuel assemblies or in storage.

Only four experiments with UZrH fuel are available in the ICSBEP Handbook (NEA, 2020); two from IEU-COMP-THERM-003 and two from IEU-COMP-THERM-013. However, experiments from IEU-COMP-THERM-013 also involve erbium in the fissile and thus cannot be easily used for feedback on TSL of UZrH. The ICSBEP Handbook contains six additional experiments with zirconium hydride moderator (HEU-COMP-MIXED-003) that do not contain UZrH fuel; however, they can also be used to test the TSL of H-ZrH and Zr-ZrH but exhibit potentially high experimental uncertainties.

To satisfy the integral needs for criticality safety, the objective of new experiments would be to test the TSL of Zr-ZrH and H-ZrH but also the zirconium cross sections in the thermal energy range. There are some existing experiments that have yet to be evaluated that could partially satisfy the need. Experiments from the crystal facility were recently completed at the Joint Institute for Power and Nuclear Research – Sosny of the National Academy of Sciences of Belarus and were presented at the International Conference on Nuclear Criticality (ICNC) in 2019. (Watson, 2019). The critical assemblies represented the cores collected from three types of fuel assemblies with different structures, surrounded by assemblies and units of a side reflector of either zirconium hydride or stainless steel. The moderator was zirconium hydride $ZrH_{1.9}$. The fuel was composed of a UO_2-Ni-Cr matrix with a 45% ^{235}U enrichment. If such experiments could be submitted to the ICSBEP and approved of by the technical review group (TRG) subgroup and then included in the handbook, the priority level could be reduced to 3.

TSL: Polyethylene at low temperature

The lack of low temperature benchmarks for criticality calculation validation and nuclear data testing is internationally recognised. At the recent ICNC, in September 2019, papers from the United Kingdom (Watson, 2019) and France (Milin, 2019) highlighted the lack of validation data for low temperature calculations, with a specific application to nuclear material transport. The International Atomic Energy Agency's (IAEA's) Regulations for Safe Transport of Radioactive Materials, SSR-6, echoes the US 10 CFR 71 requirements asking packages be analysed to -40°C. Benchmarks at temperatures below room temperature are needed to fill this gap down to -40°C for many materials, including plutonium, uranium, common moderator materials (water/ice, polyethylene) and common structural materials. The ENDF/B-VIII.0 release was the first library to include a polyethylene TSL at temperatures lower than room temperature, down to -40°C, and integral experiments are needed to validate the new data (Gan and Wilson, 2019). Polyethylene TSL validation at low temperature was given higher priority than other integral data at low temperature due to unexpectedly large reactivity changes calculated using the ENDF/B-VIII.0 low temperature polyethylene TSLs, up to 2.5% effect in k_{eff} when going from room temperature to -40°C (Norris and Percher, 2021).

Experimental solution reactors for solutions, slurries and powders handling needs

A number of needs were identified relating to the need for a solution reactor capability. Advanced fuel cycle reprocessing will require additional data for process solutions with uranium and plutonium together, higher plutonium isotopes, and other actinides and might require engineering mock-ups of the requisite process equipment designs to ensure safe, subcritical design and operation. Data is also needed on the evolution of supercritical excursions in solutions, including research on the physics of solution excursions and their consequences. There are a number of unknowns in this area, including the dynamics of solution criticality accidents, the evolution of radiolytic gases from solution criticalities, radioactive material release fractions, and radiochemical effects on the solution. These kinds of experiments can provide multi-physics benchmark information to allow for validation of solution accident modelling and codes. While considerable data is available from CRAC (Barbry, 1973), SILENE (Barbry, 1994), SHEBA (Cappiello et al., 1997), and TRACY (JAEA, 2003), these programmes have been limited to pure uranyl nitrate solution systems. In addition to needs for precise basic critical data for other solution systems (e.g. chlorides, fluorides, sulphates, phosphates), other actinides, slurries and powders, additional excursion yield data are needed, especially for slurries and damp powders, for which there are none.

Criticality studies: Source of neutrons for research and testing for CAAS and dosimetry

Another key use of critical facilities is as a neutron source for chain reaction research and qualification of dosimetry and criticality accident alarm systems (CAAS). There is a need for neutron spectra that encompass the whole energy range, from fast to thermal. Key needs include:

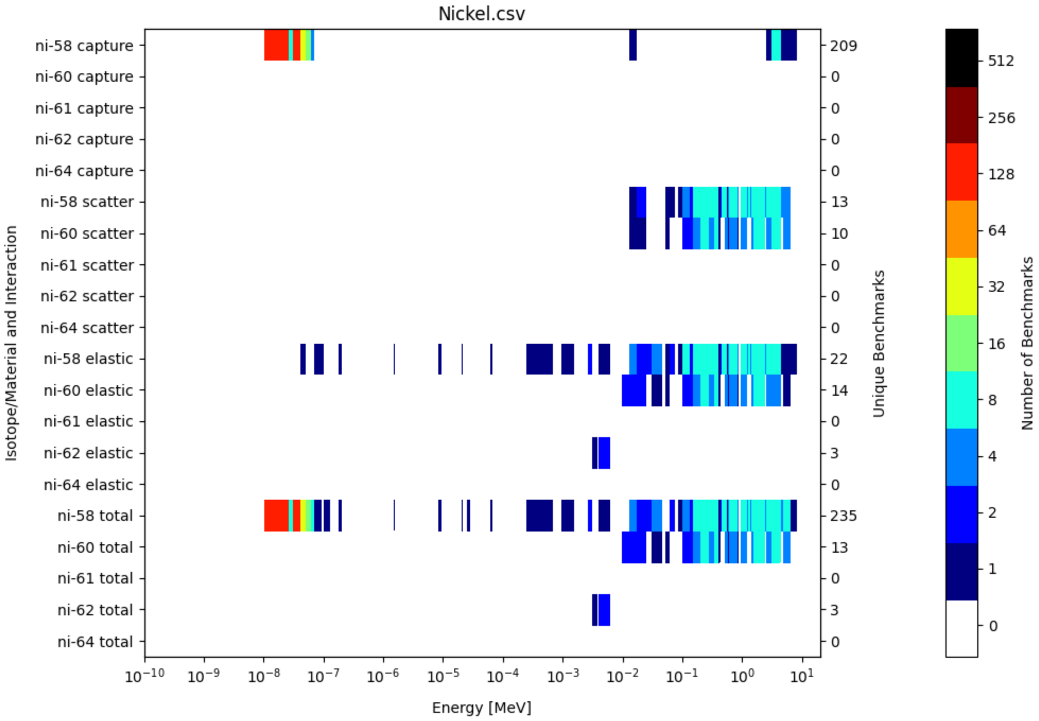
1. to train and validate the management of post-accident situations, such as management of re-entry and stabilisation for ongoing criticality accidents and the validation of post-accident devices (robots, etc.);
2. to design, validate and calibrate nuclear instruments (including radioprotection devices), reactor monitoring, CAAS response, accident detection for various kinetics (in free air or behind shielding) and exercises for accident dosimetry intercomparison;
3. to study radiobiology, physical, and biological dosimetry of mixed g/n irradiations;
4. to study the link between the number of fissions and doses (+ attenuation effect);
5. to study the release of the FP;
6. to improve the knowledge in prompt and delayed gammas;
7. as an experimental tool in neutron physics, such as studies of generation time, features of delayed neutrons, fission yields, branching ratios, temperature effects, critical and subcritical experiments (new fuels [Pu, MOX], minor actinides, structural material, matrix, neutron poison, BUC, etc.), reactivity measurements (perturbation), random neutron physics (neutron noise technique) and neutron and gamma intrinsic sources (neutron initiation experiments).

2.3.4. Priority 3 needs

Structural materials: Ni

Nickel is a commonly used structural material, often found as the main alloying agent in stainless steels. Two survey forms outlining experimental needs for nickel as a thermal neutron absorber were submitted. While there are many critical experiments that contain Ni (mainly as a component of steel), as shown in Figure 8, the existing ICSBEP benchmarks are inadequate to assess the weak absorption provided by Ni at thermal energies due to their low sensitivity. The nuclear criticality safety evaluations supporting many US liquid waste processing operations currently credit the presence of neutron absorbers, including Ni, in large, geometrically unfavourable liquid waste storage tanks to preclude criticality (Kersting and Losey, 2018) Ni is not a traditional strong neutron absorber (such as boron, gadolinium), but is instead a weaker absorber that was disposed in the tanks along with the fissile material.

Figure 8. ICSBEP sensitivity heat map for nickel isotopes

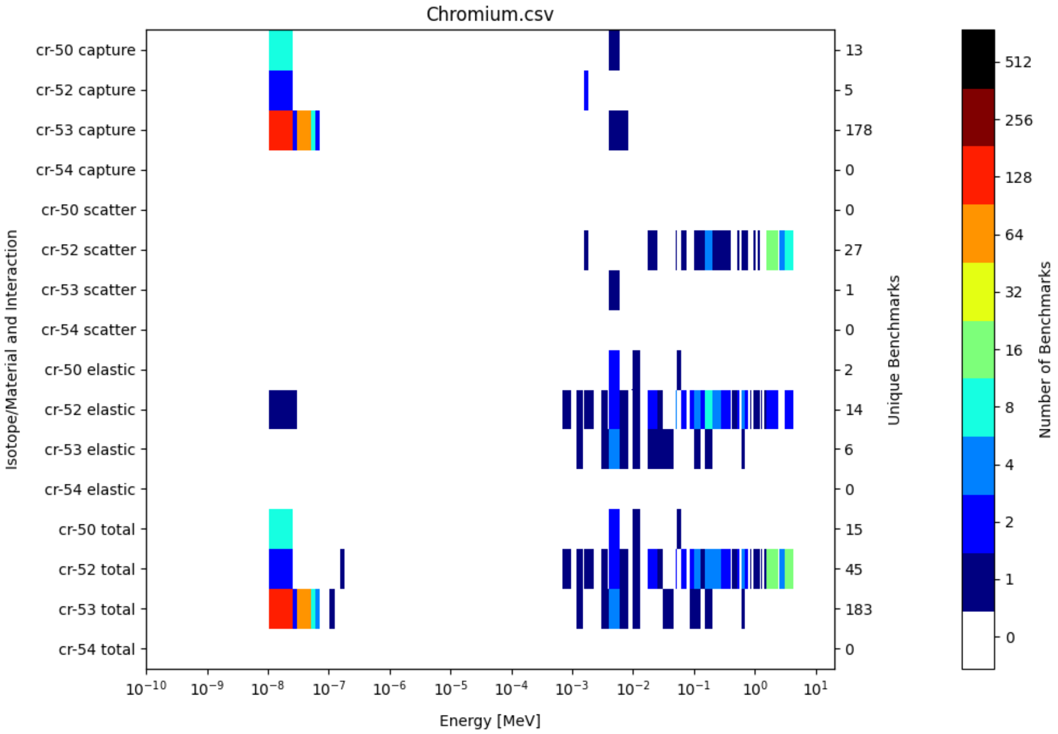


Source: NEA data, 2022.

Structural materials: Cr

Chromium is a commonly used structural material, often found as the main alloying agent in steel. Two survey forms outlining experimental needs for chromium were submitted. While there are many critical experiments that contain chromium (mainly as a component of steel), there are few experiments that are sensitive to chromium cross sections, particularly in the intermediate energy regime, as shown in Figure 9. The existing ICSBEP benchmarks are inadequate to assess the weak absorption provided by Cr at thermal energies due to their low sensitivity. Cr is not a traditional strong neutron absorber (such as boron, gadolinium), but is instead a weaker absorber that was disposed in the tanks along with the fissile material. The nuclear criticality safety evaluations supporting many US liquid waste processing operations currently credit the presence of neutron absorbers including Cr in large, geometrically unfavourable liquid waste storage tanks to preclude criticality (Kersting and Losey, 2018). An additional need for Cr in the intermediate energy region would be used to assess resonance capture by Cr, especially in Fe/Cr alloys.

Figure 9. ICSBEP sensitivity heat map for chromium isotopes

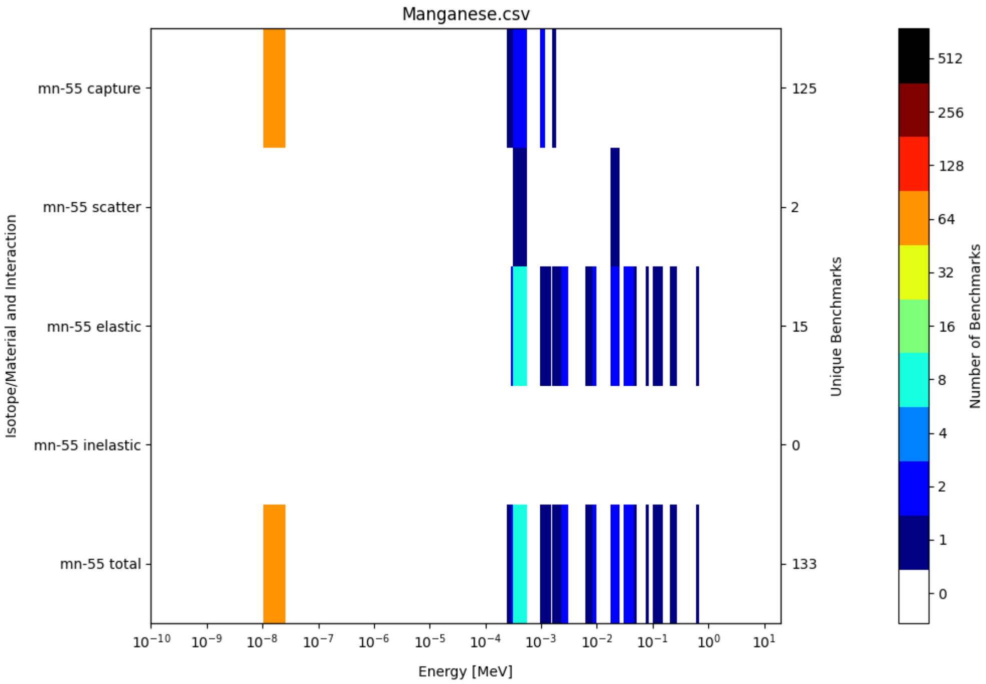


Source: NEA data, 2022.

Structural materials: Mn

Manganese is a commonly used structural material and is thus often analysed as part of a criticality safety evaluation. There are some critical benchmarks that have sensitivity to Mn, as shown in the plot in Figure 10. However, the existing ICSBEP benchmarks are inadequate to assess the weak absorption provided by Mn at thermal energies due to their low sensitivity. Mn is not a traditional strong neutron absorber (such as boron or gadolinium), but is instead a weaker absorber that was disposed in the tanks along with the fissile material. The nuclear criticality safety evaluations supporting many US liquid waste processing operations currently credit the presence of neutron absorbers in large, geometrically unfavourable liquid waste storage tanks to preclude criticality (Kersting and Losey, 2018).

Figure 10. ICSBEP sensitivity heat map for manganese isotopes

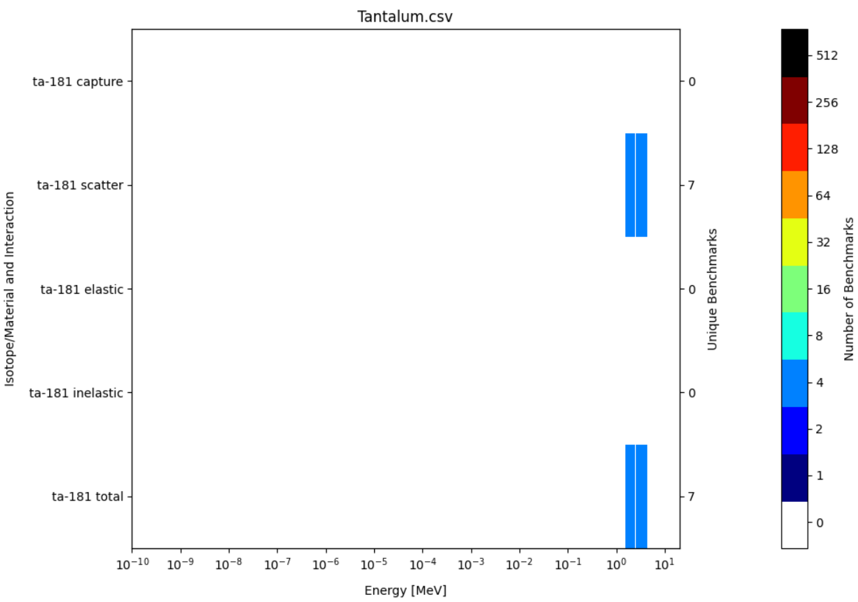


Source: NEA data, 2022.

Structural materials: Ta

Tantalum is a metal that has specialised uses in high-temperature nuclear operations, including as the material of construction of crucibles used for plutonium reprocessing. There are very few benchmarks that are sensitive to Ta, as shown in Figure 11. The main interest from a criticality safety perspective is as a reflector in a fast neutron energy spectrum.

Figure 11. ICSBEP sensitivity heat map for tantalum isotopes



Source: NEA data, 2022.

Structural materials: F

Fluorine is a key element for molten salt reactors, where fluorine is present in the fuel as well as in the moderator. Generally, k_{eff} is not sensitive to the fluorine in the fuel but can be very sensitive to the fluorine in the moderator, for example hydrogen fluoride (HF).

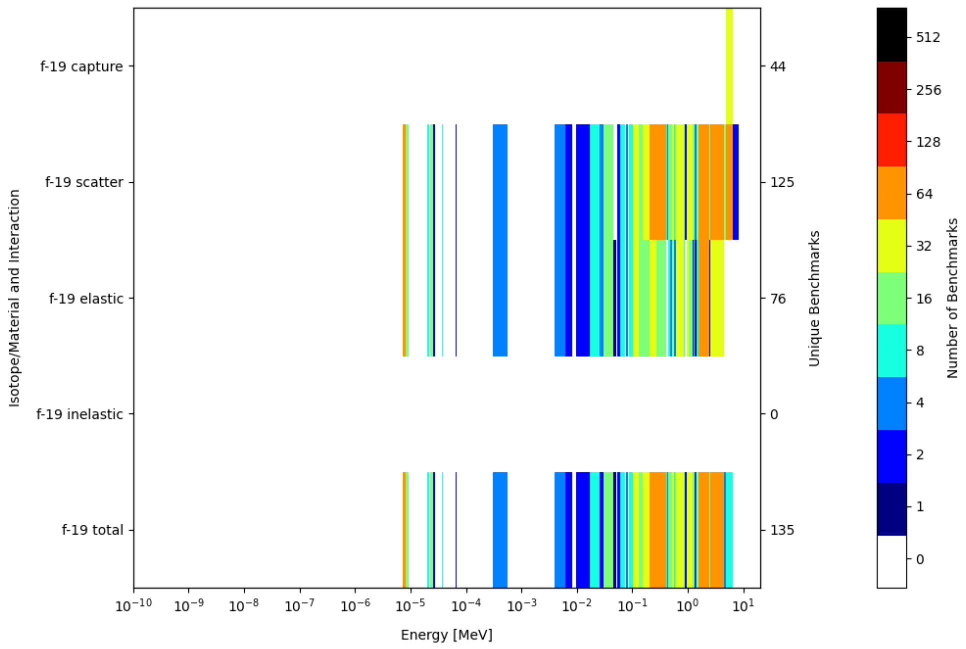
Fluorine is also encountered during fuel fabrication in the enrichment and conversion to UO_2 steps. During the enrichment step, uranium is chemically in the form of UF_6-HF and UO_2F_2 (in case of water introduction). During the conversion step, it is in the form of UO_2F_2. Motivated by these operations, the Institute for Radiological Protection and Nuclear Safety (IRSN) initiated a new evaluation of fluorine cross sections. However, few experiments (only two series) with UO_2F_2 are available in the ICSBEP Handbook as shown in Figure 12 (NEA, 2020); their sensitivities to the cross sections of fluorine are low and one of them exhibits a potential experimental bias since it shows a large overestimation of k_{eff} for all codes and nuclear data libraries. Only one experiment with UF_6-HF sensitive to the cross sections of fluorine is known in the ICSBEP Handbook and the same conclusion can be drawn as for UO_2F_2 experiments: a very large discrepancy between calculated k_{eff} and the benchmark k_{eff} is seen and an experimental bias cannot be excluded.

Other application fields where fluorine can impact criticality safety are storage, reprocessing and criticality accident studies.

As a consequence, there is a need for experiments with UF6-HF that cover the thermal, epithermal and fast energy ranges in terms of k_{eff} sensitivity to nuclear data. Capture and scattering cross sections of fluorine as well as TSL of H-HF and F-HF should be tested with such experiments. Additionally, leakage spectra from suitable fluoride with well-defined pointwise source (^{252}Cf) may also help in looking for bugs in evaluation.

A recent experiment was completed in the United States that can partially meet the experiment need, mainly in the unresolved resonance region and faster energies. The Critical Unresolved Region Integral Experiment (CURIE) was a measurement campaign performed at National Criticality Experiments Research Centre (NCERC) in 2020. It used alternating plates of polytetrafluoroethylene (PTFE), also known as Teflon, and the highly enriched uranium (HEU) Jemima plates reflected by copper, assembled on the Comet critical assembly machine. The main purpose of the experiment was to interrogate the unresolved resonance region of ^{235}U. The CURIE experiments are also sensitive to fluorine in the intermediate and fast energy spectrum. Work on the ICSBEP benchmark for CURIE is still underway, so the final benchmark results are still not available. Testing of the draft benchmark input file using different nuclear data libraries (ENDF/B-VIII.0, ENDF/B-VII.1, JEFF-3.3, JENDL-4.0u) has yielded large differences in k_{eff}, particularly for the Japanese Evaluated Nuclear Data Library (JENDL-4.0u) when changing only fluorine nuclear data libraries. Since CURIE does not cover the thermal energy region, additional experiments may be needed for the thermal and low epithermal region.

Figure 12. ICSBEP sensitivity heat map for fluorine isotopes



Source: NEA data, 2022.

Slab- or plate-type fuels

Slab- or plate-type fuels have shown to be important to resolving calculational biases for fuel cycle facilities and research reactors such as the Jules Horowitz material testing Reactor (JHR), under construction at the French Alternative Energies and Atomic Energy Commission (CEA) in Cadarache, France. JHR fuel will be U_3Si_2 dispersed into an aluminium matrix, with a uranium density of 4.8 g U/cm^3 and a ^{235}U enrichment varying from low-enriched uranium (LEU) up to a maximum ^{235}U enrichment of 27% optimising the loading of the reactor.

Slab- and plate-type fuels are mainly used in research reactors. These fuels are composed of uranium enriched (from LEU to HEU) inside metal matrices (Si, Al, Mo, etc.). The main difficulty is encountered during the fuel fabrication because the thickness of the plates, the distance between plates (moderation ratio) and the nature of the moderator (water, polyethylene, alcohol, etc.) vary according to the steps of the process.

The main interest from a criticality safety perspective is an experiment in a thermal and epithermal spectrum with LEU or intermediate enriched uranium (IEU).

TSL for HF

Hydrofluoric acid is encountered in criticality safety during the enrichment step of fuel fabrication where uranium is chemically in the form of UF_6-HF. Only one experiment with UF_6-HF and sensitive to the cross sections of fluorine is known in the ICSBEP Handbook and a large discrepancy between calculated k_{eff} and the benchmark k_{eff} can be pointed out. Enrichment operation validation was a motivation for the IRSN to initiate a new evaluation of fluorine cross sections and look at a new evaluation of the TSL of H-HF and F-HF using existing experimental data and molecular dynamics simulations. Moreover, as the discrepancy between the calculated k_{eff} and the benchmark k_{eff} is large, an experimental bias cannot be excluded. A potential experimental bias in the only existing integral data provides justification for new experiments involving the same fissile medium in thermal and intermediate energy spectra and for which k_{eff} would be sensitive to the capture, scattering cross sections of F, and to the TSL of HF.

Low temperature

The lack of low temperature benchmarks for criticality calculation validation and nuclear data testing is recognised internationally. At the recent ICNC in September 2019, papers from the United Kingdom (Watson, 2019) and France (Milin, 2019) highlighted the lack of validation data for low temperature calculations, with a specific application of nuclear material transport. The IAEA's Regulations for Safe Transport of Radioactive Materials, SSR-6, echoes the US 10 CFR 71 requirements requiring packages be analysed to -40°C. The WPNCS convened a working group to complete an inter-code comparison calculational benchmark focused on the effect of temperature on the neutron multiplication of pressurised water reactor fuel assemblies in water. Substantial interest was generated in the benchmark, as 12 institutions from 9 countries participated. As reported by a paper given at ICNC (Gan and Wilson, 2019), differences in the k_{eff} prediction between nuclear data libraries were found and were especially notable for JENDL-4.0, but without an experimental benchmark it was difficult to determine the most appropriate data for low temperature applications. Benchmarks at temperatures below room temperature are needed to fill this gap down to -40°C for many materials, including plutonium, uranium, common moderator materials (water/ice, polyethylene) and common structural materials.

Additional low temperature needs arise from space applications, as temperatures can be as low at 2 K in outer space. Simulations have shown that when a thin ^{235}U foil is surrounded by a low absorbing moderator and reflector materials (such as heavy water) and their temperature lowered to 4 Kelvin, the fission process is greatly enhanced. Simulations have yielded critical masses on the order of 35 to 70 grams of uranium. The reason for this dramatic decrease in the critical mass is that the fission cross-section increases from 580 barns for thermal neutrons to 3 000 barns for neutrons having energies of 0.001 eV (cold neutrons or neutrons in a low temperature [4 Kelvin], low absorbing moderator/reflector). However, no integral benchmarks exist at these temperatures to test the validity of these predictions.

High temperature

Though it is well known that k_{eff} is sensitive to temperature, historically the larger safety margins and conservative approaches used in criticality safety evaluations have limited the interest for temperature-sensitive benchmarks. However, it has more recently become evident that there is a strong need for more accurate predictions of the temperature sensitivity of k_{eff} and other parameters. The range of applicability essentially covers all parts of the nuclear fuel cycle and beside subcriticality it is important for predicting criticality excursions (including accidents). Specific applications of interest are transport conditions (up to 800°C) and storage pools for irradiated nuclear fuel (up to 120°C without boiling), including under excessive water moderation conditions (e.g. checker-board patterns with water holes or specific flux traps) that can result in large k_{eff} increases with temperature. ^{238}U is important for the Doppler effect in low-enriched uranium. Since both UO_2 fuel and MOX fuel are involved in these applications, ^{235}U, ^{239}Pu and ^{240}Pu are also involved. A gadolinium (Gd) burnable absorber, integrated with the fuel, is a factor that affects temperature-dependence. This also applies to the effects of control rods containing boron and soluble boron in the moderator is another parameter of criticality safety interest. The most important medium is pressurised water from room temperature up to 250°C, where up to about 120°C without boiling may be credible with pressure provided by the depth of fuel storage pools. The thermal scattering law data for this temperature range require validation to allow predictive calculations to be trusted.

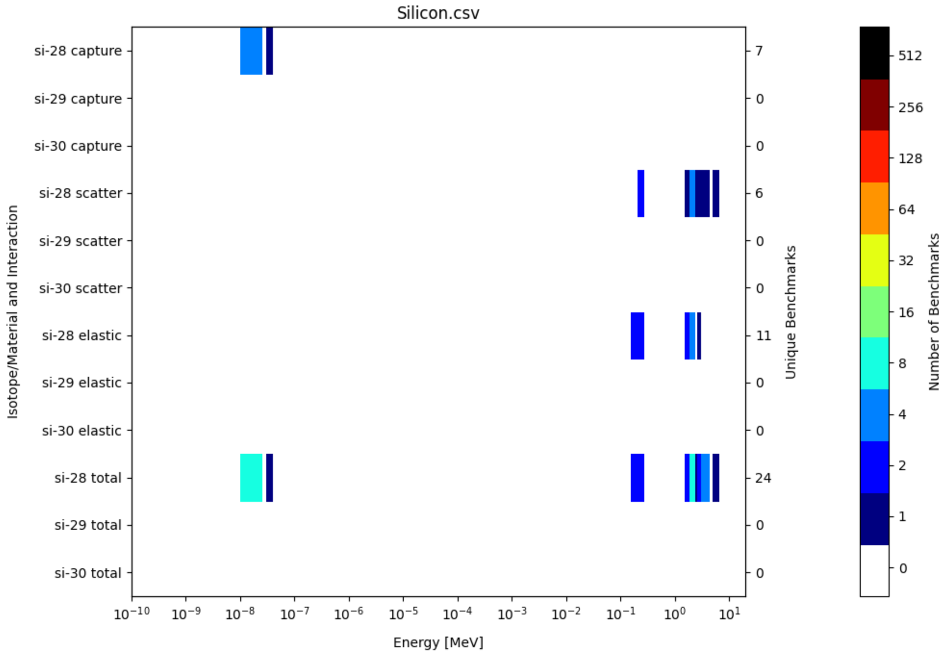
There are few benchmarks in the ICSBEP Handbook that cover these temperatures and different fuel designs. A survey of the current ICSBEP Handbook lists only 43 experiments conducted at a temperature above 20°C. Proprietary measurements and benchmarks from power reactor start-ups from room temperature, primarily boiling water reactors (BWRs) as well some research reactor measurements, are available. The ideal experiments would include fuel, moderator and absorber materials in designs that are representative of real light water reactor fuel rods and assemblies under normal and abnormal conditions. All temperatures below “hot” reactor operating conditions are of interest. Changing as little as possible between measurements at different temperatures allows for a reduction in the uncertainties of the relative effects (cancellation of unknown absolute uncertainties). The temperature effect can then be determined with high accuracy even if the absolute uncertainty of a single measurement is larger. Experiments with partial density water are also of interest as many applications involve analysis over the full range of water densities.

2.3.5. Priority 2 needs

Structural materials: Si

Silicon is a commonly found element as SiO_2 in concrete and is often included as part of a criticality safety evaluation. There are a few critical benchmarks that have sensitivity to Si, as shown in the plot in Figure 13. However, the existing ICSBEP benchmarks are inadequate to assess weak absorption provided by Si at thermal energies due to their low sensitivity. The nuclear criticality safety evaluations supporting many US liquid waste processing operations currently credit the presence of neutron absorbers, including Si, in large, geometrically unfavourable liquid waste storage tanks to preclude criticality (Kersting and Losey, 2018). Si is not a traditional strong neutron absorber (such as boron or gadolinium), but is instead a weaker absorber that was disposed in the tanks along with the fissile material.

Figure 13. ICSBEP sensitivity heat map for silicon isotopes

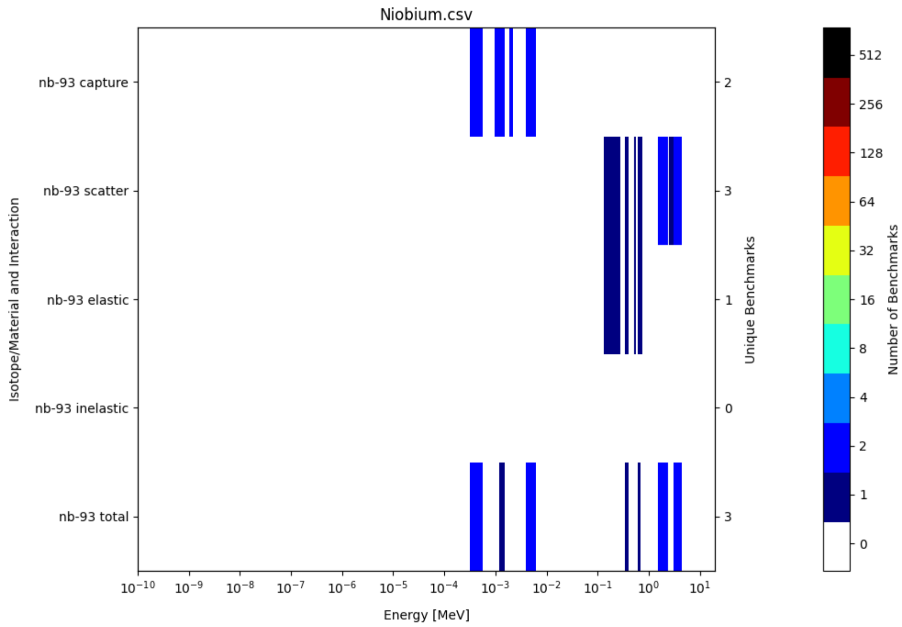


Source: NEA data, 2022.

Structural materials: Nb

Niobium is a metal that has specialised uses in nuclear operations, including as the material of construction of dissolver vessels for plutonium reprocessing. There are few benchmarks that are sensitive to Nb, as shown in Figure 14. The main interest from a criticality safety perspective is as a reflector over the entire neutron energy spectrum.

Figure 14. ICSBEP sensitivity heat map for niobium isotopes



Source: NEA data, 2022.

Structural materials: W

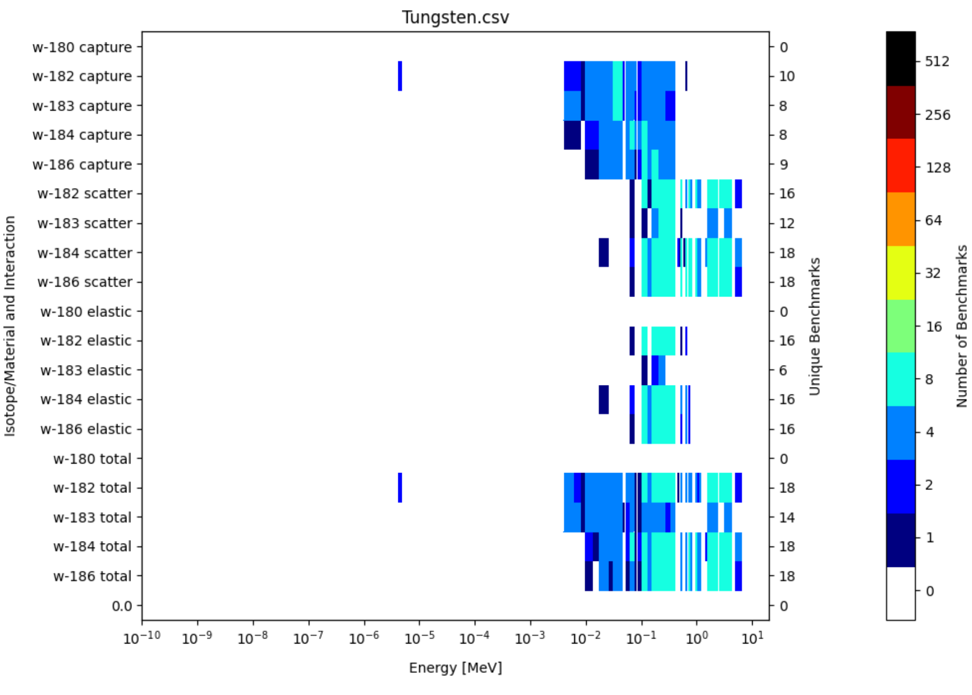
Tungsten is a high-density metal used in laboratory operations such as hot labs/cells in order to protect electrical and electronic devices from high levels of radiation and therefore a premature ageing of the materials. It is also used as a collimator for various counting devices/detectors in place of lead.

In the criticality safety studies of such configurations, the theoretical fissile media could be ^{239}Pu or ^{235}U combined with an upper criticality mass and/or moderation limit. In the former case, the neutron spectrum is largely thermal whereas in the latter case it is epithermal. Configurations with non-moderated fissile media are unusual, if not totally excluded, because the facility must perform a strict moderator exclusion. That is impossible, at least in the CEA facilities.

In this context, and following a conservative criticality safety approach, tungsten (W) is used as a reflector in the criticality safety demonstration studies for very neutron-thermal to epithermal configurations.

There are approximately 20 experiments that are sensitive to W, mainly in the fast spectrum, as shown in Figure 15. The main interest from a criticality safety perspective is as a reflector over thermal to epithermal neutron energy spectrums.

Figure 15. ICSBEP sensitivity heat map for tungsten isotopes



Source: NEA data, 2022.

TSL: PMMA

Polymethyl methacrylate (PMMA), with the chemical formula $C_5O_2H_8$ and commonly called Lucite or Plexiglas, is a common moderator material often used to approximate water in critical experiments because of its similar hydrogen density. Work done at the Rensselaer Polytechnic Institute in the United States identified only five ICSBEP benchmarks as being potentially sensitive to Lucite thermal scattering, with a maximum sensitivity of approximately 1.5% difference between Lucite thermal scattering in ENDF/B-VIII.0 and the free gas approximation (Danon, 2018). The ENDF/B-VIII.0

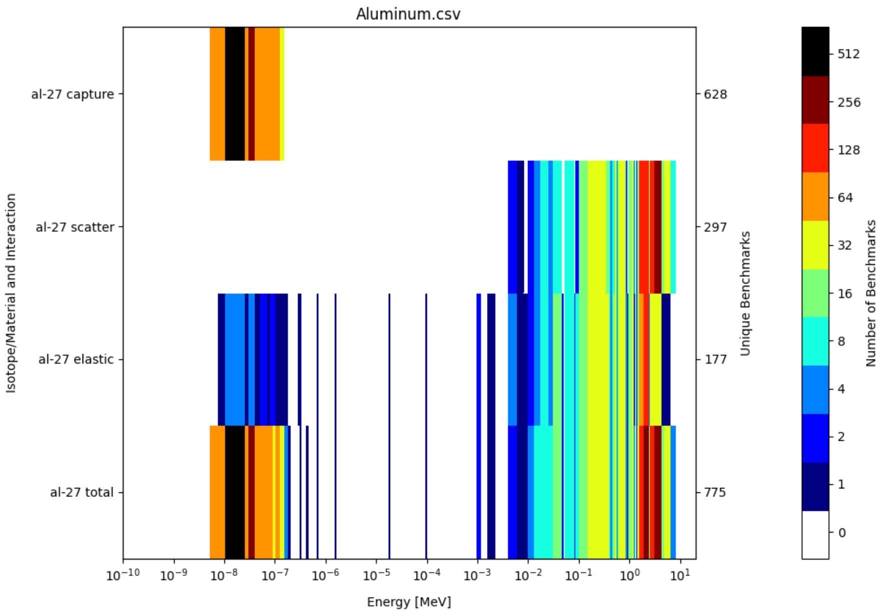
release was the first library to include a TSL for PMMA, and integral experiments are needed to validate the new data (Brown et al., 2018).

2.3.6. Priority 1 needs, lowest priority

Structural materials: Al

Aluminium is a commonly used material in nuclear operations, including as a fuel cladding material for nuclear reactor fuel. There are many critical benchmarks that have sensitivity to Al, as shown in the plot in Figure 16. However, the existing ICSBEP benchmarks are inadequate to assess weak absorption provided by Al at thermal energies due to their low sensitivity. The nuclear criticality safety evaluations supporting many US liquid waste processing operations currently credit the presence of neutron absorbers, including Al, in large, geometrically unfavourable liquid waste storage tanks to preclude criticality (Kersting and Losey, 2018). Al is not a traditional strong neutron absorber (such as boron or gadolinium), but is instead a weaker absorber that was disposed in the tanks along with the fissile material. There is also an additional need for intermediate neutron spectra systems reflected by aluminium, which could be used to validate aluminium scattering cross section systems relevant to criticality safety, including storage arrays and within transport casks.

Figure 16. ICSBEP sensitivity heat map for aluminium isotopes

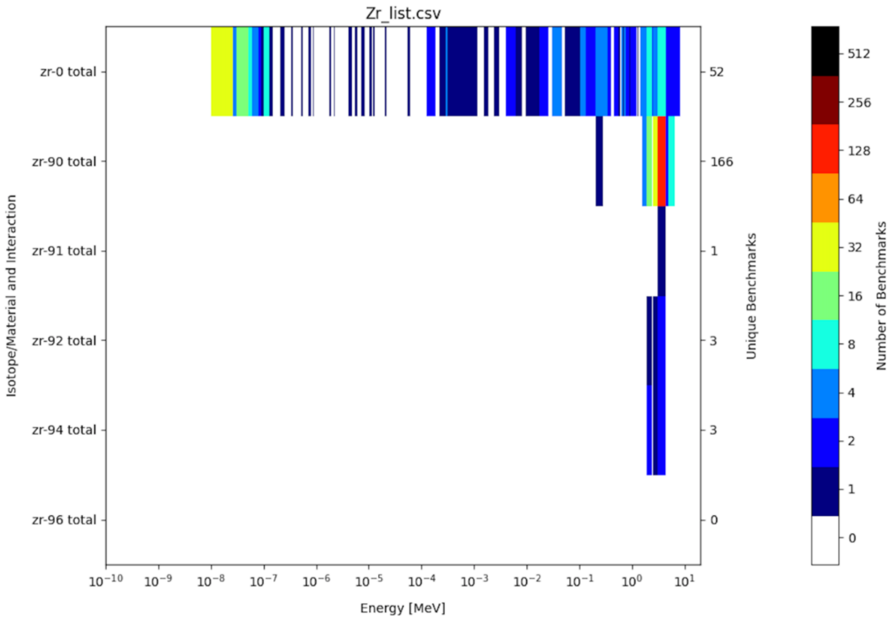


Source: NEA data, 2022.

Structural materials: Zr

Zirconium is commonly used as a fuel cladding material for nuclear reactor fuel. There are a few critical benchmarks that have sensitivity to Zr, as shown in the plot in Figure 17. The existing ICSBEP benchmarks are inadequate to assess weak absorption provided by Zr at thermal energies due to their low sensitivity. The nuclear criticality safety evaluations supporting many US liquid waste processing operations currently credit the presence of neutron absorbers, including Zr, in large, geometrically unfavourable liquid waste storage tanks to preclude criticality (Kersting and Losey, 2018). Zr is not a traditional strong neutron absorber (such as boron or gadolinium), but is instead a weaker absorber that was disposed in the tanks along with the fissile material.

Figure 17. ICSBEP sensitivity heat map for zirconium isotopes



Source: NEA data, 2022.

2.4. Existing proprietary experiments

2.4.1. VENUS

VENUS-T

VENUS was originally a thermal, water-moderated, zero-power reactor that served to support pressurised water reactors (PWRs) and BWRs between 1964 and 2007 with sets of UO_2 (4% enrichment) and MOX (1-12% enrichment) fuel pins. Parameters measured at VENUS-T included the critical water level, reactivity coefficient of the water level, reactivity effects, axial and horizontal fission rate distribution, spectrum indices and kinetic parameters.

VENUS-T experimental programmes:

- 1964-1966: Mock-up BR3 VULCAIN (spectral shift reactor);
- 1967-1978: Pu recycling in light water reactors (LWRs); 27 studied configurations;

- 1982-1988: LWR PV Surveillance Programme (VENUS-1, Fresh PWR Reference Core, VENUS-2, Low Leakage Core, VENUS-3, PLSA Core);
- 1990-2000: MOX licensing programmes (VIP licensing, VIPO safety, VIPEX plant operation, NBN - licensing BWR, IMP weapon grade Pu);
- 2001-2006: VENUS with 100 cm fuel pins (Burn-up Credit investigation, REBUS-PWR, REBUS-BWR).

Among a large number of experiments, several international benchmarks were published, including on predictions of neutron embrittlement in the reactor pressure vessel (NEA, 2000), and mixed oxide fuel core experiments (NEA, 2003; NEA, 2005; Longoni et al., 2006; Baeten et al., 2008). A database for the validation of reactor physics codes for the calculation of the loss of reactivity due to burn-up for PWR fuel (burn-up credit), both for UO_2 and MOX fuel bundles, was established in mock-up experiments (REBUS) (Danon, 2018). All fuel pins and materials of the VENUS-T vessel are still available.

VENUS-F

In order to support the Multi-purpose HYbrid Research Reactor for High-tech Applications (MYRRHA) accelerator-driven system (ADS) design, VENUS-T was transformed into the fast neutron facility VENUS-F with solid core components (Pb, Bi, SS, Al_2O_3, C-12, U 30%) within the GUINEVERE programme (2008-2011) (Kochetkov et al., 2017). Since then the facility has served to develop and validate a method for subcriticality measurement for MYRRHA in the frame of three projects funded by the European Commission: FREYA (2011-2015) (Kochetkov et al., 2018), MYRTE (2016-2017) (Kochetkov, Wagemans and Vittiglio, 2011) and MYRACLE (2017-2019). Also, ten critical VENUS-F configurations were investigated in the frame of these projects, devoted to nuclear data and codes validation of fast Pb and Bi cores (Kochetkov et al., 2016; Krása, et al., 2017; Kochetkov, 2016; Fridman, Kochetkov and Krása, 2017; Sarotto et al., 2018; Barbry et al., 2003; Leclaire, Duhamel and Le Dauphin, 2011). These configurations varied in the number of fuel assemblies (FA) in the core, FA composition, reflector material and presence of mock-ups of in-pile sections (IPS) in the core. The programmes of the measurements included: criticality, kinetic parameters, spectral indices, fission rates distributions, reactivity effects of coolant and IPS void, fuel Doppler, fuel agglomeration, water penetration in the core, fuel assemblies and structural materials. These results have not yet been fully evaluated following the ICSBEP or International Reactor Physics Experiments Database (IRPhE) standards. However, since most of them are proprietary, they are not currently planned to be submitted to the handbooks.

2.4.2. Valduc

Haut taux de combustion (HTC) and Fission Products Programme

More than 2 000 critical experiments were conducted at the CEA Valduc Centre for Nuclear Studies from 1963 to 2013 (Loaiza and Gehman, 2006). Among them, 800 experiments from about 50 series were included in the ICSBEP Handbook of critical experiments. These experiments were carried out on various experimental devices (Apparatus B, C, D, MARACAS, etc.) covering a wide range of application cases, fissile media and energy spectra and followed the validation needs along with the expansion of nuclear fuel cycle applications in France. That is the reason why two specific programmes were launched at the end of the 1980s. With the progressive growth of the ^{235}U enrichment of UO_2 fuel in nuclear facilities up to 4.5%, it was necessary to take into account the credit of burnt fuel for justifying the subcriticality of nuclear installations.

As a result, a first experimental programme called HTC in French, or high burn-up in English, dedicated to the validation of actinides, which represent a major part of the anti-reactivity brought by actinides and Fissions Products (9 100 pcm for a 17 × 17 PWR), was realised in 1988-1991. It involved 2 500 HTC rods manufactured in Germany, simulating fuel burnt up to a 37.5 GWd/t burn-up but without FPs. The content in plutonium was equal to 1.1 wt%. The content of plutonium in ^{240}Pu was set equal to 24.3 wt% and uranium was enriched to 1.57 wt% in ^{235}U. Four phases with lattices of HTC rods were defined:

- a first one (18 cases), where the HTC rods were immersed in pure water with a variable moderation ratio;
- a second one (41 cases), where the HTC rods were immersed in borated water or in water poisoned by gadolinium with a variable moderation ratio; the concentration in boron varied between 0.09 g/L and 0.5 g/L; the concentration in gadolinium varied between 0.02 g/L and 0.5 g/L;
- a third one (26 cases), where four lattices of HTC rods in absorbing canisters (Boral, Cd, borated steel) were immersed in water; the moderation ratio was variable;
- a fourth one (71 cases), where four lattices of HTC rods in absorbing canisters (Boral, Cd, borated steel) were reflected by lead (10 cm) or stainless steel (15 cm) in water; the moderation ratio was variable;
- a fifth one (49 cases), where two or four lattices of HTC rods were in interaction configuration.

The HTC programme encompassed 210 experimental cases and some reproducibility cases.

Following the HTC programme, the FPs programme aimed at validating the anti-reactivity worth of six FPs representing half of the total anti-reactivity worth of all FPs (around 6 000 pcm) in the thermal energy spectrum. A test zone was created at the centre of the configuration with a tank containing a solution of FPs. This tank was surrounded by a driver lattice of Valduc U(4.738%)O_2 rods. These FPs (^{103}Rh, ^{133}Cs, ^{143}Nd, ^{149}Sm, ^{152}Sm, ^{155}Gd) were non-volatile and stable. Four phases corresponding to a progressive validation of FPs were defined.

In the first phase, called “physical type” (45 cases), FPs were dissolved one by one or in a mixture in an acidic solution in a small tank (6.2 cm × 6.2 cm). The aim was to validate the cross sections of FPs in the thermal energy spectrum.

In the second and third phases, called “Elementary Dissolution” (89 cases), FPs were dissolved in an acidic solution or in a uranyl nitrate solution in a larger tank (14.3 cm × 14.3 cm) that also hosted UO_2 of HTC rods. The idea was to be more representative of reprocessing plant dissolvers, with a partial dissolution of rods in the nitrate solution and to validate the physical models dealing with the overlap of resonances implemented in the APOLLO2 code.

In a fourth phase, called “Global Dissolution” (14 cases), no more internal tank was used. FPs were dissolved directly in the driver lattice of UO_2 or HTC rods. This configuration is fully representative of a reprocessing plant dissolver at an advanced step when compared with previous phases.

The FP programme gathered a total of 148 experiments that were performed from 1998 to 2004 at the CEA Valduc Centre for Nuclear Studies. Some reference experiments without FPs were defined and can help highlight the bias introduced by FPs in the configurations using dedicated methodologies for exhibiting nuclear data biases.

Both programmes were co-financed by the Compagnie générale des matières nucélaires (COGEMA), now ORANO, in the framework of a common programme of interest (PIC). These programmes have been evaluated following the ICSBEP standard. The experimental uncertainties were assessed and propagated in terms of Δk_{eff}. However, since they are proprietary, they were not submitted to an ICSBEP review and cannot be found in the ICSBEP Handbook.

MIRTE 2.2

The two experiments of the MIRTE 2 programme involve two screens made of proprietary resins of BORA and VYAL-B separating two lattices of U(4.738%)O_2 rods at a 1.6-cm square pitch. These resins are mixtures of polyvinyl resins, zinc borate and aluminium hydrate. Their composition is confidential since the experiments are subject to a non-disclosure agreement with AREVA NC (now ORANO) until 2029. They are respectively 20 mm and 40 mm thick.

MIRTE 2.3

The MIRTE experimental programme focuses on the validation of structural materials in various reflecting and interacting configurations. In its MIRTE 1 and MIRTE 2.1 and MIRTE 2.2 phases, the structural materials of the MIRTE programme took the shape of thin screens (interacting configuration) or thick screens (interacting and reflecting configurations). The objective was that k_{eff} be sensitive to the capture and scattering cross sections of the materials in the thermal energy spectrum.

The MIRTE 1, MIRTE2.1 and MIRTE 2.2 programmes corresponded to a selection of materials that could meet the needs of criticality safety practitioners. The experiments of the programme are public and delivered in the ICSBEP Handbook.

In 2013, before the shutdown of the Valduc criticality laboratory, experiments were conducted on Apparatus B with a view to test structural materials in epithermal energy spectrum. These experiments were performed in the framework of the MIRTE Programme (McClure et al., 2020). They involved sleeves of copper or stainless steel surrounding Valduc U(4.738%) rods in a test zone surrounded by a driver lattice of Valduc U(4.738%)O_2 rods. The test zone was either in water or in an aluminium box pierced with holes hosting the Valduc sleeved rods. This configuration has the advantage of showing higher sensitivities of k_{eff} to the capture cross sections of copper and iron in an epithermal energy range than previous MIRTE experiments. The sensitivity in the epithermal energy range could unfortunately not be increased, partly due to the limitation of UO_2 rods (1 261) available at Valduc. Reproducibility experiments were also realised to ascertain the experimental uncertainties determined by calculation. Reference experiments without sleeves were also performed. All in all, the programme comprises six cases. The experiments were financed through a PIC by AREVA NC (now ORANO) and should be made available in the ICSBEP Handbook in 2022.

2.4.3. CEA Cadarache, EOLE and MINERVE

CEA contributed to the study of reactor physics by designing and performing integral experiments for the experimental validation of neutron calculation tools, protection (gamma and neutron attenuation in materials), and basic nuclear data on three critical mock-ups at Cadarache: EOLE (PWR and BWR spectra), MINERVE (all types of spectra), and MASURCA ("fast" and accelerator-driven lattice spectra). Despite their sometimes unique features, all three facilities were definitively shut down in 2017 and 2018 for safety issues related to reinforced earthquake requirements that were not achievable without costly refurbishment work. These critical mock-ups were low-power reactors. Their neutronic behaviours can be directly extrapolated with physical phenomena encountered in power reactors (to a close representativity factor). In EOLE, the experiments conducted have always been designed in such a way that the C/E (calculation/experimentation) deviation is directly the calculation error that would be obtained in the industrial application (representativity factor of the mock-up r = 1 as it used the same fuel and the same geometry as PWR and BWR assemblies).

EOLE ZPR and associated programmes

The EOLE zero power facility went critical in December 1965. The facility comprised a reactor block offering biological shielding for operation with a flux level up to 109 n cm-3 s-1 in the core. The regulatory limit was 100 W.

In this structure, an aluminium (AG3) tank of approximately 2.3 m in diameter and 3 m high was built to receive all experimental structures that were renewed at each programme. All configurations were run with light water, in fully reflected conditions. The facility was coupled to a thermoregulation station able to control both boron concentration and water temperature on a large range of temperatures (5°C to 90°C). The criticality was maintained using a dedicated and adapted pilot rod.

The first experiments were dedicated to heavy water lattices for CEA purposes. In 1970 the EOLE facility changed from heavy water to light water applications. The programmes were as follows:

- 1978-1985: first LWR programmes for both experimental validation of calculation schemes for neutron absorber clusters (CAMELEON program), safety of PWR fuel storage (CRISTO-1, 2 and 3), temperature coefficients for uranium oxide (UOX) and MOX fuels in PWR hot conditions (CREOLE programme). The CREOLE programme was provided as an ICSBEP benchmark. This experiment allowed, for example, a precise form of the ^{235}U η factor to be obtained.
- 1985-1988: the ERASME programme studied under-moderated MOX lattices. Experimental data are potentially cross sections in epithermal spectra for Pu. Some k_{eff} measurements are included in the ICSBEP.
- 1989-2005: EOLE was mainly dedicated to plutonium recycling studies in light water reactors (PWR and BWR) through 4 first-of-a kind programmes: EPICURE for 30% MOX load, followed by MISTRAL (100% MOX load in PWR), BASALA and FUBILA (100% MOX load in BWRs). These unique programmes provided major data for MOX validation in both thermal and low epithermal spectra (through 30% to 100% void measurements).

From 2006, the programmes were mainly dedicated to mock-up neutron fluence in stainless steel reflectors and steel/water interfaces up to the reactor vessel, through the FLUOLE (2006-2007) and FLUOLE2 (2012-2015) experimental programmes.

In 2009-2010, the PERLE Programme experimentally validated stainless steel cross sections for heavy Gen-III reflectors. The PERLE feedback was mainly on the important reduction of uncertainties on ^{56}Fe nuclear data, in particular scattering data, and its inclusion in the JEFF-3 data library.

Until its definitive closure in December 2017, EOLE was used to consolidate JHR neutronic calculation options through a full mock-up of the JHR core (AMMON programme 2010-2012) and participated, with the EPILOGUE programme (2016-2017), in the experimental validation of the in-core instrumentation of the EPR™ Gen-III+ reactor.

MINERVE Reactor associated and programmes

The reactor was built in 1959 in Fontenay aux Roses (Paris) and moved to Cadarache in 1976, where it went critical again in 1977. It is a coupled core composed of two zones:

- The driver zone comprises material testing reactor (MTR) type aluminium/uranium alloy plate assemblies under water. It is surrounded by a graphite reflector.
- The experimental zone receives dedicated movable lattices introduced into a 70 × 70 cm² cavity in the centre of the driver zone. This experimental zone reproduces neutron spectra with light water lattices (MELODIE), under-moderated lattices (MORGANE-S and MORGANE-R), and fast lattices (ERMINE, based on MASURCA fast ZPR stockpile).

The reactor was submerged under 5 m of light demineralised water and controlled using four hafnium rods operating both in control and safety mode.

Definitively shut down in December 2017 together with EOLE (they shared the same building) for safety issues related to earthquake hazards, MINERVE was mainly used for thermal cross-section and resonance integral measurements, as well as for studies on plutonium recycling and uranium systems using the oscillation technique in closed and open loop system. It also served as an important tool for education and training activities for nuclear engineering Master students and French Navy operators.

- From 1959 to 1972, MINERVE was dedicated to the important neutron fast spectrum ERMINE Programme, where major neutron characteristics of Pu and U systems were investigated in k_∞=1 lattices: Doppler effects with heated samples, reactivity effects by substitution and oscillation of dedicated samples using local/global techniques for unfolding scattering effects from a global absorption measurement.
- From 1973 to 1993, several programmes for PWR were carried out (MELODIE and MORGANE), alternatively with fast ERMINE phases and complementing the CAMELEON and ERASME mock-up programmes made in parallel in EOLE (see previous paragraph).

From 1993 until the end of its lifetime, MINERVE was dedicated to major programmes that were of utmost importance for the JEFF community and the French industry. All programmes were done in the MELODIE PWR experimental lattice (loaded with either UO_2 or MOX fuel pins).

- Burn-up credit (1993-2001): this experimental programme stems from the growing interest for the consideration of fuel wearing in criticality safety between CEA and COGEMA (now ORANO). The aim was to optimise the various facilities of the cycle with respect to criticality safety constraints, more specifically the consideration of minor actinides and stable and non-gaseous absorber FPs, enabling significant improvements in facilities dimensioning for transportation or fuel reprocessing.

- CERES Programme (1992-1995): from collaboration between the research centres at Winfrith and Cadarache, as part of the official CEA/UK Atomic Energy Agency (UKAEA) collaboration on water reactors. Its objective was to provide an experimental benchmark for the validation of nuclear data (in particular JEF2.2) on actinides and on FPs used to calculate fuel burn-up and for criticality studies. Experiments were conducted in the DIMPLE reactor at Winfrith and MINERVE reactor at Cadarache based on common samples manufactured at Cadarache. The sample comprised bot fresh UO_2 and MOX, and burnt UO_2 samples (from 20 to 60 GWd /t).
- High Burn-Up (HTC) Programme (2003-2004): reactivity analysis combined with isotopic analysis of high burnt UO_2 and MOX PWR samples (up to 6 cycles).
- Oscillation in Minerve of isotopes in Eupraxic Spectra (OSMOSE) Programme (2005-2008): the experimental programme was designed within the framework of CEA/Électricité de France (EDF) joint work. It has also been the subject of I-NERI collaboration between the US Department of Energy (DoE) and CEA since 2001. It complemented the burn-up programmes, providing specific experimental data (absorption cross sections) on heavy nuclei: ^{232}Th, 233U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{244}Cm and ^{245}Cm. The experiments were made in both epithermal and very thermal (dissolver) spectra.
- OCEAN Programme (2005-2008): it completed the OSMOSE programmes for the main absorbers and FPs in various spectra by providing specific experimental data (capture cross sections) on the following isotopes: ^{155}Gd, ^{157}Gd, Gd-nat, ^{177}Hf, ^{178}Hf, ^{179}Hf, ^{180}Hf, ^{166}Er, ^{167}Er, ^{169}Er, ^{170}Er, ^{160}Dy, ^{161}Dy, ^{162}Dy, ^{163}Dy, ^{164}Dy, ^{151}Eu, Eu-nat, ^{153}Eu.

From 2010, MINERVE served as a reference benchmark for developing innovative instrumentation or revisiting experimental techniques, such as neutron noise, or providing additional data for new material samples. A large part of the current knowledge included in the JEFF3.3 nuclear data library is issued from the MINERVE programmes.

2.4.4. KRITZ

The KRITZ zero power reactor (critical assembly) operated in Studsvik, Sweden, from 1969 to 1975. The reactor core allowed full-length fuel rods and complete fuel assemblies of the BWR and PWR types. The reactor pressure vessel was designed to allow temperatures of up to 250°C without water boiling. Criticality was achieved only by axial water level regulation and was maintained long enough for stable measurements.

Appendix B of the IRPhE evaluation KRITZ-LWR-RESR-004 (Mennerdahl, 2019) from 2019 contains a short description of all KRITZ measurements, including the proprietary ones.

Proprietary KRITZ measurements

There are three major sets of KRITZ measurements completed after KRITZ-1 and KRITZ-2 (from which some measurements have been evaluated and other could yet be evaluated; see below). KRITZ-3, KRITZ Pu-75 and KRITZ-4 (also referred to as KRITZ BA-75) all involve BWR and PWR fuel assemblies. KRITZ-3 and KRITZ-4 are detailed in (Stammler et al., 1996; Lee et al., 2014). They were sponsored by power reactor designers and remain proprietary, as recently confirmed by Studsvik Nuclear. They are still of primary value to fuel design and core management software designers. Without accessing the proprietary information, it is difficult to estimate if the information is sufficiently detailed to allow an accurate and independent uncertainty IRPhE Handbook evaluation. This is, however, likely, considering that the temperature effects are the primary values.

KRITZ-3

The KRITZ-3 measurements (about 25) were made in the summer of 1973. They include PWR fuel rod clusters from Obrigheim, Germany, and absorber rods from Kraftwerk union (KWU) and Combustion Engineering (CE), of the United States. Both UO_2 and MOX fuel rods were used. The typical layout of the KRITZ-3 core can be found in (ANP, 2011). Temperatures ranged from 20ºC to 90ºC and from 200ºC to 250ºC.

KRITZ Pu-75

Around 45 criticality measurements were performed in April and May of 1975. Temperatures ranged from 20ºC to 90ºC, and from 200ºC to 245ºC. 21 Garigliano BWR fuel assemblies containing MOX fuel rod “islands” and 4 Gd rods were investigated through criticality and local power distribution measurements, sponsored by General Electric and Enel (Italy). No public references to recent application of these benchmarks have been found.

KRITZ-4 (BA-75)

Referred to as KRITZ BA-75 by experimenters, these measurements (around 200) were carried out from August to December 1975, addressing BWR fuel assemblies containing varying contents of the burnable absorber (BA) gadolinium. Temperatures ranged from 20ºC to 90ºC, and from 200ºC to 245ºC.

The KRITZ-4 benchmark measurements are frequently quoted, and the conclusions and results presented indicate a high quality of the benchmarks. A figure of the core layout can be found in (Smith, 2009).

Evaluated and published KRITZ measurements

There are currently some KRITZ evaluations in the IRPhE Handbook. In 1990, Studsvik Nuclear released previously proprietary data for some measurements for the benefit of NEA studies. This resulted in three IRPhE evaluations in 2009 involving UO_2 and MOX fuel clusters in the KRITZ-2 set of measurements. Each evaluation contains two critical water level measurements where reactor shutdowns and some fuel rods were replaced (after activation) after each measurement, which significantly changed design boron concentrations.

In 2019, an evaluation of KRITZ-1 measurements was published, with 37 measurements of UO_2 fuel clusters with UO_2 (1.35% ^{235}U enrichment) between 20°C and 250°C. There were four series with different core designs or initial boron concentration. Only the temperature changed, with water level adjustments to obtain and preserve criticality, between measurements in the same series.

Further KRITZ-1 and -2 measurements available, in principle, for evaluation

Studsvik Nuclear has agreed to allow evaluation of further KRITZ-1 and KRITZ-2 measurements for the benefit of the IRPhE Handbook. The more than 300 early KRITZ-1 measurements (1969 to 1971) with BWR fuel assemblies involved water temperatures up to 90°C. Another about 300 KRITZ-1 measurements (in 1971 and 1972) include BWR fuel assemblies at temperatures up to 250°C. KRITZ-2 included about 50 measurements with BWR fuel assemblies, with MOX rods in some measurements. About 300 critical fuel rod cluster measurements (excluding about 30 that were sponsored by CE) involved BWR and MOX fuel rods identical to those involved in the 3 KRITZ evaluations from 2009. There were many measurements up to 250°C. The information is not published and the data needed for a detailed evaluation is not easily available.

2.5. Experimental facilities

This section highlights some of the many criticality experiment facilities available to perform experiments listed in the previous sections of this report. These facilities each provide unique fuels, reflectors, moderators and capabilities. The subsections highlight these unique characteristics for each facility. This list does not cover all criticality experiment facilities worldwide as some of the facilities were not able to be contacted or were unable to share their information before the report was published. The facilities included in this report are: VENUS (Belgium), IPEN (Brazil), ZED-2 (Canada), LR-0 (Czech Republic), RSV TAPIRO (Italy), the Static Critical Facility (Japan), the National Criticality Experiments Research Centre (United States), Sandia Critical Experiments Facility (United States) and CROCUS (Switzerland). There are known to be facilities in Belarus, China, Japan and Russia that were not included in this report.

2.5.1. SANDIA (SNL, New Mexico, United States)

Facility contact: Gary Harms

Overview description and general facility mission

The Sandia Pulsed Reactor Facility (SPRF) is a small nuclear reactor research facility located in Technical Area V at Sandia National Laboratories/New Mexico. Historically (1961–2007), the primary purpose of the SPRF was to provide pulsed and steady-state neutron irradiation services in support of a variety of defence applications and related research and development. The SPRF was used to house and permit operations of SPR I, SPR II, and SPR III, state-of-the-art high-performance fast burst reactors. In the late 1980s, the Space Nuclear Thermal Propulsion (SNTP) Critical Experiment was operated at SPRF. SPRF and SNTP have since been removed. Since 2007, the primary purpose of the SPRF has been to perform critical assembly experiments and operations, identified as SPRF – Critical Experiments (SPRF/CX). The critical experiments performed at Sandia are funded by the DoE Nuclear Criticality Safety Program (NCSP) in support of expanding and developing overall criticality safety.

SPRF/CX provides a shielded location for performing critical experiments that employ different reactor core configurations and fuel types. The facility offers the capability for water-moderated critical experiments with the ability to modify the core configuration and reactor tank to evaluate various reactor cores for pitch, moderator characteristics and other criteria. Currently, there are two active CX series, the Burn-up Credit Critical Experiments (BUCCX) and the Seven Percent Critical Experiment (7uPCX).

The facility is also used to provide hands-on nuclear criticality safety training. The experiments and training activities at SPRF/CX are supported by the DoE NCSP, funded and managed by the National Nuclear Security Administration for the DoE.

Description of the available experimental assemblies where integral experiments could be performed to meet the needs (include specific assemblies with their capabilities and limitations)

The SPRF/CX provides a flexible platform for performing water-moderated and water-reflected critical experiments with UO_2 fuel rod arrays. Approach-to-critical experiments with the number of fuel rods in the array or the moderator/reflector height as the approach variable are routinely performed to determine critical configurations. The current authorisation basis design limitations are metal clad UO_2 fuel, enrichment less than 20%, light water moderator, and less than 500 kg of fuel. The authorisation basis can be modified to accommodate future critical experiments that fall outside the current limits.

The BUCCX was designed to investigate the effect of FP materials on critical systems. The BUCCX assembly is a water-moderated and water-reflected array of zirconium-clad triangular-pitched UO_2 fuel rods. Some of the rods can be modified to allow placement of experiment materials between the fuel pellets in the rod. Two sets of grid plates allow for array configurations with a 2.0 cm or 2.8 cm pitch.

The 7uPCX was designed to investigate critical systems with fuel for light water reactors in the enrichment range above 5% ^{235}U. The 7uPCX assembly is a water-moderated and water-reflected array of aluminium-clad UO_2 fuel rods. Two sets of grid plates, each having 2025 fuel rod locations configured in a 45 x 45 square-pitched array, are available for experiments. The grid plates offer array configurations with a 0.80 cm or 0.85 cm pitch, which are in the same fuel-to-water ratio range of the current US inventory of pressurised water reactors.

Fuel and material available

BUCCX fuel is 4.3% enriched UO_2 fuel rods with an outer diameter of 1.4 cm and a fuelled length of 48.7 cm. There are 350 fuel rods available for experiments. In addition to the fuel rods, there are 144 experiment fuel rods designed to mimic the fuel rods neutronically, while allowing access to the fuel pellets in the rod so the experiment material can be placed between the fuel pellets.

7uPCX fuel is 6.9% enriched UO_2 fuel rods with an outer diameter of approximately 0.6 cm and a fuelled length of about 48.8 cm. There are 2 175 fuel rods available for experiments. In addition to the fuel rods, sets of experiment rods having the same outer dimensions as the fuel rods are available. The experiment rods are used to investigate material effects on the 7uPCX array. Currently, titanium and aluminium experiment rods are available with plans to fabricate tantalum experiment rods.

Ongoing programmes

SPRF/CX is currently working on two experiment series to measure the temperature effects on critical systems. The first series is a collaboration with Oak Ridge National Laboratory (ORNL) focused on measuring the critical size of a fuel rod configuration at several temperatures. The temperature of the critical assembly will be set and an approach-to-critical experiment on the number of fuel rods in the critical assembly or the water depth in the core tank will be performed. This second series is led by Sandia National Laboratory (SNL) and will measure the inversion temperature of the isothermal reactivity coefficient. The fuel rod array will be set and the temperature of the critical assembly will be varied to determine the temperature that yields the highest reactivity of the system.

The IRSN is leading a collaboration with the SNL to perform an experiment series to contribute to the validation of molybdenum in the thermal energy spectrum. The critical experiments started in 2022 at SPRF/CX. New triangular-pitched grid plates will be fabricated for the experiments. Critical array configurations with molybdenum sleeves centred around 7uPCX fuel rods will be measured using approach-to-critical experiments on the number of fuel rods in the array.

The ORNL is collaborating with the SNL to develop a capability for testing the epithermal/intermediate cross sections of materials using 7uPCX. This is achieved by placing material test samples in a central test region that is surrounded by a tightly packed triangular-pitched array driven by an exterior fuel region. The test region incorporates a cadmium lining as a thermal neutron filter. The critical configuration uses tantalum as the material test sample with the option for testing additional martials in the future. New triangular-pitched grid plates with a central test region and tantalum experiment rods will be fabricated for the experiments.

Notable past programmes (references to ICSBEP/IRPhE evaluations)

The BUCCX series has produced two critical benchmark evaluations that are documented in the ICSBEP Handbook.

- LEU-COMP-THERM-079: Ten critical experiments performed in 2002 that focused on measuring the effect of rhodium on critical systems.
- LEU-COMP-THERM-099: Seventeen critical experiments performed in 2017-2018 that measured the effects of titanium and aluminum sleeves in the fuel array on critical array size.

The 7uPCX series has produced six critical benchmark evaluations that are documented in the ICSBEP Handbook.

- LEU-COMP-THERM-080: Eleven critical experiments performed in 2009-2012 that focused on measuring the effect of various water hole patterns on the critical array size with 0.80 cm pitch.
- LEU-COMP-THERM-078: Fifteen critical experiments performed in 2011-2012 that measured the effect of various water hole and aluminum replacement rod patterns on the critical array size with 0.85 cm pitch.
- LEU-COMP-THERM-096: Nineteen critical experiments performed in 2014-2015 that explored partially reflected arrays with 0.80 cm pitch.
- LEU-COMP-THERM-097: Twenty-four critical experiments performed in 2015-2016 that measured the effects of titanium and aluminum rod replacements in the fuel array on critical array size with 0.80 cm pitch.
- LEU-COMP-THEM-101: Twenty-two critical experiments performed in 2019 that focused of investigating partially reflected arrays with 0.855 cm pitch.
- LEU-COMP-THERM-102: Twenty-seven critical experiments performed in 2020 that measured the effects of decreasing the fuel-to-water ratio on the critical array size.

Capabilities for additional measurements/unique capabilities

SPRF/CX offers the ability to perform subcritical benchmark experiments with subcritical multiplication factors in excess of 100. The Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and IRSN plan to take advantage of this capability by performing high multiplication subcritical benchmark experiments. Each organisation plans to use separate detector systems on the same subcritical experiments at SPRF/CX to provide the first intercomparison of three separate detector systems. The experiments will serve as a valuable resource for validating time-dependent radiation transport software as well as non-destructive assay techniques for subcritical multiplication calculations. SPRF/CX will provide the facility and well-characterised subcritical configurations. Minor facility modifications will allow the different detector and data acquisition systems to be accommodated.

2.5.2. VENUS - Vulcan Experimental NUclear Study (SCK CEN, Mol, Belgium)

Facility contact: Anatoly Kochetkov

Overview description and general facility mission

The water-moderated PWR-type zero power reactor VENUS was commissioned in 1964. VENUS is a flexible experimental reactor with a maximal thermal power of 500 Watts. In 2008, VENUS-T was re-built as a fast lead-based reactor (VENUS-F) to support research in ADS MYRRHA. To simulate the ADS principle, a fast lead/lead-bismuth VENUS-F core could be coupled with the GENEPI-3C deuterium accelerator. VENUS-F is capable of performing the experiments in subcritical and critical regimes. VENUS-F is used for accurate measurements in view of code validation and verification of on-line subcritical methods to be used for ADS. Since all components of VENUS-T are available, the current VENUS-F can be transformed back to a PWR type in approximately one year.

Description of the available experimental assemblies where integral experiments could be performed to meet the needs (include specific assemblies with their capabilities and limitations)

The VENUS-F reactor consists of a stainless steel (SS) square casing that is inserted in the round tank of the previous VENUS-T water-moderated reactor. This SS casing can be filled with 144 (12 x 12) square assemblies (8x8 cm). In turn, the assemblies can be filled with round or square rodlets of metallic uranium (30 wt% enriched), lead, bismuth, alumina or SS, graphite and lead blocks. The SS casing also comprises six safety and two control rods and a dozen reflector assemblies with holes for the insertion of detectors. The height of the core is 60 cm. Around the core there are 40 cm top and bottom lead reflectors, as well as a radial reflector around the casing, filling the whole 160 cm diameter VENUS vessel. In ADS mode, the four assemblies in the core centre are replaced with the GENEPI-3C beam tube that contains the TiT target vessel.

Fuel and material available

VENUS-F solid core components (rodlets and blocks) are Pb, Bi, SS, Al_2O_3, C-12, U30%. All fuel pins UO_2 (4 %), MOX (1-12 %), materials and the VENUS-T vessel are still available, too.

Ongoing programmes

The programmes in VENUS-F are currently devoted to validation of the methods for online subcriticality measurement and code\data for MYRRHA.

Notable past programmes (references to ICSBEP/IRPhE evaluations)

Several international benchmarks have been published, including on prediction of neutron embrittlement in the reactor pressure vessel (NEA, 2000), and on mixed oxide fuel core experiments (NEA, 2003). A database for the validation of reactor physics codes for the calculation of the loss of reactivity due to burn-up for PWR fuel (burn-up credit), both for UO_2 and MOX fuel bundles, was established in mock-up experiments (REBUS).

Capabilities for additional measurements/unique capabilities

The external neutron source is provided by the GENEPI-3C, which was designed by the Centre national de la recherche scientifique (CNRS) and is a deuteron accelerator coupled to a tritiated titanium target located at the core mid-plane of the VENUS-F reactor. GENEPI-3C accelerates deuterons up to 220 keV. Their interaction with the TiT target mainly generates a quasi-isotropic field of ~14 MeV neutrons through T(d,n)4He fusion reactions. Three modes are available for the operation of the accelerator: pulsed mode, continuous mode and continuous mode with short beam interruptions. In the work presented here, the last two were used.

2.5.3. NCERC - National Criticality Experiments Research Centre (LANL, Nevada, United States)

Facility contact: David Hayes

Overview description and general facility mission

NCERC is a general-purpose criticality experiments facility located inside the Device Assembly Facility (DAF) at the Nevada National Security Site (NNSS). From 1967 to 2006, the Los Alamos Critical Experiment Facility (LACEF) team conducted experiments at Los Alamos National Laboratory's Technical Area 18 (TA-18). In 2006, operations ceased and LACEF began the process of relocating operations to NNSS.

NCERC is capable of performing experiments in the subcritical, critical, supercritical and super-prompt critical regimes. Experiments conducted at NCERC can utilise an inventory of unique nuclear material items, including HEU and WGPu items in various material forms, (metal, oxide, etc.) that are highly configurable. These items can be configured with a wide array of interstitial and/or reflector materials.

Description of the available experimental assemblies where integral experiments could be performed to meet the needs (include specific assemblies with their capabilities and limitations)

The experimental capabilities at NCERC include subcritical experiments and four critical assembly machines. The four critical assembly machines are named Comet, Planet, Flattop and Godiva IV.

Subcritical configurations of special nuclear material (SNM) are built by hand. The configurations vary in SNM type, mass, form and geometry, resulting in a wide range of subcritical neutron multiplication (from near 1 to about 20). These configurations often include moderator and/or reflector materials, and are primarily used for training, radiation measurements, and to provide information for the criticality safety community.

Comet is a general-purpose, heavy-duty vertical lift critical assembly machine used to conduct critical and subcritical experiments, nuclear safety studies and criticality safety training (Izawa et al., 2019). The machine consists of a movable platen and an upper, stationary platform. Operations are performed by installing two subcritical configurations made up of fissile material and reflectors on both platforms, and then raising the lower platen towards the stationary platform. When fissile material is present, reactivity can be added by raising the movable platen and decreasing the distance between the two portions of the system, or by inserting fissile material into a reflector. Among Comet's advantages is its operational flexibility. Comet is able to accommodate a plethora of configurations with loadings of up to 20 000 lbs on the stationary platform and 2 000 lbs on the lower platen. The Comet assembly is limited to an excess reactivity of 80 cents.

The Planet vertical assembly machine is a light duty, general-purpose, vertical lift critical assembly machine comprised of an upper stationary platform and a lower movable platen. The Planet assembly machine was originally built as a light duty alternative to the Comet vertical assembly machine. The primary purpose of Planet is to conduct critical experiments by remotely bringing together two halves of a critical assembly into a critical configuration. Gravity is used to provide a shutdown mechanism. The simple, yet effective, vertical lift allows for a wide variety of potential designs and is able to meet varied experimental needs. Critical experiments are used to determine the critical masses of fissile and fissionable material (uranium, plutonium, neptunium, etc.). Planet is able to accommodate a load of 2 000 lbs on the stationary platform and 1 000 lbs on the movable platen. The Planet critical assembly is limited to an excess reactivity of 80 cents.

Flattop is a simple one-dimensional geometry, fast benchmark critical assembly, consisting of a spherical fissile core surrounded by a 1 000 kg spherical natural uranium (NU) reflector. The two available cores of SNM are HEU metal (uranium 93% ^{235}U by weight percent) and δ-phase plutonium metal (plutonium 4.8% ^{240}Pu by atom percent). The reflector consists of two movable quarter-spheres and a stationary hemisphere. Originally assembled in the late 1950s, Flattop was used to develop and to validate nuclear data and simple one-dimensional, two-region computational modelling. The range of experimental capabilities is fairly narrow, given its fixed geometry. However, this makes it excellent for validation and comparison of results obtained over several decades. Foil activation measurements performed at TA-18 and NCERC compare favourably, demonstrating the reliability of the results and emphasising the necessity for the unique capabilities of Flattop. The Flattop critical assembly is limited to an excess reactivity of 80 cents when using the uranium core and 50 cents when using the plutonium core.

Godiva IV is a fast burst critical assembly constructed of approximately 65 kg of HEU fuel alloyed with 1.5% molybdenum for strength. The cylindrical core is nominally six inches tall and seven inches in diameter. Godiva IV was designed and built in 1967, following several earlier incarnations of uranium burst assemblies. Godiva is one of the last such critical assemblies in the United States, and can be used for studies of super-prompt critical behaviour as well as irradiations and demonstrations. Godiva is limited to performance of bursts with less than 1.15 dollars of excess reactivity.

Fuel and material available

NCERC is home to an array of uranium and plutonium metal fuels in many geometric forms such as plates, discs, hemi-shells. Although there is currently a limited inventory of other material forms such as oxides, carbides and hydrides, these materials are approved for use in criticality experiments. In terms of reflector/moderator materials, NCERC also maintains an array of materials such as beryllium, tungsten, tantalum, molybdenum, polyethylene and copper. The previous list is in no way exhaustive, and practically any material can be used in criticality studies at NCERC.

Ongoing programmes

NCERC is collaborating on several ICSBEP evaluations and is working on several experiments. A majority of these experiments are funded through the NCSP. These campaigns are a collaboration between several DoE sites including the Los Alamos National Laboratory, Lawrence Livermore National Laboratory and Oak Ridge National Laboratory.

An experimental campaign based off the Zeus series was completed in 2018. The campaign examined the effect of introducing voids into four critical systems containing lead interstitials and a copper reflector. The systems differed in their nuclear materials. Two different systems utilised uranium fuels. The first system utilised HEU as a fuel, while the second contained a mixture of HEU and natural uranium (effective 21-22% enrichment). An adaptation of Zeus, named Jupiter, was designed to use zero power plutonium reactor (ZPPR) plates of various enrichment. It was first used for lead void measurements but can be adapted to other interstitial materials. The third system contained WGPu, and the fourth system used a central region of reactor grade plutonium surrounded by WGPu. Both systems were built in the Jupiter framework. The first three systems are being analysed as ISCBEP benchmarks.

An experimental campaign is examining tantalum using the Thermal/Epithermal eXperiments (TEX) baseline assembly, which has already been included in the ICSBEP Handbook as PU-MET-MIXED-002. The first set of TEX experiments were performed on Planet in 2017-2018 using tantalum as a diluent material. The configurations including the Ta diluent are compiled into a separate ICSBEP benchmark, PU-MET-MIXED-003 (in progress).

An experimental campaign designed to be sensitive to the uranium unresolved resonance region was measured in 2020, consisting of an HEU system with a Teflon interstitial and a copper reflector. This experiment is being compiled into an ICSBEP benchmark. NCERC is performing a critical and subcritical measurement on a bare, spherical HEU system using a wide array of detection systems. This programme is intended to compare neutron noise measurements between different detection systems, and to provide validation data in the form of a subcritical and a critical ICSBEP benchmark.

NCERC is also preparing to perform an experiment examining the thermal scattering law in both Lucite and polyethylene. This experiment will be performed using a system based on the TEX experiment (PU-MET-MIX-002).

Notable past programmes

Although the initial experiments predate NCERC, it is worth mentioning the Zeus experiment series. The Zeus experiment was designed as a test bed for intermediate energy experiments. The experiment features a large copper reflector intended to shrink the system size without generating a bimodal neutron energy distribution. This series was used to examine effects of graphite, iron and polyethylene.

The TEX experiments address nuclear data and validation needs for the criticality safety and nuclear data communities by creating critical experiments that test a wide range of fission energies, from thermal to fast. The TEX-Pu measurements used plates of plutonium with various thicknesses of polyethylene moderators to create a baseline set of critical configurations. By using different thicknesses of polyethylene moderators, the neutron energy spectrum of the experiment was changed from fast to thermal, including some mixed or intermediate energy spectra configurations. The TEX experiments were performed on Planet in 2017-2018. The baseline TEX configurations have been compiled into an ICSBEP benchmark, PU-MET-MIXED-002.

The Kilopower Project, a jointly funded venture between the National Nuclear Security Administration (NNSA) and the National Aeronautics and Space Administration (NASA), demonstrated the technological readiness of a small space fission power source for space science and human exploration power needs. The culmination of this project was the KRUSTY tests (McClure et al., 2020). These tests were split into four experimental phases, all performed at NCERC utilising the Comet assembly.

The Component Critical Experiments (Phase 1) assessed the bias in neutron multiplication due to the beryllium oxide neutron cross-section data. The experiment consisted of a hollow, cylindrical uranium core. Cold Critical Experiments (Phase 2) consisted of a setup similar to Phase 1, with a few additions. To simulate the reactor's operating environment, the core was placed in a vacuum chamber installed above the stationary platform on Comet. The Warm Critical Runs (Phase 3) included three intermediate power runs with the same vacuum chamber setup as in Phase 2, but with a single reflector configuration and no control rod. These tests determined parameters used to model the neutronic and thermal behaviour of the KRUSTY experiment. Phase 3 began with a 0.15 dollar free run-on 7 March 2018. The next day, 8 March 2018, a 0.30 dollar run of KRUSTY was performed on Comet. Phase 3 testing concluded with a 0.60 dollar run of KRUSTY performed on 14 March 2018. KRUSTY testing at NCERC culminated with the Nuclear System Test (phase 4). This test investigated the nuclear-powered performance of the fully integrated KRUSTY reactor and its power conversion system. The powered run lasted 28 hours and consisted of dozens of reactivity transients to test the system in its entirety. Five configurations from the Component Critical Experiments (Phase 1) have been evaluated as KRUSTY: Beryllium oxide and stainless steel reflected cylinder of HEU Metal, HEU-MET-FAST-101 for submission to the ICSBEP Handbook.

Capabilities for additional measurements/ unique capabilities

NCERC is home to several additional capabilities including neutron noise measurement systems, a count room to measure activation/fission foils, and radiation generating devices. The neutron noise measurement systems include systems to examine Rossi-α, Feynman Variance-to-Mean, pulsed neutron source measurements. The systems include sets of ^{3}He detectors as well as plastic/liquid scintillators. The count room includes well-characterised HPGE detectors and an 8-channel alpha spectrometer. One of the HPGE systems is mounted on a computerised sample changer capable of automatically switching between several samples. NCERC maintains and operates multiple radiation generating devices including XRS X-ray generators, D-T neutron generators and a 6 MeV Betatron.

2.5.4. STACY - Static Experiment Critical Facility (JAEA, Tokai, Japan)

Facility contact: Kenya Suyama

Overview description and general facility mission

STACY is a critical assembly located at the NUCEF (NUclear fuel Cycle safety Engineering research Facility) in the Tokai Research and Development Centre of the Japan Atomic Energy Agency (JAEA). From 1995 to 2011, critical experiments were performed of homogeneous and heterogeneous core configurations using uranium nitrate solution fuel and low-enriched uranium dioxide fuels. In addition, a lot of criticality data were obtained by changing the density of the solution fuel, shapes and sizes of the core tanks, reflector conditions, etc. In 2011, an experiment with solution fuel was completed and it has been remodelling to a tank type light water moderation heterogeneous system using uranium oxide fuels from 2020, especially in order to clarify the criticality characteristics of fuel debris caused by the accident at TEPCO's Fukushima Daiichi Nuclear Power Station. The new STACY is expected to reach its first criticality in 2023.

The new STACY will be able to experiment in critical and subcritical (Izawa et al., 2019). For the purpose of clarifying the critical characteristics of fuel debris, it is possible to prepare and analyse pseudo fuel debris pellets using known materials (concrete, stainless steel, etc.) at the attached facility. A drive mechanism can be installed to load a small amount of measurement sample during operation of the critical assembly. However, this is not a pile oscillator.

Description of the available experimental assemblies where integral experiments could be performed to meet the needs (include specific assemblies with their capabilities and limitations)

The neutron moderation condition of STACY is allowed to be 0.9–11.0 in the core average fuel-to-moderator volume ratio (Vm/Vf). The new STACY will provide a drive mechanism for loading a small amount of measurement sample during its operations. The mechanism is currently in the design phase and a maximum reactivity of 30 cents is acceptable. In addition, there are plans to prepare a large number of general-purpose sheath tubes that can hold gas detectors, activation detectors, moderator or structural materials, void and samples for reactivity measurement. Of these contents, moderators or structural materials and reactivity measurement samples are not allowed to have an axial distribution.

Fuel and material available

The new STACY's ^{235}U 5 wt.% enriched uranium oxide fuel rods will be fixed in light water using grid plates. The axial core size will be controlled by changing the water level of the light water. The fuel for the new STACY consists of 900 fuel rods with E110 zirconium alloy cladding, along with the former STACY's 400 uranium dioxide fuel rods (^{235}U 5 wt.% enriched, Zircalloy-4 cladding). Additionally, unirradiated ^{235}U 5 wt.% enriched uranium oxide fuel powder will be prepared to make pseudo fuel debris. The reflector and moderator are light water, and boric acid can be dissolved in the light water. At present, it is not permitted to use anything other than light water as the main reflector/moderator. There are no restrictions on the types of materials that can be loaded, but there are restrictions on the integral reactivity.

Ongoing programmes

After the first criticality, the new STACY will be used exclusively to obtain the criticality characteristics of the materials, which simulate the composition of fuel debris. For clean core configurations and typical experimental core configurations with pseudo fuel debris or some other materials, co-operation with ICSBEP activities is being prepared.

Notable past programmes

N/A

Capabilities for additional measurements/ unique capabilities

At this time, the new STACY has only obtained the minimum necessary equipment permission to measure the critical characteristics of fuel debris. The user will be able to add equipment as needed with its permission.

2.5.5. ZED-2 - Zero Energy Deuterium (Canadian Nuclear Laboratories, Chalk River, Ontario, Canada)

Facility contact: Julian Atfield

Overview description and general facility mission

ZED-2 is a heavy water-moderated zero power reactor located at the Chalk River Laboratories site of the Canadian Nuclear Laboratories, where it has operated since first critical in 1960. The reactor was originally constructed to confirm lattice physics for the Canadian Pressurised Heavy Water moderated power Reactor (PHWR) programme. It has since been used to confirm and validate the reactor physics design of all Canadian power reactors and to conduct a variety of campaigns and experiments supporting advanced fuel cycles, next generation power reactors and other research reactors.

The reactor fundamentally consists of a 3.3 m diameter by 3.3 m high “calandria” vessel surrounded by a graphite reflector. Movable steel beams span the headspace above the calandria, from which fuel assemblies can be suspended. There is a broad variety of lattices that can be studied, owing to the flexibility in assembly type and lattice pitch. A fuel configuration is made critical by pumping heavy water into the calandria, up to moderator heights limited to 265 cm.

ZED-2 is one of the few remaining zero power lattice reactors in the world, and one of the fewer still heavy water types. As of 2021, over 2 500 critical cores have been assembled in ZED-2, with over 200 first-of-a-kind cores in the facility. The facility mission is to support the science and technology needs of the Canadian government (including the Canadian Nuclear Safety Commission, regulating nuclear safety in Canada). ZED-2 also strives to maintain availability for any group or customer who wish to use the facility. To date, other work has included commercial projects in support of PHWRs and detector calibration.

Description of the available experimental assemblies where integral experiments could be performed to meet the needs (include specific assemblies with their capabilities and limitations)

The ZED-2 reactor itself is the single experimental critical assembly available for testing. The nature of ZED-2 provides a large test region in which to perform a variety of integral experiments. There are defined limits on reactor physics parameters (such as mean neutron generation time, and moderator level coefficient of reactivity) that must be satisfied by the experiment for it to proceed. After these conditions are met, a variety of fuels and materials can be used in a critical or subcritical assembly, as described in the subsequent section.

ZED-2 is currently limited to a heavy water moderator with a maximum height of 265 cm. Heavy water moderator purity is permitted to be between 99.8% and 97.5 weight % D_2O. The limits on moderator heating for typical experiments is up to 45°C. The maximum thermal power of the reactor is 200 W, which corresponds to peak thermal flux of approximately 1 x 10^9 n/cm^2/s and fast flux peak of 5 x 10^8 n/cm^2/s. With the typical fuel assemblies used in the facility, the core configuration can be rapidly rearranged, sometimes in a matter of days.

Fuel and material available

The facility maintains access to a variety of fuel types, some of which are sufficient for full core measurements, while others exist only in quantity to perform substitution experiments (i.e. using other fuels to drive a small region of test fuel). The fuels available are most often in the form of a 50 cm multi-element bundle, in the style of

PHWRs, though other full-length rods and assemblies exist. The fuels available for full core measurement include 28-element natural uranium oxide and 43-element LEU oxide (0.95 % ^{235}U in U). Sufficient natural uranium material for substitution experiments exists in other oxide forms, as well as uranium carbide, uranium silicide in an aluminium matrix, and uranium metal. Some bundles, intended for low coolant voiding reactivity, include elements with burnable neutron absorbers. Higher enrichment LEU is also available in some fuels.

The bundles are largely clad in zirconium alloys. Fuel strings composed of these bundles are placed in "channels", used to contain most fuels. These channels are mostly made of aluminium alloys, though some zirconium alloy channels exist. Channels can be filled with simulated coolant as required (no active cooling is required by the fuel owing to the low power).

Mixed oxide bundles are available in a variety of types, including depleted U and Pu bundles simulating a mid-burn-up natural uranium oxide bundle, as well as $(^{233}U,Th)O_2$, $(^{235}U,Th)O_2$ and $(Pu,Th)O_2$.

As previously stated, the moderator is heavy water, with a graphite reflector. Currently, heavy water, light water and air are most frequently used as a simulated coolant.

While some materials may not be immediately available to the facility as listed above, the use of other materials is not precluded. Previous programmes in the reactor have included LEU and HEU fuels in Zr and Al matrices, for instance. Simulated coolants have also included organics, helium, carbon dioxide and cast lead-bismuth. While such material is either not currently available or not regularly used, there are no insurmountable barriers to experiments using such fuels and coolants. Various solid and liquid neutron absorbers have also been tested. The facility is quite permissive with the fuels and materials, which can be used, providing the reactor physics parameters fall within the required envelope.

One currently existing exception to materials that can be used is a limitation on FP inventory in the facility, which precludes the use of spent fuel in the facility.

Ongoing programmes

A programme obtaining new measurements relevant to the reactor physics of PHWR-type lattices was completed in 2021 and is expected to resume in the future. The highlight of this programme was the inclusion of simulated mid-burn-up PHWR fuel in the form of the aforementioned (Pu, depl. U)O_2. This programme focused on the ongoing development of power transient measurement techniques and reduction of experimental uncertainties. The transients included addition and draining of moderator, at-power addition of coolant and absorber rod insertion. Thus, time domain transient data from an array of in-core neutron detectors for the confirmation of kinetics parameters have been generated with multiple cores. Development of neutron flux perturbing devices to measure the reactor transfer function was also part of this work. The measurement of the transfer function provides integral frequency domain data against which to test kinetics parameters.

At present, the possibility of producing experimental data relevant to small modular reactors and Gen-IV systems is being studied.

There are ongoing efforts to submit draft ICSBEP/IRPhE benchmarks for evaluation, pending internal review and approval.

Notable past programmes

As one of few heavy-water critical facilities in the world, ZED-2 measurements have been evaluated for inclusion in international benchmark evaluation handbooks. Criticality measurements of a hexagonal lattice of natural uranium metal fuel assemblies in heavy water were compiled for the ICSBEP Handbook, LEU-MET-THERM-003. Criticality measurements on a lattice of 28-element natural UO_2 fuel assemblies with simulated D_2O and air coolant were compiled for the IRPhE Handbook, ZED2-HWR-EXP-001.

Capabilities for additional measurements/unique capabilities

The facility has an associated counting lab, which provides the capability to measure activation materials to characterise core absolute flux, flux distributions and reaction rates as required. The facility retains the capability to conduct flux distribution and reaction rate measurements within a lattice cell, as well as within a fuel assembly (i.e. within a fuel pin). This lab also facilitates detector calibration using ZED-2.

Seven hot channel assemblies have been historically used to achieve temperatures up to 300°C for fuel/coolant temperature coefficient measurements for fuel strings of up to five bundles per assembly.

A recently developed capability is the rapid flooding of voided (air-cooled) fuel channels with D_2O on the timescale of tens of seconds. This capability can be deployed for up to 48 channels at present.

An ex-core rig for the addition of liquid coolant, without opening the reactor shielding, can be used to study coolant void reactivity worth with liquids other than D_2O.

An array of neutron detectors is available for in-core and ex-core neutron flux measurements, and can be used for time domain and/or frequency domain kinetics measurements.

Soluble moderator poison capabilities are available.

There are graphite reflector positions that can be removed and substituted with other reflectors.

2.5.6. LR-0 (Centrum výzkumu Řež, Husinec –Řež, Hlavní 130, Czech Republic)

Facility contact: Vlastimil Juříček (Vlastimil.Juricek@cvrez.cz)

Overview description and general facility mission

Reactor LR-0, located in Řež, near Prague (Czech Republic), is an experimental pool-type light water-moderated zero power reactor. The LR-0 hexagonal fuel elements are in a radial sense identical and axially shortened to 125 cm with regard to VVER-1000 nuclear power plant fuel. The moderator can be demineralised water or water with diluted boric acid. The power control is achieved either by adjusting the moderator level and boron acid concentration and/or by control rod positions.

The main characteristic of LR-0 is the flexibility of the supporting structures, allowing an arbitrary composition of the core. The specificity of the LR-0 reactor is its start-up by gradual fuel flooding by water moderator pumping into the reactor vessel. The experiments are realised at atmospheric pressure and room temperature. Continuous maximal operating power is 1 kW with neutron thermal-flux density ≈ 1.10^{13} $n \cdot m^2 \cdot s^{-1}$.

The LR-0 reactor has been designed in a way that makes it suitable for neutron-physical experiments on VVER-type cores in a wide range of fuel assemblies, fuel enrichment, with varying concentrations of boron acid in moderator, and different positions of absorption elements in the fuel assemblies. An important part of the research was the modelling and experimental validation of radiation damage of the materials of reactor in-core trims and VVER reactor pressure vessels simulators. The LR-0 is a zero power experimental reactor that provides an experimental, scientific, and technical base for experiments studying reactor core physics and shielding of light water reactors (VVER, PWR), experiments related to the storage of spent fuel.

LR-0 reactor cores, which are assembled from 6 to 55 assemblies with different ^{235}U enrichment, can be utilised as a driver zone surrounding central area with 1, 7 or 12 experimental modules filled with various materials to be investigated in LWR neutron spectrum. This arrangement makes it possible to carry out neutron physics experiments related to new trends in nuclear energy (Gen-IV). Experiments were performed with modules filled with graphite, fluoride salt FLiBe and SiO_2.

The LR-0 reactor design allows:

- A flexible model of reactor active core configurations. The vessel can utilise up to 121 fuel assemblies (usually 6-32 are used). Supporting technical equipment allows arrangements with different enrichment and experiment geometries with various inserted models or materials.
- A simple choice of function (emergency, experimental or control) for each cluster on the panel control device.
- Changes in the concentration of boric acid and insertion of experimental clusters to achieve the required critical moderator height for the experiment.
- Relatively easy change of core configuration by removal and insertion of individual assemblies. Ensuring an exact reactor core geometry is made possible by a support structure (desk) and side mounting. The reactor core can be adapted to measure different cores using different support desks.
- Easy access to the core. After opening of the shielding platforms, the reactor core is accessible either by circular or square holes in the lid of reactor vessel. If the radiation level permits it, it is possible to use the ladder to step down to the core handling platform. More extensive operations (assembly, disassembly of the core) can be performed after the reactor’s circular lid has been removed.
- The reproducibility of measurements of physical conditions, which is ensured by the precision of assembly of the structure of the core and fuel assemblies (geometry) and precision measurements of all parameters of the experiment (moderator critical level and the temperature, the concentration of boron acid in the moderator, position of absorption of clusters, neutron flux density, etc.).
- A high level of reactor reactivity control and safety in both standard and non-standard conditions, including emergency situations.

Experiments at the LR-0 reactor

- Critical experiments of various core loading and/or with different materials inserted into the core or inserted as reflector: Some of them are presented in ICSBEP and IRPhEP handbooks.
- Reactor kinetics - space and time distribution of thermal neutrons. VVER-1000 space kinetics – two-dimensional (three-dimensional) neutron response on pseudo rod drop (trapezoidal movement of one absorbing cluster at the critical state).

- Fuel element gamma scanning - FPs gamma spectrometry of radial and/or axial pin power distribution over the core.
- 2D/3D neutron flux measurement on the cores with different loading using neutron activation analysis or in-core neutron detectors.
- Neutron and gamma spectra measurements in various sections of the core, in and over reactor pressure vessel (RPV) model, in the model of VVER-1000 type biological shielding.
- Neutron and photon spectra measurement over the reactor pressure vessel simulator of the VVER 1000 (VVER-440) model. The space-energy distribution of the mixed neutron – photon radiation field has been measured over RPV simulator thickness in the VVER-1000 engineering benchmark assembly in the LR-0 experimental reactor with a multi-parameter scintillation spectrometer. The spectra have been measured in front of the RPV, in 1/4, 1/2, 3/4 of its thickness and behind the RPV simulator in the energy range of ~ 0.5 to ~ 10 MeV. The measurements were performed in the frame of the project REDOS within the Fifth Frame Work Programme of the European Community 1998 – 2002. The presented measured data consists of integral data – ratios of integral photon and neutron fluxes in measuring points and differential photon spectra in the measured fine structure and in the BUGLE energy group format.
- Scientific research in the field of radiation transport through various materials. It used detectors that measure not only the number but also energy of incident particles. Reactor LR-0 uses this type of detector in the experiments, where it is necessary to determine the nature of neutron field outside the fuel lattice, as in experiments determining radiation damage to the reactor pressure vessel. The basic method of neutron spectrometry is the proton recoil method using hydrogen-filled proportional detectors and scintillation detectors with a stilbene crystal. Spectral measurements can be performed on simple symmetrical geometries (spheres, cylinders) with an external neutron source or directly on the reactor in a different position of the core.

Key technical specifications:

Table 3: CVR LR-0 reactor key specifications

Reactor type	**Light-water, zero-power, pool-type**
Maximal thermal output	Continuously up to 1 kW
Fuel type (pins and assembly)	Shortened VVER-1000, Shortened VVER-440
^{235}U enrichment	2 – 4.4 wt.%
Number of fuel pins in assembly VVER-1000 type	312
Assembly lattice pitch	23.6 cm
Core	
Fuel element grid	Triangular
Number of fuel assemblies	6 – 32 (max. 121)
Moderator	
Chemical composition	Demineralised water or demineralised water with boron acid
Concentration of H_3BO_3	0 – 7 (g/kg)
Change of concentration during operation	N/A
Reactor control system	
Absorbing clusters in core	6-16
Control rods in assembly (VVER-1000 only)	18
Absorbing material in control rod	B_4C

Source: CVREZ, 2022.

Description of the available experimental assemblies where integral experiments could be performed to meet the needs (include specific assemblies with their capabilities and limitations)

- Reference neutron field (defined in IRDFF-II) and well-characterised HPGe usable for measuring gamma activities, also suitable for measurement of integral cross sections or validation of the present evaluations of nuclear data libraries. The spectrum was identified as being indistinguishable from ^{235}U PFNS in region > 6 MeV, so in case of reactions with threshold > 6 MeV, SACS averaged in ^{235}U PFNS can be measured directly.
- Stainless steel simulator of VVER reactor internals, usable for studies of heavy reflectors on criticality.
- Material insertions: CF_2, SiO_2, NaCl, LiF-NaF for validation of the effect of structural components on criticality.
- Mock-up of VVER-1000 reactor, usable for validation of reactor dosimetry issues and spatial distribution of spectra in important components.

Fuels and materials available

- fuel elements of ^{235}U nominal enrichment: 1.6 %, 2 %, 3.0 %. 3.3 %, 3.6 %, 4.4 %;
- experimental modules with dimensions equal to VVER-1000 assembly with filling: nuclear grade graphite, sand (SiO_2), FLiBe salt, NaCl, PVC;
- 900 kg D_2O (>99% isot. purity);
- 48 kg F^7LiBe;
- 500 kg of well-defined SiO_2;
- 500 kg of nuclear grade graphite;
- sand for silicon-based experiment.

Ongoing programmes

FLiBe

Within the co-operation of the US DoE and the Ministry of Industry and Trade of Czech Republic, research and development (R&D) related to molten salt reactors is being carried. The LR-0 reactor runs an experimental programme aiming at reactivity feedback measurement with hot FLiBe salt (~600°C) in thermal/epithermal neutronic spectrum. A module made for hot salt to be inserted into a conventional LR-0 core is currently being tested at room temperature.

Integral experiments for neutronic XS (cross section) libraries evaluation

The LR-0 multi-zone core of LR-0 allows insertions of large samples (up to hundreds of litres) of various materials either in the reactor centre or on the periphery, making it possible to test various neutron reactions including absorption, elastic and inelastic scattering, and (n,2n). The last elements focused on included silicone, graphite, chlorine and fluorine.

Measurements of SACS averaged in ^{235}U

A reference neutron field was identified in the LR-0. It was proofed that the spectrum is indistinguishable from the ^{235}U prompt fission neutron spectrum in the region above 6 MeV. The SACS averaged in ^{235}U PFNS are fundamental quantities usable in the evaluation of nuclear data. Thanks to the support of the IRDFF-II community, there is ongoing measurement of spectral averaged cross sections of reactions with a threshold above 6 MeV.

Study of heavy reflector physics

A mock-up of the internals of the VVER-1000 reactor is in the LR-0 reactor. It is possible to move the well-defined core to a given model (in which centre a reference neutron field has been identified). The effect of the internals is simply evaluated by comparison of a reference case with a standard water reflector.

Pin power density measurement

It has been shown that the power density is proportional to the fission density. This fission density can be easily measured by the gamma activities of selected FPs induced during the experiment with well-defined time schedules. The most of experiments focusing on pin power density is being carried out in the VVER-1000 mock-up, where the data are applicable to safety studies of VVER reactors.

In-core and ex-core neutron spectroscopy

The LR-0 is a versatile tool with a lot of room, so there are places where neutron and gamma spectra are measured. It is often in the centre of the insertion to study the material effect on the neutron field or behind the core. In the LR-0, there is a simulator of reactor internals, and behind the vessel is a simulator of the VVER-1000 RPV and concrete biological shielding. The spectra have been measured in these locations. In the past there was a focus on the situation in the RPV, while new experiments are focusing on the distribution in the internals and in concrete shielding.

Notable past programmes

Several benchmarks from experiments on the LR-0 reactor or in the neutron generator laboratory have been presented and reviewed at various ICSBEP/IRPhE meetings in the last ten years. Some benchmarks are listed in handbook ICSBEP or IRPhE.

- LEU-COMP-THERM-086, VVER physics experiments: hexagonal lattices (1.275 cm pitch) of low enriched U(3.6, 4.4 wt.% ^{235}U)O_2 fuel assemblies in light water with H_3BO_3;
- LEU-COMP-THERM-087, VVER physics experiments: hexagonal lattices (1.22-cm pitch) of low-enriched U(3.6, 4.4 wt.% ^{235}U)O_2 fuel assemblies in light water with variable fuel-assembly pitch;
- LR(0)-VVER-RESR-001 CRIT-COEF-RRATE, VVER physics experiments: hexagonal lattices of low enriched U(2.0 - 3.3 WT.% ^{235}U)O_2 fuel assemblies in light water with central control assembly mock-up;
- LR(0)-VVER-RESR-003 VVER-1000 physics experiments: hexagonal lattices (1.275 cm pitch) of low enriched U(3.3 wt.% ^{235}U)O_2 fuel assemblies in light water with graphite and fluoride salt insertions in central assembly;
- LR(0)-VVER-RESR-002 VVER-1000 mock-up physics experiments: hexagonal lattices (1.275 cm pitch) of low enriched U(2.0, 3.0, 3.3 wt.% ^{235}U)O_2 fuel assemblies in light water with H_3BO_3;

- LR(0)-VVER-RESR-004 VVER-1000 physics experiments: hexagonal lattices (1.275 cm pitch) of low enriched U(3.3 wt.% $^{235}U)O_2$ fuel assemblies in light water 75As(n, 2n), 23Na(n,2n), 90Zr(n,2n), 89Y(n,2n) reaction rates;
- RCR ALARM-CF-FE-SHIELD-002, measurement of fast neutrons leakage spectra from iron spheres with ^{252}Cf source in centre.

Capabilities for additional measurements/ unique capabilities

- There are planned oscillators for the study of reactor dynamics – and the measurement of kinetic parameters will be possible.
- Neutron detectors, neutron spectrometry systems and data evaluation method for neutron spectra 100 keV - 10 MeV.
- Centrum výzkumu Řež (Research Center Řež) (CVR) operates a set of radiation generating devices including ^{252}Cf (1E9 n/s in 2015), $^{241}AmBe$, $^{238}PuBe$, a D-T source (14 MeV neutrons) and a 10 MW research reactor which can be used both as a strong neutron source and as a quasi-monoenergetic beam behind 1 m thick Si filter. ÚJV, the parent company of CVR, operates a medical accelerator; a positron emission tomography (PET) is available for deep penetration experiments.
- The neutron sources, namely ^{252}Cf, are being used to measure the leakage spectra from material spheres or through slabs for nuclear data library validation (integral experiments). Mostly, the source is transported into the centre by a flexo-rabbit system. There are many material geometries that can be used.
- Various materials in spherical, slab and cylindrical geometries are available in the LR-0 reactor and surrounding laboratories.
  - Spherical geometry with hole for placement of aluminium transport capsule with neutron source into the sphere centre.
    - Fe sphere: outer diameter of 20 cm, 30 cm, 50 cm, 100 cm (the sphere with diameter of 100 cm allows inside measurement in a special hole, where it is possible to create a variable layer of iron using inserts);
    - Ni – sphere: outer diameter of 20 cm, 50 cm;
    - D_2O sphere, stainless steel wall: outer diameter of 30 cm, removable Cd cover;
    - H_2O sphere: outer diameter of 30 cm (identical with D_2O sphere), 50 cm (Al wall);
    - PE sphere: outer diameter of 30 cm, 24.5 cm (tube for neutron source goes 0.5 cm bellow the centre).
  - Slab geometry – square
    - Cu cube – dimension 49.5 × 48.5 × 48 cm;
    - Stainless steel cube (EU-X6CrNiTi18-10 (1.4541), US-321, RUS-08KH18N10T) – dimension 49.5 × 48.5 × 48 cm.
  - Cylindrical (desk layer) geometry:
    - The arrangement consists of individual discs with a diameter of 90 cm (exceptionally 100 cm) and a thickness of usually 10 cm. The axis of the cylinder thus assembled is at a height of 1 m above the ground. The source is located in a vertical channel in the axis of an iron disk or in the gap between the disks (one disk is removed).
      - Fe: diameter of 90 cm × thickness 10 cm - 10 pieces;
      - stainless steel: diameter of 90 cm × thickness 10 cm - 5 pieces;
      - PE: diameter of 90 cm × thickness 10 cm;

- PE: diameter of 90 cm × thickness 20 cm;
- PE: diameter of 90 cm × thickness 0.2 cm - 9 pieces;
- PE with B: diameter of 90 cm × thickness 10 cm;
- Pb: diameter of 100 cm × thickness 5 cm;
- D_2O: diameter of 90 cm × thickness 4 cm;
- D_2O: diameter of 90 cm × thickness 6 cm;
- D_2O: diameter of 90 cm × thickness 50 cm;
- Cd: diameter of 90 cm × thickness 0.1 cm (Al cover);
- Al: diameter of 90 cm × thickness 0.1 cm;
- B_4C: diameter of 90 cm × thickness 2 cm (loose powder);
- Cu cube: dimension 49.4 × 49.5 × 48.2 cm;
- graphite cube: dimension 30 × 30 × 30 cm;
- graphite cylinder: dimension o.d. 60 x 60 cm.

Laboratories supporting experiments on the LR-0 reactor:

- HPGe spectrometry laboratory (vertical detector with cooler) for isotopic composition and gamma activity determination of materials and activation foils with certified spectrometer.
- HPGe spectrometry laboratory (horizontal detector cooled with liquid nitrogen) for gamma scanning of irradiated fuel pins (e.g. for reactor power – axial/radial distribution mapping).

2.5.7. IPEN/MB-01 (Instituto de Pesquisas Energéticas e Nucleares, São Paulo, Brazil)

Facility contact: Adimir dos Santos

Overview description and general facility mission

The IPEN/MB-01 research reactor had its first criticality in November 1988 and has ever since been of major significance to Brazilian reactor physics research, achieving international recognition for experiment comparison and validation (benchmarks). In this facility it is possible to build many different core configurations (i.e. rectangular, square and cylindrical), as versatility and flexibility were both taken into account on its initial project. The core is a fissile material assembly, inserted in a water tank, where the chain reaction is self-maintained and controlled at low power levels in normal operation. Low power levels allow the feedback effects of temperature to be negligible. The core is primarily driven by neutrons with energies similar to light water-moderated reactors, allowing the experimental verification of the calculation methods, reactor cell and mesh structures, control rod effectiveness, isothermal reactivity coefficients and core dynamics due to reactivity insertions. The first standard IPEN/MB-01 core had UO_2 rod-type fuel, 4.3% enriched in ^{235}U and using B_4C and Ag-In-Cd rods for safety and control of the reactor. The facility is located at IPEN/CNEN-SP (Nuclear and Energy Research Institute), in Sao Paulo, Brazil.

The IPEN/Mb-01 reactor has four major objectives: 1) to serve as a benchmark facility, mainly for the ICSBEP and IRPhE projects at the NEA; 2) to serve as an educational facility for graduate and post-graduate courses at the University of Sao Paulo; 3) to serve as an experimental facility for the development of master and doctoral theses at the University of Sao Paulo; and 4) to train and retrain the operators of the PWR power facilities ANGRA-I and -II. Previous experiments performed at the IPEN/MB-01 reactor comprised: critical and subcritical configurations for the ICSBEP, buckling and extrapolation length, spectral characteristics, reactivity measurements, temperature reactivity coefficient, effective kinetic parameters, reaction rate distributions and power distribution. Most of the former experiments had two objectives: to serve as a doctoral thesis at the University of Sao Paulo and to serve as reactor physics benchmark experiments for the IRPhE.

Description of the available experimental assemblies where integral experiments could be performed to meet the needs (include specific assemblies with their capabilities and limitations)

This facility consists of a 28 x 26 rectangular array of UO2 fuel rods of 4.3486 wt.% enriched uranium and clad by stainless steel (SS-304) inside a tank filled with light water. The maximum allowed power is 100 W. The control of the IPEN/MB-01 reactor is via two control banks diagonally placed. The control banks are composed of 12 Ag-In-Cd rods and the safety banks of 12 B4C rods. The square pitch of the IPEN/MB-01 reactor was chosen to be close to the optimum fuel-to-moderator ratio (maximum $k\infty$). This feature favours the thermal neutron energy region and mainly the ^{235}U events. The reactor core configuration is flexible, but it is limited to a square array of 30 x 30 fuel rod positions. It can be utilised for several reactor experiments, but it is limited to a minimum reactor period of 14 seconds for safety reasons. The frames that hold the reactor core can support an extra load of 300 kilograms. The baffle and the heavy reflector experiments performed in this facility had this limitation.

Fuel and material available

There are a total of 680 fuel rods with some spares and a total of six dismountable fuel rods.

Ongoing programmes

Within the scope of the new research reactor project, the Brazilian Multipurpose Reactor (RMB), a new critical configuration was designed for the IPEN/MB-01. After thirty years of work, the rod-type fuels were replaced by plate-type fuels to validate the RMB calculation methodologies as well as the nuclear data libraries used. The RMB is an open pool-type reactor with a maximum power of 30 MW, the core being a 5 x 5 configuration of 23 fuel elements made of U_3Si_2-Al, with an average density of 3.7 gU/cm^3 and 19.75 % enriched in ^{235}U, and two positions available in the core for material irradiation devices. The main goals of the RMB are the production of radioisotopes, silicon doping, neutron activation analysis, nuclear fuel and structural material testing and the development of scientific and technological research using neutron beams.

The new IPEN/MB-01 core has a 4 × 5 configuration, with 19 fuel elements, consisting of U_3Si_2-Al, 2.8 gU/cm^3 and 19.75% enriched in ^{235}U, plus one aluminium block. The IPEN/MB-01 new plate-type fuel assembly uses Cadmium wires as burnable poison, like the one used in the RMB core to control core power density and excess of reactivity during operation. The core is also reflected by four boxes of heavy water (D_2O) inserted in a moderator tank of light water. The maximum nominal power is 100 W and, for a safe operation, the critical assembly has both safety and auxiliary systems. Figure 18 shows the former rod-type fuel core and the new plate-type core. Figure 19 provides some details on the new arrangement.

Figure 18. Photographs of the rod-type fuel arrangement of the IPEN/MB-01 research reactor core (top) and the new plate-type fuel arrangement (below)

Rod-type fuel core

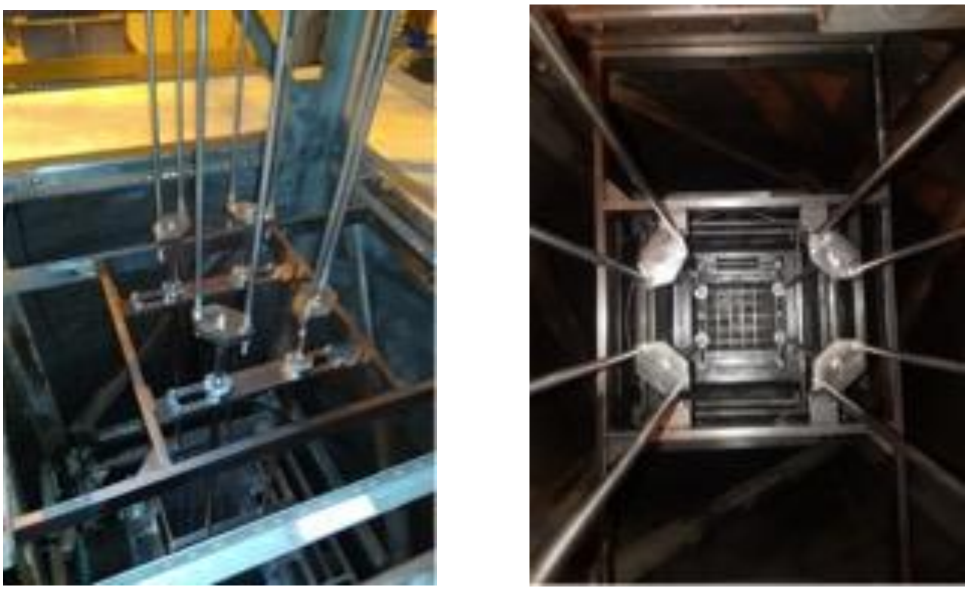


Plate-type fuel core

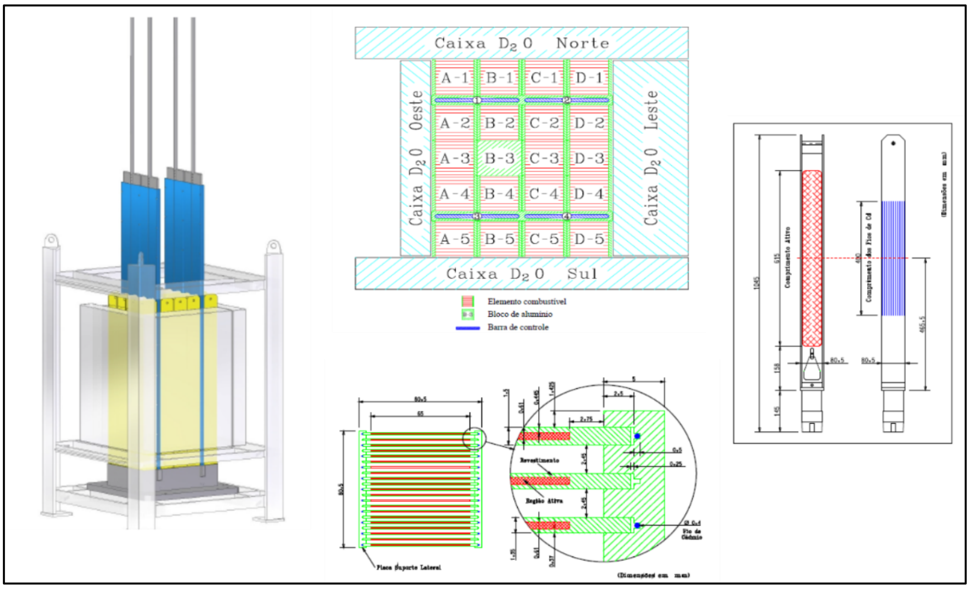
Source: IPEN, 2022

Notable past programmes

Since 2004, the experiments performed at the IPEN/MB-01 research reactor facility have been under benchmark processes under the NEA projects ICSBEP and IRPhE. These experiments can be classified as critical and subcritical configurations for ICSBEP and several classical reactor physics experiments such as isothermal reactivity coefficients and effective delayed parameters measurements. A considerable number of evaluations and detailed information is available in the ICSBEP and IRPhE handbooks. Some recent approved benchmarks include:

- ICSBEP/SUB-LEU-COMP-003: subcritical loading configurations of the ipen/mb-01 reactor with soluble boric acid in the moderator;
- ICSBEP/leu-comp-therm-103: critical loading configurations of the IPEN/MB-01 REACTOR composed of fuel rods and UMo plates in its core centre;
- IRPhE/IPEN(MB01)-LWR-RESR-019: U(n,f) and ^{238}U(n,γ) Reaction Rates Across the Fuel Pellet Radius of the IPEN/MB-01 Reactor;
- IRPhE/IPEN(MB01)-LWR-RESR-015: reactor physics experiments in the IPEN/MB-01 reactor with heavy reflectors composed of carbon steel and nickel.

Figure 19. Drawing showing details of the new plate-type fuel arrangement of the IPEN/MB-01



Source: IPEN, 2022.

Capabilities for additional measurements/unique capabilities

The IPEN/MB-01 research reactor facility possesses several capabilities including: neutron noise measurement systems, Germanium counters to measure activation/fission foils, and radiation generating devices. The neutron noise measurement systems include systems to perform APSD, CPSD, and Rossi-α, Feynman Variance-to-Mean. The control bank positioning system is one of the most accurate systems in the world and has a relative accuracy of 0.07 mm and an absolute accuracy of 0.1 mm. The control system has allowed several challenging experiments such as the inversion point of the isothermal reactivity coefficient.

2.5.8. RSV TAPIRO (Italian National Agency for New Technologies, Energy and Sustainable Economic Development [ENEA], Rome, Italy)

Facility contact: Luca Falconi

Overview description and general facility mission

The RSV TAPIRO nuclear research reactor is a fast neutron source. The reactor name comes from the Italian acronym TAratura PIla Rapida Potenza ZerO (Fast Pile Calibration at Zero Power). It was built to support an experimental program on fast reactors and has been in operation since 1971. It can operate at a maximum power of 5 kW, and the neutron flux at the centre of the core at full power is about $4\times10^{12} n\cdot cm^{-2}\cdot s^{-1}$. The reactor core is a cylinder made of highly enriched metallic uranium (weight 98.5% U; 1.5% Mo) surrounded by a reflector made of copper. RSV TAPIRO is able to provide a family of neutron spectra of extremely variable hardness (about pure fission spectrum near the core centre). This remarkable feature makes the reactor most suitable to many metrology applications, also taking into account that a good spherical symmetry of the neutron flux shape was evidenced by a joint ENEA-SCK CEN experimental campaign during the 1980s. RSV TAPIRO is used in many areas for: validation of calculation codes for Gen-IV reactor designs; fast neutron damage; benchmark for nuclear data testing; evaluation of fast neutron damage induced on electronic components; qualification of chains of innovative detectors; hands-on experience in nuclear engineering courses.

Description of the available experimental assemblies where integral experiments could be performed to meet the needs (include specific assemblies with their capabilities and limitations)

The RSV TAPIRO is equipped with many experimental channels that allow the installation of devices and experiences in areas of high flow. Each channel consists of a metallic cylindrical jacket and a plug for shielding purposes. The channels have a gradually reducing section to lower the gamma streaming effect. Each channel plug is essentially constituted by a casing filled with shielding material for the entire section, and it is provided with a copper extension occupying the area of penetration in the reflector. This extension may be modified to host the sample container. The plugs are provided with three holes available for remote control or power cables that might be needed in the experiments. A diametral channel allows irradiation of small metallic foils and targets in a region, the core centre, characterised by a neutron spectrum close to the fission one. The experimental equipment is complemented by a thermal column. The purpose of the thermal column is to provide an epithermal neutron flux, allowing at the same time the assembling of large experimental equipment.

Fuel and material available

^{235}U is used as reactor fuel in RSV TAPIRO. Fission chambers are available for measurements in RSV TAPIRO channels.

Ongoing programmes

RSV TAPIRO is involved in the AOSTA (Activation of OSMOSE Samples in TApiro) Experimental Programme. This programme has been developed in the framework of the NEA Expert Group on Integral Experiments for Minor Actinide Management between ENEA and CEA. The organisations wish to carry out joint research aimed at studying the feasibility of a selected minor actinide irradiation campaign in the RSV TAPIRO fast neutron source research reactor located at the ENEA Casaccia centre.

Notable past programmes

N/A

Capabilities for additional measurements/unique capabilities

The main feature of the RSV TAPIRO is the unique capability of its neutron field, which means it can be used for routine benchmark field referencing. It is also notable for the neutron spectrum in the centre of the core, where the RSV TAPIRO can furnish a neutron spectrum that is quite close to a fission spectrum.

2.5.9. CROCUS (EPFL, Switzerland)

Facility contact : Mathieu Hursin

Overview description and general facility mission

CROCUS is zero power reactor (100W) used for teaching and research purposes. It serves primarily for EPFL physics students (2nd and 3rd year) and since September 2008 for students in the international master degree programme in Nuclear Engineering jointly offered by two Swiss Federal Institutes of Technology, EPFL at Lausanne and ETHZ at Zurich. The reactor is also available for training of the nuclear power plant personnel and regulatory body specialists in Switzerland. Since 2014, an experimental program in reactor physics has been launched focusing mainly on noise measurements, dosimetry and the production of high resolution (space) data for code validation.

Description of the available experimental assemblies where integral experiments could be performed to meet the needs (include specific assemblies with their capabilities and limitations)

CROCUS is a light-water moderated reactor limited to a fission power of 100 W, corresponding to a neutron flux of ~2.5 10^9 neutrons per second at the centre of the core. The cylindrical core is approximately 60 cm in diameter and 100 cm in height. The core is located in a tank of 132.4 cm diameter, filled with demineralised light water, which serves both as moderator and radial reflector. It operates at room temperature with water circulation near to atmospheric pressure. The reactor is located in a 1.5 m thick concrete square structure as physical and shielding protection. The cavity can be opened from a side-door and a top-lid.

Fine control of the CROCUS reactor is achieved either via the water level, which can be adjusted to an accuracy of ±0.1mm, or by means of two control rods, each containing B4C pellets, located diagonally opposite each other at the edge of the core.

Fuel and material available

The fuel consists of two concentric inner and outer zones respectively composed of: 336 uranium oxide rods with an enrichment of 1.806 wt% and a pitch of 1.837 mm; as well as 172 metallic uranium rods 0.947 wt% enriched and a pitch of 2.917 mm.

Ongoing programmes

Various research programs are currently ongoing at CROCUS. The main ones are listed below.

- PETALE: analysis of the heavy steel reflector experiments with dosimetry measurements at different depth in a massive composed of mono-elemental slabs.

- VOID: reconstruction of the void profile in a two mixture flow in the reflector of CROCUS through neutron noise measurements.
- NECTAR: measurement of the flux profile within a fuel rod of the CROCUS reactor (both radial and azimuthal).
- SAFFROON: mapping of the thermal flux in the CROCUS core through 150 fiber-based neutron detectors.

Notable past programmes (references to ICSBEP/IRPhE evaluations)

A benchmark on CROCUS have been published in IRPHE, see CROCUS-LWR-RESR-001 for details.

Capabilities for additional measurements/unique capabilities

The reactivity effect of adding a heavy reflector made of stainless steel, Ni or Cr slabs could be investigated in a thermal reactor system.

3. Conclusion

The Subgroup on Experimental Needs for Criticality Safety Purposes (SG-5) asked the international nuclear criticality safety community about its integral experiment needs and ranked the identified needs in terms of priority. A total of 25 independent integral needs were identified and ranked. The top three needs (ranked as Priority 5) were intermediate energy experiments targeting ^{240}Pu and ^{238}U, chlorine and maintaining facilities to provide hands-on criticality safety training.

A section of the report was dedicated to describing existing proprietary experiments that might be used to meet some of the prioritised needs. Experiments from Valduc and Cadarache in France, VENUS in Belgium and the KRITZ facility in Sweden were detailed (see section 2.4).

An additional report section highlighted some of the many criticality experiments facilities available to perform some of the prioritised experiments (see section 2.5). These facilities each provide unique fuels, reflectors, moderators and capabilities, and the subsections aimed to highlight these unique characteristics for each facility. The listing did not cover all criticality experiment facilities worldwide as some of the facilities were not able to be contacted or were unable to share their information before the report was published. The facilities included in the report are: VENUS (Belgium), IPEN (Brazil), ZED-2 (Canada), LR-0 (Czech Republic), RSV TAPIRO (Italy), the Static Critical Facility (Japan), the National Criticality Experiments Research Centre (United States), Sandia Critical Experiments Facility (United States) and CROCUS (Switzerland). There are known to be facilities in Belarus, China, Japan and Russia that were not included in this report.

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Appendix: Forms

Survey form 1: United States, LLNL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 9/6/19

Name: Catherine Percher

Institution: Lawrence Livermore National Laboratory

Country: USA

Email: percher1@llnl.gov

2. **Methodology used to highlight the needs:**
   Coverage in ICSBEP

3. Experimental needs:

Domains to be covered	x Fuel fabrication x Reprocessing x Transportation ☐ Burn-up credit applications x Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring x Other *If other: Nuclear Data Validation*
Description of the Application	*The US Department of Energy Nuclear Criticality Safety Program (NCSP) convened a multi-national Thermal Epithermal eXperiments (TEX) meeting in July of 2011 to discuss the data and experimental needs of criticality safety practitioners. The number one and two priority integral experiment data needs were for ^{239}Pu and ^{240}Pu, with special emphasis on cross section performance in the intermediate energy range (from 0.625 eV to 100 keV). All plutonium systems have some amount of ^{240}Pu, although MOX applications would have a higher need for ^{240}Pu integral validation.*
Isotope/element/medium of interest	*^{240}Pu*
Functionality of the element/medium	x Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other: ……………………………………………….*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Fission, Scattering (Elastic and Inelastic), Capture*
Energy spectra**	☐ Fast ☐ Intermediate ☐ Thermal x Whole
Importance for criticality safety	☐ High x Medium ☐ Low
Current Knowledge Level	☐ Known x Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*In the 2018 version of the ICSBEP handbook, there are a number of experiments that use >10% ^{240}Pu material, but the majority of them are thermal systems. Having additional configurations with a large percentage of fissions in the intermediate and fast regions would allow for better data testing of ^{240}Pu.*
Experiments of interest***	*Very simple assemblies that have a minimum of materials to allow for efficient data validation. Assemblies that span multiple energy decades would be very useful.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 2: France, IRSN

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 2019

Name: I. Duhamel

Institution: IRSN

Country: France

Email:

2. **Methodology used to highlight the needs:**

3. Experimental needs:

Domains to be covered	☒ Fuel fabrication ☐ Reprocessing ☒ Transportation ☐ **Burn**-up credit applications ☒ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	*UO2 and UO2-PuO2 powders (U enrichment being lower than 5%,) with low moderation ratio and MOX fuel assemblies in dry storages or in transport casks*
Isotope/element/medium of interest	*UO2, PuO2, UO2-PuO2 with about 20% of ^{240}Puin Pu and LEU*
Functionality of the element/medium	☒ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other:*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*U238, Pu239 and Pu240 cross sections (capture, fission, ν, etc.)*
Energy spectra**	☐ Fast ☒ Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	☐ High ☒ Medium ☐ Low
Current Knowledge Level	☐ Known ☒ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*Very few existing experiments in epithermal energy spectra. Some existing experiments are of bad quality (PCM001, PCM002 and PCI002)* *Some BFS experiments are available in ICSBEP handbook* *TEX experiments with Pu9 will be available soon in ICSBEP handbook* *No experiment with LEU in intermediate spectra (238U) neither with high quantity of 240Pu*
Experiments of interest***	*Very simple assemblies with minimum of materials to allow for efficient data validation. Assemblies that span multiple energy decades would be very useful.*

** If known (based on sensitivity studies for example)*

*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*

**** if known*

Survey form 3: France, CEA

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 24, 2019

Name: P. Casoli / F.-X. Giffard / D. Noyelles

Institution: CEA

Country: France

Email: Pierre.CASOLI@cea.fr / francois-xavier.giffard@cea.fr / david.noyelles@cea.fr

2. **Methodology used to highlight the needs:**

Needs for data for little moderated Pu and UPu oxides

3. Experimental needs:

Domains to be covered	■ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ……………………………………*
Description of the Application	
Isotope/element/medium of interest	**Pu and UPu oxides**
Functionality of the element/medium	■ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other: ……………………………………………….*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	☐ Fast ■ Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	☐ High ■ Medium ☐ Low
Current Knowledge Level	☐ Known ■ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 4: Japan, NSR

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: Aug. 29, 2019

Name: Toshihisa Yamamoto

Institution: Secretariat of Nuclear Regulation Authority (SNR)

Country: Japan

Email: toshihisa_yamamoto@nsr.go.jp

2. **Methodology used to highlight the needs:**

Critical experiments under the condition of being flooded with seawater is the basic image of the proposal. It would be much desirable if the temperature of the seawater can be controlled by electrical heater.

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ **Burn**-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ■ Other *If other: …critical safety assessment in sea water flooding*
Description of the Application	*Japanese reactors are all located on the seashore. Under the severe accident condition, most of the reactors have to rely on seawater as the only water resource which is large enough to cope with the accident. As the seawater contains Cl-35 which has about 40 barns to thermal neutrons, seawater has the potentiality to be used as an easy-to-prepare neutron absorber to prevent unintentional criticality. Criticality measurements under various temperature conditions are considered to be useful for future safety regulatory activities.*
Isotope/element/medium of interest	*Chrolide-35, Sodium-23, Chrolide-37 (in solution)*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ☐ Reflector ■ Absorber ☐ Other *If other: ………………………………………………..*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Capture*
Energy spectra**	☐ Fast ☐ Intermediate ■ Thermal ☐ Whole
Importance for criticality safety	☐ High ■ Medium ☐ Low
Current Knowledge Level	☐ Known ■ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*Unknown (only numerical simulations are available)* *Related paper: M. Zerkle, "The Composition of Seawater and the Effect of Seawater Immersion on Reactivity", ICNC2015, Charlotte, NC, USA, Sep. 2015.*
Experiments of interest***	*Unknown*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 5: United States, LLNL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 9/6/19

Name: Catherine Percher

Institution: Lawrence Livermore National Laboratory

Country: USA

Email: percher1@llnl.gov

2. **Methodology used to highlight the needs:**
   Current ICSBEP survey

3. Experimental needs:

Domains to be covered	x Fuel fabrication x Reprocessing ☐ Transportation ☐ **Burn**-up credit applications x Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring x Other *If other: Nuclear Data Validation*
Description of the Application	*US DOE criticality safety operations have identified a programmatic need for validation cases for operations involving chlorine compounds, such as electrorefining and aqueous chloride systems.*
Isotope/element/medium of interest	*Cl*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator x Reflector x Absorber ☐ Other *If other: ……………………………………………….*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Capture, Scattering*
Energy spectra**	☐ Fast ☐ Intermediate ☐Thermal x Whole
Importance for criticality safety	x High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known x Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*Currently, the International Criticality Safety Evaluation Project (ICSBEP) Handbook contains five configurations with chorine, two as part of HEU-SOL-THERM-044 and three as part of LEU-SOL-THERM-045. Only one of the cases (HST-045-03) is very sensitive to Cl-35. Additionally, for all five cases from ICSBEP, the chlorine material used was poly-vinyl chloride (PVC), which is a polymer whose composition uncertainties could introduce significant error into the experiment.*
Experiments of interest***	*Chlorine reflected assemblies at all energy spectra, themal absorption experiments with dispersed chlorine.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 6: United States, LANL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 7/24/2019

Name: Nicholas Thompson

Institution: Los Alamos National Laboratory

Country: United States of America

Email: nthompson@lanl.gov

2. **Methodology used to highlight the needs:**

Leaders and members of the Nuclear Criticality Safety Division at LANL were surveyed and asked about experimental needs.

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication X Reprocessing ☐ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	*Aqueous Reprocessing. Ability to perform aqueous reprocessing is significantly limited by not having benchmarks sensitive to chlorine.*
Isotope/element/medium of interest	*Chlorine*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ☐ Reflector X Absorber ☐ Other *If other: ....*.
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	☐ Fast X Intermediate X Thermal (mostly thermal but epithermal would also help) ☐ Whole
Importance for criticality safety	X High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known X Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*There are some benchmarks sensitive to chlorine at thermal, but only one sensitive to chlorine above 1 eV.*
Experiments of interest***	*Solution system with Pu would be optimal, but may not be possible. Most benchmarks that are sensitive to chlorine use PVC, it would be better if this benchmark did not use PVC.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 7: United States, LANL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 9/3/2019

Name: Nicholas Thompson

Institution: Los Alamos National Laboratory

Country: USA

Email: nthompson@lanl.gov

2. **Methodology used to highlight the needs:**

Leaders and members of the Nuclear Criticality Safety Division at LANL were surveyed and asked about experimental needs.

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ **Burn**-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring X Other *If other: Any application with stainless steel or Fe/Cr alloys*
Description of the Application	*Many applications use stainless steel.*
Isotope/element/medium of interest	*Chromium and Iron/Chromium alloys*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ☐ Reflector X Absorber ☐ Other *If other: ……………………………………………….*
Nuclear data of interest* (capture, scattering, $S(\alpha,\beta)$, ν, etc.)	*Capture, scattering*
Energy spectra**	☐ Fast X Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	X High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known X Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*Only a handful of ICSBEP benchmarks are sensitive to chromium in the intermediate energy region.*
Experiments of interest***	*Critical experiments with varying Fe/Cr alloys and pure Cr if possible.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 8: United States, LLNL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 9/6/19

Name: Catherine Percher

Institution: Lawrence Livermore National Laboratory

Country: USA

Email: percher1@llnl.gov

2. **Methodology used to highlight the needs:**
   Sensitivity studies of application cases

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication x Reprocessing ☐ Transportation ☐ Burn-up credit applications x Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring x Other *If other: Nuclear Data Validation*
Description of the Application	*The nuclear criticality safety evaluations supporting US liquid waste processing operations currently credit the presence of neutron absorbers in the large, geometrically unfavorable liquid waste storage tanks to preclude criticality. These are not the traditional strong neutron absorbers used for reactor reactivity control (such as boron, gadolinium, etc.), but are instead weaker absorbers such as aluminum, chromium, iron, manganese, nickel, silicon, and zirconium that were disposed to the tanks along with the fissile material.*
Isotope/element/medium of interest	*Al, Cr, Fe, Mn, Ni, Si, Zr as absorbers*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ☐ Reflector x Absorber ☐ Other *If other: ………………………………………………….*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Capture*
Energy spectra**	☐ Fast ☐ Intermediate x Thermal ☐ Whole
Importance for criticality safety	☐ High x Medium ☐ Low
Current Knowledge Level	☐ Known x Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*Currently, the International Criticality Safety Evaluation Project (ICSBEP) Handbook contains four uranium, not plutonium, configurations where iron acts as an absorber, but there is too little iron present in the assemblies to provide much sensitivity to the absorption cross section. There is one uranium benchmark with nickel absorption sensitivity, although at a low level of sensitivity, and there are no manganese absorption sensitive benchmarks.*
Experiments of interest***	*Thermal plutonium experiments that optimize sensitivity to the absorber.*

** If known (based on sensitivity studies for example)*

*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*

**** if known*

Survey form 9: United States, LANL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: May 2021

Name: N. Thompson

Institution: LANL

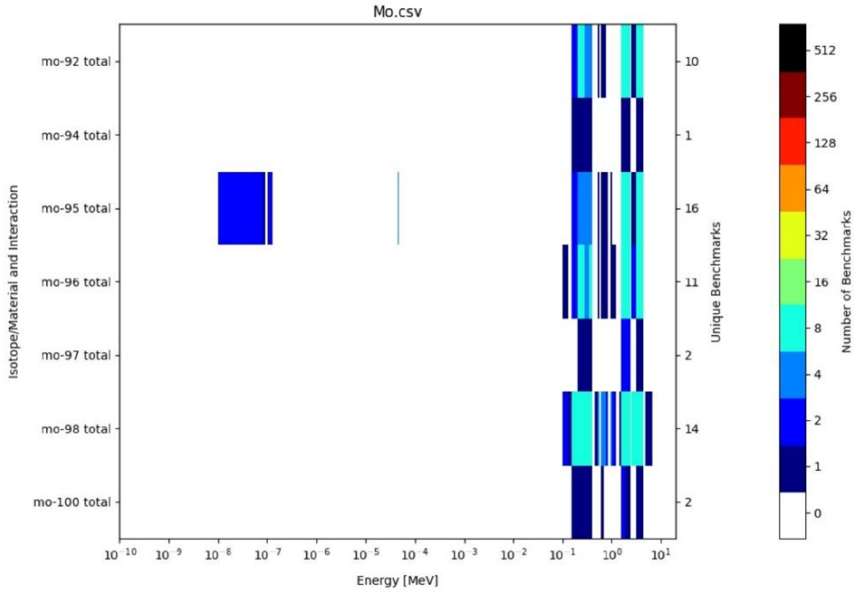
Country: USA

Email: nthompson@lanl.gov

2. Methodology used to highlight the needs:

Survey was taken of various nuclear criticality safety needs throughout the US. Molybdenum has many uses, including as an alloy for uranium in certain nuclear fuels (research reactors, space reactors, and advanced fuel concepts) and in some accelerator targets. Improving Mo nuclear data has also been identified by the US Nuclear Criticality Safety Program (NCSP) as a priority, and NCSP has funded differential measurements and new resonance region evaluations of Mo. Mo is also a stable fission product and the ultimate goal of NCSP is to take credit for Mo in transportation, fuel storage, and reprocessing activities.

Heatmaps of existing integral benchmark sensitivities were also used to determine whether existing benchmarks are sufficient to validate new evaluations based on new differential data. However, there are very few benchmarks sensitive to Mo, and most of these benchmarks are sensitive to Mo only in the fast neutron energy region – no benchmarks exist with adequate sensitivity to Mo in the resonance region to validate resonance region nuclear data. This can be seen in the figure below.



3. Experimental needs: Resonance Region Mo

Domains to be covered	X Fuel fabrication X Reprocessing X Transportation X **Burn**-up credit applications X Storage X Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	*Numerous applications – nuclear fuels, accelerator targets, and fission products.*
Isotope/element/medium of interest	*Molybdenum*
Functionality of the element/medium	☐ Fuel X Moderator ☐ Separator ☐ Reflector X Absorber X Other *If other: Alloy in some fuels, fission fragment*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Resonance region capture, total*
Energy spectra**	☐ Fast X Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	☐ High X Medium ☐ Low
Current Knowledge Level	☐ Known X Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	*Integral benchmark focused on resonance region capture of Mo.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*

***** if known*

Survey form 10: France, IRSN

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: August 2020

Name: N. LECLAIRE

Institution: IRSN

Country: France

Email:

2. **Methodology used to highlight the needs:**

3. Experimental needs: Molybdenum

Domains to be covered

☐ Fuel fabrication ☒ Reprocessing ☐ Transportation
☒ **Burn**-up credit applications ☐ Storage ☐ Final disposal
☐ Criticality accidents studies ☐ sub-criticality monitoring
☐ Other *If other: ....*

Description of the Application

UPuMoZr fuel residues with a density of 2.6 g/cm3 in water. The mixture is representative of a fuel burn at 50 GWd/t.

The UPuMoZr fuel residues are found at the bottom of the dissolvor in the reprocessing plant.

The characteristics of the fuel are described below.

Element	*U*	*Pu*	*Mo*	*Zr*
Contents in wt. %	*6.06*	*2.43*	*63.40*	*28.11*
Isotope	*235U*	*238U*		
Enrichment in wt. %	*1*	*99*		
Isotope	*239Pu*	*240Pu*	*241Pu*	*242Pu*
Content in wt. %	*57.2875*	*25*	*16.25*	*1.4625*

Isotopics of Molybdenum.

Isotope	*92Mo*	*95Mo*	*96Mo*	*97Mo*	*98Mo*	*100Mo*
Contents in wt. %	*1*	*21*	*3*	*23*	*25*	*27*

Isotope/element/medium of interest

Natural molybdenum in UPuMoZr dissolution residues and in lowly moderated by water.

Functionality of the element/medium

☒ Fuel ☐Moderator ☐ Separator
☐Reflector ☒ Absorber ☐ Other
If other:

Nuclear data of interest*
(capture, scattering, S(α,β), ν, etc.)

Capture in the thermal energy or epithermal range

Energy spectra**

☐ Fast
☒ Intermediate
☒ Thermal
☐ Whole

Importance for criticality safety

☒ High
☐ Medium
☐ Low

Current Knowledge Level

☐ Known
☐ Partially Known
☒ Unknown

Known validation shortfalls and assessment of available integral data* **	*The MIRTE experiments involving molybdenum are the best existing experiment. However, they are not sensitive enough when compared with the application case sensitivities.*
Experiments of interest* **	*Experiments that involve molybdenum in sleeves or in foils and that use fuel rods that are well-characterized would be of interest.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 11: France, IRSN

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 2019

Name: I. Duhamel

Institution: IRSN

Country: France

Email:

2. **Methodology used to highlight the needs:**

3. Experimental needs:

Domains to be covered	☒ Fuel fabrication ☐ Reprocessing ☒ Transportation ☐ **Burn**-up credit applications ☒ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	*UZrH fuel assemblies*
Isotope/element/medium of interest	*UZrH*
Functionality of the element/medium	☒ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other:*
Nuclear data of interest* (capture, scattering, $S(\alpha,\beta)$, ν, etc.)	*TSL for UZrH* *Zr cross sections*
Energy spectra**	☐ Fast ☐ Intermediate ☐ Thermal ☒ Whole
Importance for criticality safety	☐ High ☒ Medium ☐ Low
Current Knowledge Level	☐ Known ☒ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*Only 1 existing experiment in ICSBEP* *One experiment presented at ICNC by S. SIKORIN performed in Crystal facility (not in ICSBEP yet)*
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 12: United States, LLNL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 9/6/19

Name: Catherine Percher

Institution: Lawrence Livermore National Laboratory

Country: USA

Email: percher1@llnl.gov

2. **Methodology used to highlight the needs:**
   Current ICSBEP survey

3. Experimental needs:

Domains to be covered	x Fuel fabrication x Reprocessing x Transportation ☐ Burn-up credit applications x Storage x Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring x Other *If other: Nuclear Data Validation*
Description of the Application	*The US Nuclear Criticality Safety Program has funded the development of new thermal scattering (S α,β) laws, a number of which were released as part of the ENDF/B-VIII.0 data library in December 2017. Hydrogenous polymers like polyethylene and Lucite (plexiglass) are often found in nuclear applications in the form of shielding and contamination control (bags, gloves, etc).*
Isotope/element/medium of interest	*Cl*
Functionality of the element/medium	☐ Fuel x Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other: ……………………………………………….*
Nuclear data of interest* (capture, scattering, $S(\alpha,\beta)$, ν, etc.)	*Thermal scattering*
Energy spectra**	☐ Fast ☐ Intermediate X Thermal ☐ Whole
Importance for criticality safety	x High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known x Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*In a survey of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook, there are not many experiments that are sensitive to thermal scattering for solid moderators like Lucite and polyethylene. The current configurations with polyethylene are not very sensitive to polyethylene thermal scattering, and there are very few Lucite critical benchmarks due to the lack of a thermal scattering law until the recently published ENDF/B-VIII.0 library.*
Experiments of interest***	*Polyethylene and Lucite moderated thermal plutonium and uranium experiments.*

** If known (based on sensitivity studies for example)*

*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 13: France, IRSN

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 2019

Name: M. Duluc

Institution: IRSN

Country: France

Email: matthieu.duluc@irsn.fr

2. **Methodology used to highlight the needs:**

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ **Burn**-up credit applications ☐ Storage ☐ Final disposal ☒ Criticality accidents studies ☐ sub-criticality monitoring ☐Other *If other: ………………… …………………*
Description of the Application	*Pu solution encountered in reprocessing plants and research facilities at various concentration, Gen-4 fuels based on Plutonium* ▪ *95 % of criticality accident in nuclear facilities occurred with solution* ▪ *40 % of criticality accident in nuclear facilities occurred with Plutonium solution*
Isotope/element/medium of interest	*Plutonium solution*
Functionality of the element/medium	☒ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other:*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	☐ Fast ☒ Intermediate ☒ Thermal ☐ Whole
Importance for criticality safety	☐ High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known ☐ Partially Known ☒ Unknown
Known validation shortfalls and assessment of available integral data***	*No experiments with Pu or U-Pu solution* *Existing HEU solutions experiments*
Experiments of interest***	*Transient experiments (such as in SILENE with HEU) to study Phenomenology and kinetic of criticality accidents and test radiation protection instrumentations* ▪ *Thermodynamics and thermal-hydraulic behavior of solution (pressure, "sloching effect")* ▪ *Feedback effect* ▪ *Boiling and heat loss effect* ▪ *Radiolysis (production/release)* ▪ *Release rate of fission products*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 14: France, IRSN

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 2019

Name: M. Duluc

Institution: IRSN

Country: France

Email: matthieu.duluc@irsn.fr

2. **Methodology used to highlight the needs:**

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☒ Criticality accidents studies ☐ sub-criticality monitoring ☐Other *If other: ....*
Description of the Application	*A solution reactor to study, validate and train people about criticality accident*
Isotope/element/medium of interest	*Solution reactor (uranium, plutonium or U-Pu)*
Functionality of the element/medium	☒ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other:*
Nuclear data of interest* (capture, scattering, $S(\alpha,\beta)$, ν, etc.)	
Energy spectra**	☐ Fast ☒ Intermediate ☒ Thermal ☐ Whole
Importance for criticality safety	☒ High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known ☒ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*No solution facility currently known to study, validate and train people about criticality accident*
Experiments of interest***	*Solution reactor :* • *to perform reference experiments to validate criticality accident tools (evolution of the power as a function of the time and dose calculation (fixed source code));* • *to train and validate the management of Post accident situations: (Management of reentry and stabilization for on-going criticality accidents) and the validation of Post accident devices (robots, etc.)* • *to design, validation, calibration of nuclear instruments (radioprotection devices and reactors control) (CAAS response, Accident detection for various kinetics (in free air or behind shielding), Accident dosimetry intercomparison exercices)*

	• *to study radiobiology, physical and biological dosimetry of mixed g/n irradiations* • *to study the link between the number of fissions and doses (+ attenuation effect)* • *to study the release of the fission products* • *to improve the knowledge in prompt and delayed gamma* • *to be used as an experimental tool in Neutron Physics (Input data (Generation time, features of delayed neutron, fission yields, branching ratio, temperature effect, etc.), Critical and Sub-critical experiments (New fuels (Pu, MOX), minor actinides, structural material, matrix, neutron poison, BUC, etc)., Reactivity measurements (perturbation), Random neutron physic (Neutron noise technic), Neutron and gamma intrinsic source (neutron initiation experiment))* • *to train people (Phenomenology and kinetic of criticality accident, Accident dosimetry exercise, Reentry and accident stabilization exercise)*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 15: United States, LANL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 9/3/2019

Name: Nicholas Thompson

Institution: Los Alamos National Laboratory

Country: USA

Email: nthompson@lanl.gov

2. **Methodology used to highlight the needs:**

Leaders and members of the Nuclear Criticality Safety Division at LANL were surveyed and asked about experimental needs.

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication X Reprocessing ☐ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	*Reprocessing*
Isotope/element/medium of interest	*Pu238*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ☐ Reflector X Absorber ☐ Other *If other: ....*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	☐ Fast ☐ Intermediate X Thermal ☐ Whole
Importance for criticality safety	☐ High ☐ Medium X Low
Current Knowledge Level	☐ Known X Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	*Solution system with Pu238 and Pu239*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 16: France, CEA

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 24, 2019

Name: P. Casoli / J.-S. Borrod / M. Laget

Institution: CEA

Country: France

Email: Pierre.CASOLI@cea.fr / Jean-sebastien.borrod@cea.fr / michael.laget@cea.fr

2. **Methodology used to highlight the needs:**

Needs of a neutron/gamma source to test criticality accident dosimetry systems

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ **Burn**-up credit applications ☐ Storage ☐ Final disposal ■ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other:* ....
Description of the Application	**Needs of a neutron/gamma source to test criticality accident dosimetry systems**
Isotope/element/medium of interest	Not available.
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other:* **Not available**
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	☐ Fast ☐ Intermediate ☐ Thermal ■ Whole
Importance for criticality safety	■ High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known ■ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 17: United States, LANL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: **9/3/2019**

Name: **Nicholas Thompson**

Institution: **Los Alamos National Laboratory**

Country: **USA**

Email: **nthompson@lanl.gov**

2. **Methodology used to highlight the needs:**

Surveyed nuclear criticality safety experts at various US labs.

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ■ Reprocessing ☐ Transportation ☐ Burn-up credit applications ■ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	In solution, need to credit to support criticality safety analyses
Isotope/element/medium of interest	Nickel, in combination with other metals
Functionality of the element/medium	☐ Fuel ■ Moderator ☐ Separator ☐ Reflector ■ Absorber ☐ Other *If other: ....*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	Total, capture
Energy spectra**	☐ Fast ☐ Intermediate ■ Thermal ☐ Whole
Importance for criticality safety	☐ High ■ Medium ☐ Low
Current Knowledge Level	☐ Known ■ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	Very few critical benchmarks are highly sensitive to nickel
Experiments of interest***	Critical experiments with Pu and nickel

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 18: United States, LANL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 9/3/2019

Name: **Nicholas Thompson**

Institution: **Los Alamos National Laboratory**

Country: **USA**

Email: **nthompson@lanl.gov**

2. **Methodology used to highlight the needs:**

Leaders and members of the Nuclear Criticality Safety Division at LANL were surveyed and asked about experimental needs.

3. Experimental needs:

Domains to be covered	X Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ **Burn**-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	*Plutonium casting*
Isotope/element/medium of interest	*Tantalum*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator X Reflector ☐ Absorber ☐ Other *If other: ....*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	X Fast ☐ Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	X High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known X Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*Only one relevant benchmark in ICSBEP*
Experiments of interest***	*Fast critical Ta measurement*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 19: Czech Republic, CVREZ

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date:17.9.2019

Name: Michal Košťál

Institution: Research Center Rez

Country: Czech Republic

Email:Michal.Kostal@cvrez.cz

2. **Methodology used to highlight the needs:**

Neutron transport description in fluorine seems to be an issue, because there were reported significant discrepancies in region 0.1 – 1 MeV in fluoride media *(„Comparison of fast neutron spectra in graphite and FLINA salt inserted in well-defined core assembled in LR-0 reactor", Ann. of Nucl.En., 83, 2015, pp. 216-225)*

3. Experimental needs:

Domains to be covered	x Fuel fabrication x Reprocessing ☐ Transportation ☐ **Burn**-up credit applications x Storage ☐ Final disposal x Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	*Fluorine is important element not only in MSR concept, but also during fuel fabrication process.*
Isotope/element/medium of interest	19F
Functionality of the element/medium	x Fuel x Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other: ....*.
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	capture, scattering, S(α,β)
Energy spectra**	x Fast x Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	☐ High x Medium ☐ Low
Current Knowledge Level	☐ Known x Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*Neutron transport in fluorine agents.*
Experiments of interest***	*Integral experiments with fluorides salts. Especially focused on criticality and neutron transport. Leakage spectra from suitable fluoride with well defined pointwise source (252Cf) may also help in looking for bugs in evaluation.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** If known*

Survey form 20: France, CEA

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 24, 2019

Name: P. Casoli / F.-X. Giffard

Institution: CEA

Country: France

Email: Pierre.CASOLI@cea.fr / francois-xavier.giffard@cea.fr

2. **Methodology used to highlight the needs:**

Needs for data for fuel in plate geometries

3. Experimental needs:

Domains to be covered	■ Fuel fabrication ☐ Reprocessing ■ Transportation ☐ Burn-up credit applications ■ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	**RJH studies, among others**
Isotope/element/medium of interest	**LEU, IEU**
Functionality of the element/medium	■ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other: ....*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	☐ Fast ☐ Intermediate ■ Thermal ☐ Whole
Importance for criticality safety	■ High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known ■ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 21: France, CEA

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 24, 2019

Name: P. Casoli / J.-S. Borrod

Institution: CEA

Country: France

Email: Pierre.CASOLI@cea.fr / Jean-sebastien.borrod@cea.fr

2. **Methodology used to highlight the needs:**

Need of a metallic core pulsed reactor to study physics and mechanics effects of a criticality accident in a metallic medium

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ **Burn**-up credit applications ☐ Storage ☐ Final disposal ■ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	**Need of a metallic core pulsed reactor to study physics and mechanics effects of a criticality accident in a metallic medium**
Isotope/element/medium of interest	**Highly enriched uranium**
Functionality of the element/medium	■ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other: ....*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	■ Fast ☐ Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	☐ High ■ Medium ☐ Low
Current Knowledge Level	☐ Known ■ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 22: France, IRSN

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: August 2020

Name: N. LECLAIRE

Institution: IRSN

Country: France

Email:

2. **Methodology used to highlight the needs:**

1. Experimental needs: fluorine in HF

Domains to be covered	☒ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: …………………………………*
Description of the Application	*During the enrichment process of uranium in UO2, uranium is converted in UF6-HF.* *Keff is very sensitive to the cross sections of fluorine and to the thermal scattering cross sections of H in HF and F in HF.*
Isotope/element/medium of interest	*Fissile materials (U, Pu) and water*
Functionality of the element/medium	☐ Fuel ☒Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other:*
Nuclear data of interest* (capture, scattering, $S(\alpha,\beta)$, ν, etc.)	Thermal scattering data of F in HF and H in HF.
Energy spectra**	☐ Fast ☒ Intermediate ☒ Thermal ☐ Whole
Importance for criticality safety	☐ High ☒ Medium ☐ Low
Current Knowledge Level	☐ Known ☐ Partially Known ☒ Unknown
Known validation shortfalls and assessment of available integral data***	*No benchmark experiments apart from HST-039 are available. However, this series is unique and a potential bias cannot be discarded*
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 23: United States, LLNL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 9/6/19

Name: Catherine Percher

Institution: Lawrence Livermore National Laboratory

Country: USA

Email: percher1@llnl.gov

2. **Methodology used to highlight the needs:**
   Current ICSBEP survey

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing x Transportation ☐ **Burn**-up credit applications ☐ Storage x Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring x Other *If other: Nuclear Data Validation*
Description of the Application	US and IAEA regulations delineate the normal conditions of transport under which a radioactive transport must be shown to be safe. In US regulations, there is a requirement that the package must be shown to be criticality safe, by assignment of a Criticality Safety Index (CSI), under normally-expected ambient temperatures between -40°C and 38°C. However, there are no benchmark experiments conducted at low temperature that would allow validation of CSI calculations completed at temperatures of -40°C.
Isotope/element/medium of interest	*^{239}Pu, ^{240}Pu, ^{235}U, ^{238}U*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other: Temperature dependency of cross sections at -40°C*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Thermal scattering*
Energy spectra**	☐ Fast ☐ Intermediate ☐ Thermal x Whole
Importance for criticality safety	x High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known x Partially Known, based on extrapolation ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*In a survey of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook, there are no critical benchmarks at temperatures below 270K.*
Experiments of interest***	*Simple assemblies using a minimum of materials for data validation purposes.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*

**** if known*

Survey form 24: United States, LANL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 27 August 2019

Name: Rene Sanchez

Institution: Los Alamos National Laboratory

Country: USA

Email: rgsanchez@lanl.gov

2. **Methodology used to highlight the needs:**

No critical experiment data exist where the moderator and reflector of a critical experiment are at extremely low temperatures. This proposal will address how the critical mass may vary as the moderator and reflector in a critical experiment cool down to cryogenic temperature.

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring X Other *If other: ...Space Reactors...*
Description of the Application	*As NASA continues the exploration of deep space, there is a need for a safe, reliable, and long lasting source of electrical energy. Temperatures in outer space can be as low as 2 K. Simulations have shown that when a thin ^{235}U foil is surrounded by a low absorbing moderator and reflector materials (such as heavy water) and their temperature lowered to 4 Kelvin, the fission process is greatly enhanced. Simulations have yielded critical masses on the order of 35 to 70 grams of uranium. The reason for this dramatic decrease in the critical mass is that the fission cross section increases from 580 barns for thermal neutrons to 3000 barns for neutrons having energies of 0.001 eV (cold neutrons or neutrons in a low temperature (4 Kelvin), low absorbing moderator/reflector).*
Isotope/element/medium of interest	*^{235}U, heavy water*
Functionality of the element/medium	x Fuel x Moderator ☐ Separator x Reflector ☐ Absorber ☐ Other *If other: ....*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Fission, capture, scattering, S(α, β)*
Energy spectra**	☐ Fast ☐ Intermediate X Thermal ☐ Whole
Importance for criticality safety	☐ High ☐ Medium X Low
Current Knowledge Level	☐ Known ☐ Partially Known X Unknown
Known validation shortfalls and assessment of available integral data***	*No integral data exist that can be applied to this application.*
Experiments of interest***	*Critical*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 25: France, IRSN

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 2019

Name: I. Duhamel

Institution: IRSN

Country: France

Email:

2. **Methodology used to highlight the needs:**

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☒ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	*Transport cask with temperature ranging from -40 °C to +38 °C for type B(U) packages (IAEA regulation)*
Isotope/element/medium of interest	*Fissile materials (U, Pu) and water*
Functionality of the element/medium	☒ Fuel ☒Moderator ☐ Separator ☒Reflector ☐ Absorber ☐ Other *If other:*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	capture, scattering, S(α,β), ν,
Energy spectra**	☐ Fast ☐ Intermediate ☐ Thermal ☒ Whole
Importance for criticality safety	☒ High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known ☐ Partially Known ☒ Unknown
Known validation shortfalls and assessment of available integral data***	*no benchmark experiments conducted at low temperatures*
Experiments of interest***	*Very simple assemblies that have a minimum of materials to allow for efficient data validation. Assemblies that span multiple energy decades would be very useful.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 26: United States, LANL

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This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 9/3/2019

Name: **Nicholas Thompson**

Institution: **Los Alamos National Laboratory**

Country: **USA**

Email: **nthompson@lanl.gov**

2. **Methodology used to highlight the needs:**

Surveyed nuclear criticality safety experts at various US labs.

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication X Reprocessing ☐ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ……………………………………*
Description of the Application	Dissolver vessel for fuel dissolution; serves as the reflector
Isotope/element/medium of interest	Niobium
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ■ Reflector ☐ Absorber ☐ Other *If other: ……………………………………………….*
Nuclear data of interest* (capture, scattering, $S(\alpha,\beta)$, ν, etc.)	Total, capture
Energy spectra**	■ Fast ☐ Intermediate ☐ Thermal ■ Whole
Importance for criticality safety	■ High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known ☐ Partially Known ■ Unknown
Known validation shortfalls and assessment of available integral data***	Very little data and no critical benchmarks
Experiments of interest***	Critical experiments with Pu and niobium

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 27: France, CEA

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Survey

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This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 24, 2019

Name: P. Casoli / F.-X. Giffard / A. Dorval

Institution: CEA

Country: France

Email: Pierre.CASOLI@cea.fr / francois-xavier.giffard@cea.fr / Aurelien.DORVAL@cea.fr

2. **Methodology used to highlight the needs:**

Needs for data for tungsten used as reflector

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ **Burn**-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ■ Other *If other:* **Laboratory studies**
Description of the Application	
Isotope/element/medium of interest	**Tungsten**
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ■ Reflector ☐ Absorber ☐ Other *If other: ………………………………………………..*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	
Energy spectra**	☐ Fast ☐ Intermediate ☐ Thermal ■ Whole
Importance for criticality safety	☐ High ■ Medium ☐ Low
Current Knowledge Level	☐ Known ☐ Partially Known ■ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 28: France, IRSN

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: September 2019

Name: I. Duhamel

Institution: IRSN

Country: France

Email:

2. **Methodology used to highlight the needs:**

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☒ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ……………………………………*
Description of the Application	*Thick Aluminum as reflector or separator in transport cask*
Isotope/element/medium of interest	*Aluminum*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☒ Separator ☒ Reflector ☐ Absorber ☐ Other *If other:*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Aluminum scattering cross sections*
Energy spectra**	☐ Fast ☒ Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	☐ High ☒ Medium ☐ Low
Current Knowledge Level	☐ Known ☒ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	*No experiments sensitive to Al in intermediate spectra*
Experiments of interest***	*Very simple assemblies that have a minimum of materials to allow for efficient data validation with high sensitivity to Al. Assemblies that span multiple energy decades would be very useful.*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 29: United Kingdom, Sellafield Ltd

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 19 May 2023

Name: Dominic Winstanley

Institution: Sellafield Ltd

Country: UK

Email: dominic.d.winstanley@sellafieldsites.com

2. **Methodology used to highlight the needs:**

Coverage in ICSBEP

Needs reflect existing high priority entries in NEA/NSC/R(2022)6

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication x Reprocessing x Transportation ☐ Burn-up credit applications x Storage x Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	• intermediate spectrum Pu240/ U238 • intermediate spectrum Pu239/ U235 *Powder handling operations, including storage, retreatment, repackaging and potential disposition options tend to have intermediate spectra where there is limited validation data. Calculated bias/ bias uncertainty values are relatively high and affect optimization of equipment designs and operational controls. Noted that TEX experiments are helping fill this gap*
Isotope/element/medium of interest	*Pu239, Pu240, U235, U238*
Functionality of the element/medium	x Fuel ☐ Moderator ☐ Separator ☐ Reflector x Absorber ☐ Other *If other: ....*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Pu239, Pu240, U235, U238 – fission, scattering (elastic/ inelastic), capture*
Energy spectra**	☐ Fast x Intermediate ☐ Thermal ☐ Whole
Importance for criticality safety	☐ High x Medium ☐ Low
Current Knowledge Level	☐ Known x Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 30: United Kingdom, Sellafield Ltd

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 19 May 2023

Name: Dominic Winstanley

Institution: Sellafield Ltd

Country: UK

Email: dominic.d.winstanley@sellafieldsites.com

2. **Methodology used to highlight the needs:**

Coverage in ICSBEP

Needs reflect existing high priority entries in NEA/NSC/R(2022)6

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing x Transportation ☐ Burn-up credit applications x Storage x Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	• *Chlorine is present in many fissile waste streams, e.g. in the form of PVC. Better validation may allow greater credit to be taken to underpin and/or increase fissile limits for waste production, storage, transport and disposal. Given large volumes of waste, associated cost savings could be high, with coincident risk benefits from production and movement of fewer packages.*
Isotope/element/medium of interest	*Cl-35*
Functionality of the element/medium	☐ Fuel ☐ Moderator ☐ Separator ☐ Reflector x Absorber ☐ Other *If other: ....*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	*Capture*
Energy spectra**	☐ Fast ☐ Intermediate ☐ Thermal x Whole
Importance for criticality safety	☐ High x Medium ☐ Low
Current Knowledge Level	☐ Known x Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 31: United Kingdom, NNL

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

The objective of this survey is to collect the needs for new experiments and to rank them according to the importance for criticality-safety (High/Medium/Low) and the current knowledge level (Known/Partially Known/Unknown).

This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: 19th May 2023

Name: Deborah Hill

Institution: National Nuclear Laboratory

Country: United Kingdom

Email: deborah.a.hill@uknnl.com

2. **Methodology used to highlight the needs:**

No structured methodology – purely influenced by current UK interests *{Plus information provided in response to urgent request, so some details are not fully developed}*

3. Experimental needs:

Domains to be covered	X Fuel fabrication ☐ Reprocessing ☐ Transportation ☐ Burn-up credit applications ☐ Storage ☐ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ……………………………………*
Description of the Application	Shortage of critical benchmark experiments for HALEU
Isotope/element/medium of interest	UK currently has Coated Particle Fuel (CPF) interests in the range from 5 – 20 $^{w}/_{o}$ ^{235}U enrichment. Current compounds of interest are (i) uranium dioxide, and (ii) uranium nitride [potentially with nitrogen-15] – but also the potential for (iii) uranium carbide, and (iv) uranium oxycarbides in due course. *{Also the potential for large quantities of carbon / graphite & silicon}*
Functionality of the element/medium	X Fuel ☐ Moderator ☐ Separator ☐ Reflector X Absorber [in case of nitrogen] ☐ Other *If other: ………………………………………………..*
Nuclear data of interest* (capture, scattering, S(α,β), ν, etc.)	• <u>All Compounds</u> – Intermediate spectra of ^{235}U and ^{238}U • <u>Nitrides</u> – (i) Scattering of N-14 and N-15, and (ii) capture of N-14 *{Suspect there are issues with the related covariance data for N}*
Energy spectra**	☐ Fast X Intermediate *{for ^{235}U and ^{238}U}* X Thermal *{Known issues in this range for N-14 & N-15 – but perhaps wider ?}* ☐ Whole
Importance for criticality safety	X High *{Primarily driven by general concern about lack of benchmarks in 5 – 20 $^{w}/_{o}$ ^{235}U enrichment range (not the specific CPF application)}* ☐ Medium ☐ Low
Current Knowledge Level	☐ Known X Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*

Survey form 32: Switzerland, PSI and NAGRA

WPNCS SG 5: Sub-Group on Experimental needs for criticality safety purpose

Survey

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This would help to compile high-priority needs for experiments in criticality safety.

1. **General information:**

Request Date: May 2023

Name: A. Vasiliev, M. Wittel

Institution: Paul Scherrer Institut, Nagra

Country: Switzerland

Email: alexander.vasiliev@psi.ch, madalina.wittel@nagra.ch

2. **Methodology used to highlight the needs:**

3. Experimental needs:

Domains to be covered	☐ Fuel fabrication ☐ Reprocessing ☒ Transportation ☒ **Burn**-up credit applications ☒ Storage ☒ Final disposal ☐ Criticality accidents studies ☐ sub-criticality monitoring ☐ Other *If other: ....*
Description of the Application	*Criticality Safety of used nuclear fuel / final repository facility*
Isotope/element/medium of interest	*Actinides and FP isotopes from the list of the WPNCS BUC benchmarks, e.g. Phase-VII*
Functionality of the element/medium	☒ Fuel ☐ Moderator ☐ Separator ☐ Reflector ☐ Absorber ☐ Other *If other: ....*
Nuclear data of interest* (capture, scattering, $S(\alpha,\beta)$, ν, etc.)	
Energy spectra**	☐ Fast ☐ Intermediate ☒ Thermal ☐ Whole
Importance for criticality safety	☒ High ☐ Medium ☐ Low
Current Knowledge Level	☐ Known ☒ Partially Known ☐ Unknown
Known validation shortfalls and assessment of available integral data***	
Experiments of interest***	*Reactivity measurements with used nuclear fuel samples*

** If known (based on sensitivity studies for example)*
*** Fast, intermediate and thermal spectra are defined as energy ranges greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively*
**** if known*