ORNL/TM-2025/3966

Proceedings for the Workshop on Applied Nuclear Data Activities 2025

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August 12, 2025

OAK RIDGE National Laboratory

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PROCEEDINGS FOR THE WORKSHOP ON APPLIED NUCLEAR DATA ACTIVITIES 2025

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Prepared by
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managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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LIST OF ABBREVIATIONS

CODA	Conference on Data Analysis
DOE	US Department of Energy
ENSDF	Evaluated Nuclear Structure Data Format
EXFOR	Experimental Nuclear Reaction Data Library
GNDS	Generalized Nuclear Database Structure
HALEU	high-assay low-enriched uranium
HST	horizontal split table
ICSBEP	International Criticality Safety Benchmark Evaluation Project
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LLM	large language model
LLNL	Lawrence Livermore National Laboratory
ML/AI	machine learning and artificial intelligence
NCERC	National Criticality Experiments Research Center
ND	nuclear data
NDA	nondestructive assay
NDIAWG	Nuclear Data InterAgency Working Group
NDWG	Nuclear Data Working Group
NIF	National Ignition Facility
NMC&A	Nuclear Material Control and Accountability
NNSA	National Nuclear Security Administration
NOFO	Notice of Funding Opportunity
NRC	US Nuclear Regulatory Commission
OCR	optical character recognition
PNDA	Pulsed Neutron Die-Away
RPI	Rensselaer Polytechnic Institute
S/U	sensitivity & uncertainty
SANPC	Software Infrastructure for Advanced Nuclear Physics Computing
SME	subject matter expert
SNS	Spallation Neutron Source
SPRF/CX	Sandia Pulsed Reactor Facility - Critical Experiments
TSL	thermal scattering law
UQ	uncertainty quantification
WANDA	Workshop for Applied Nuclear Data Activities

ACKNOWLEDGMENTS

The organizers would like to thank Lisa Felker and Brandon Hacker for their exceptional effort in handling the meeting logistics both before and during the meeting. They would like to thank Cheryll Nunes for A/V support and ensuring that all of the presentations ran smoothly throughout the course of the week.

ABSTRACT

The 2025 Workshop for Applied Nuclear Data Activities (WANDA) covered four topic areas in nuclear data: Nuclear Data and Deterrence, Nuclear Data Prioritization for Fusion, High-Assay Low-Enriched Uranium and Novel Moderators for Advanced Reactors, and Data Preservation and Data Workflows. The intention of this workshop is to connect different communities that are invested in nuclear data and have their own unique sets of needs for the purposes of sharing information, fostering collaboration in areas of shared interest, and leveraging synergistic capabilities. The attendance of federal program managers at these workshops is essential in creating awareness of the needs of their respective communities and in providing information to better guide funding investments. In each of these topical sessions, a general description of the nuclear data needs and/or capabilities was presented, along with discussions of existing capabilities that could be leveraged, potential synergistic needs or resources, and challenges that must be overcome for the application space to progress. There are many synergistic nuclear data needs among these application spaces. The discussion largely focused on increasing the accuracy of the nuclear data and better quantifying the data uncertainties that have the greatest impact on applications. The full-day session on data processing and data workflows was by nature intended to be synergistic and applicable to all technical sessions at WANDA. A notable common theme that was highlighted across all sessions was the need for accelerated delivery of nuclear data products across complex and time-consuming workflows.

1. INTRODUCTION

Nuclear data (ND) provide fundamental characterization of nuclear reactions and decays that are required to accurately model applications, including medical imaging and treatment; food safety; stellar phenomena; fission and fusion reactors; nuclear weapons; and particle accelerator facilities. The measurements and models employed to generate ND all have some inherent uncertainties, such as statistical and systematic uncertainties on measurements and some number of parameters or theoretical inputs to models. These intrinsic uncertainties are therefore propagated into the simulations of applications that rely on those ND. On a nuclide-by-nuclide basis, ND have varying levels of quality based on the time and funding devoted to improving those data. New applications requiring ND for materials not commonly used in nuclear applications may have large uncertainties because the appropriate ND are not well measured or unavailable. In the same way, new applications requiring ND for commonly used materials at different energies or in poorly studied reaction channels may also be unavailable or have large modeling uncertainties.

The US government and private companies based in the US have several new and ongoing mission spaces that require accurate radiation transport modeling and precise modeling of application uncertainties. The most recent Workshop for Applied Nuclear Data Activities (WANDA) in 2025 included community discussions among key stakeholders in some of these science and technology spaces, such as microreactors, advanced fission reactor fuels and moderators, fusion reactors, and nuclear deterrence. The goal of WANDA is to increase communication among research staff at national laboratories, universities, the US Department of Energy (DOE) program managers, and private companies. To facilitate this discussion and plan the annual workshop, the Nuclear Data Working Group (NDWG) was formed among research staff. Similarly, the Nuclear Data InterAgency Working Group (NDIAWG) was formed among DOE program managers. Both of these groups are further described in the remainder of this section.

The NDWG currently has around 50 members. As discussed in the WANDA 2024 report [8], “Each interested federal program can nominate up to two experts in ND or applications from the national laboratories who represent the program or laboratory mission interest within the NDWG, which ensures that program-specific needs are communicated between the laboratories and the NDWG. In addition to the nominations by the federal program managers, each DOE and National Nuclear Security Administration (NNSA) national laboratory is able to nominate up to two individuals to represent their missions and communicate opportunities back to their home institution.”

The NDIAWG is open to all interested federal program managers across DOE, NNSA, the National Aeronautics and Space Administration, the National Institutes of Health, the US Department of Defense, and other funding agencies. Membership has grown to 17 agencies since its beginnings in 2018. The NDIAWG communicates regularly on nuclear data needs, coordinates planned projects, and meets approximately quarterly. The NDIAWG releases an annual nuclear data Notice of Funding Opportunity (NOFO) aimed at creating crosscutting funding opportunities that are cofunded across the NDIAWG agencies. Over the years, these NOFOs have been very successful at funding a significant number of nuclear data projects across a wide variety of application areas. Active projects are highlighted in a review session at the end of each WANDA workshop. The 2025 review presentations can be found on the WANDA 2025 landing page [9].

The NDWG is responsible for determining the scope of the roadmapping sessions held during the WANDA workshops to facilitate its goals as well as those of the program managers within the NDIAWG. The chosen topics are based on current national priorities, funding agency mission goals, and input from the greater nuclear data community. The intention of WANDA is to gain consensus from the workshop participants on crosscutting nuclear data needs and actionable recommendations that will improve nuclear data across the application spaces. These recommendations are recorded in proceedings such as this one and are used to guide the NDIAWG NOFO topics. Proceedings from previous WANDA workshops can be found on the NDWG website [10]. The NDWG website also includes other publications and resources that are useful to the broader nuclear data community.

At the end of the workshop, a survey was sent to participants. Selected results are given in Figure 1. The results of this survey demonstrate the institutional breadth of the participants and indicates their overall high levels of satisfaction with the workshop. The number of first-time participants was also remarkable, showing the expansion of interest in the WANDA workshops. The survey feedback is also a strong indication that the WANDA workshops are serving their purpose in terms of funneling information about relevant ND needs to the cognizant federal program managers, as well as engaging a large number of generators, evaluators, and users of ND.

This report is organized into four sections which describe the four sessions which were held during the workshop. These sections are Nuclear Data and Deterrence, Nuclear Data Prioritization for Fusion, HALEU and Novel Moderators for Advanced Reactors, and Data Preservation & Data Workflows. Each section provides a summary describing some of the background, workshop discussions, some of the most pressing challenges in that topic area, and exciting opportunities to pursue in the future. The chairs of each session were challenged to identify future ND investment opportunities and to sort them into tables of qualitative urgency and importance. Each section of the report closes with a table specific to that session.

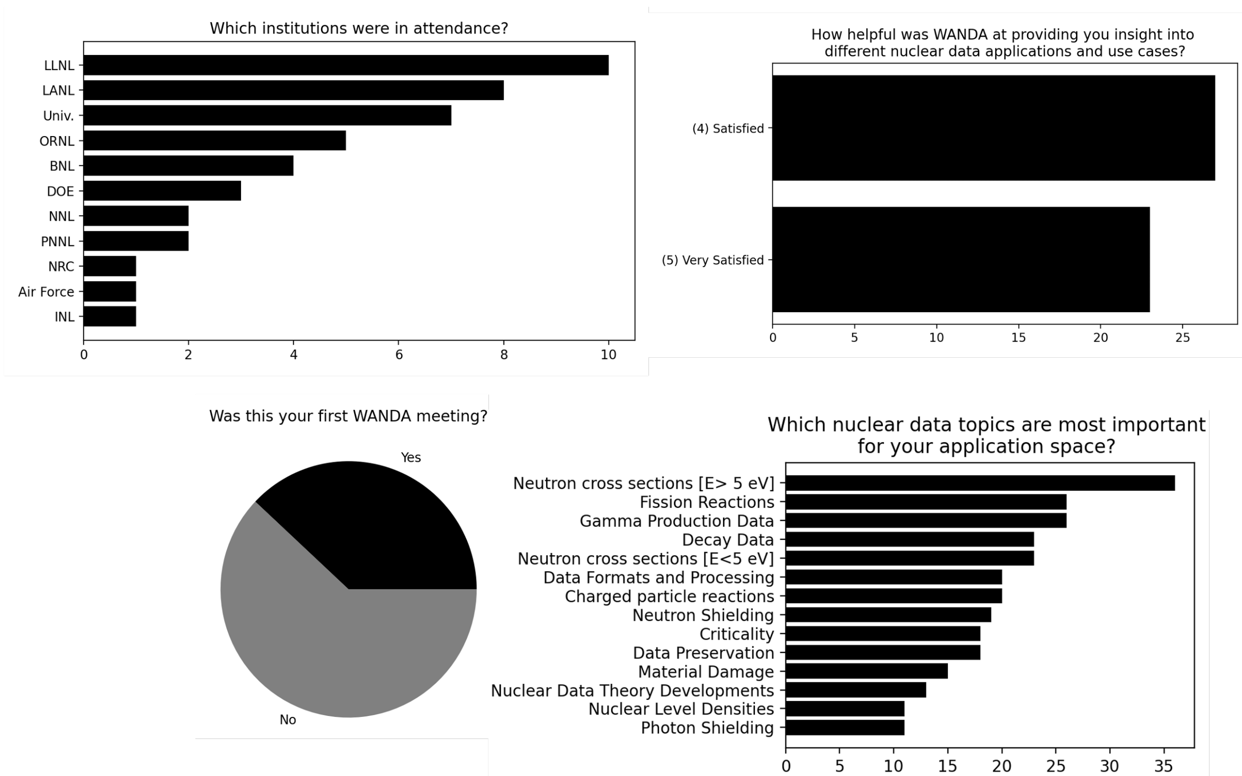

Figure 1. Selected results of the survey sent to participants of the 2025 WANDA workshop. Approximately 25% of workshop participants responded to the survey.

2. NUCLEAR DATA AND DETERRENCE

Nuclear weapons are central to the US deterrence strategy. Although nuclear weapons have not been employed since World War II, they provide a strong deterrent against aggression directed at the United States and its allies. The US maintains an active stockpile of nuclear warheads to support national defense and geopolitical relations.

The United States discontinued nuclear weapons testing in 1992 due to environmental concerns and a reduced Soviet threat. The Stockpile Stewardship Program (SSP) was launched in 1995, providing science- and engineering-based predictive capabilities upholding the nuclear deterrent. Computational modeling and simulation, along with experimental measurements, are foundational to the success of the SSP. Each year Lawrence Livermore National Laboratory and Los Alamos National Laboratory, supported by Sandia National Laboratories, provide an assessment of the safety and reliability of the US stockpile. The discontinuation of testing and new design activities were not expected when the current systems were produced. The aging stockpile has been maintained through predictive simulations, scientific analyses, and component replacements without full-scale testing. Accurate ND are critical to this effort.

The US nuclear deterrent is being modernized in response to changes in the geopolitical landscape and growing concerns regarding the capabilities of its adversaries. Advanced design and manufacturing activities are in progress to expand on computational and experimental investments established through the SSP. New design efforts depend on predictive capabilities developed through the SSP and validated by historical nuclear tests. ND and scientific expertise are essential for confidence in the modern nuclear deterrent.

ND support two key elements in deterrence applications: predictive modeling and validation. Accurate ND are needed to ensure high confidence in assessment metrics. Data uncertainties and statistically robust methods to incorporate them are also necessary. The propagation of ND uncertainties through an application space provides a quantitative measure of assessment uncertainties due to data unknowns while also highlighting areas for further attention or improvement. Similar requirements exist for validation activities, although the types of ND differ. For example, accurate neutron-induced fission cross sections are needed to determine the number of fissions occurring within a mass of fissile material. Validation of this prediction can be determined through measurements of cumulative fission product yields. Uncertainty analyses define the quality of the prediction and the acceptable validation range.

ND activities supported by the deterrent mission encompass all elements of the "pipeline." Foundational science efforts include both theory development and ongoing experimental measurements of nuclear reactions and nuclear structure. These activities include new high-performance computational platforms, complex experimental configurations, and unique facilities. Data evaluation and processing are critical for delivering new data and uncertainties for applications. Integral experiments and validation/verification reduces uncertainties and increases confidence in the delivered data. ND experts also develop and support sensitivity and uncertainty quantification (UQ) studies, often in coordination with data users in the applied space. Collaborative activities with users are crucial for meeting existing and emerging data needs.

2.1 GRAND CHALLENGES

ND use within the deterrence mission is broad, involving multiple isotopes, reactions, and decay properties. Accurate data with known uncertainties are needed for predictive modeling and simulations for a range of weapons applications. Data are also needed for validation activities, including modern interpretations of historical test data and present-day integral experiments. Prioritizing efforts and investments while meeting challenging data needs are grand challenges for ND producers supporting deterrence activities.

2.1.1 Identifying and Fulfilling ND Needs in Multi-Physics Applications

Similar to other application areas, nuclear deterrence requires multiple scientific and engineering inputs that are often interrelated. Identifying and isolating ND needs are challenging and require cross-disciplinary partnerships and computational/data development methods for sensitivity studies and uncertainty quantification. Specific actions and resources to support the identification of ND needs are summarized below.

- **Communication resources and evaluators**: Members of applications and data production teams may lack familiarity with ND. Readily accessible resources and contacts (notably evaluators) improve data use. Reaction evaluators provide essential expertise and utilize sophisticated reaction theory codes to fill gaps in the data and quantify uncertainties. A larger pool of experienced evaluators will also reduce the time between data collection and delivery for applications needs. Investments in recruitment and mentoring to increase the number of trained evaluators are needed. The US Nuclear Data Program and the NNSA Defense Programs provide training through direct mentoring with gradual changes to the number of evaluators. These activities have been recently augmented through the NDIAWG: the DOE Office of Science initiated training for new evaluators in 2025 through cross-laboratory mentoring and a short-term educational program.
- **A "curated" Experimental Nuclear Reaction Data Library (EXFOR) [11] database**: Users of ND libraries have no immediate means of determining the quality of the data of interest. In the case of nuclear reactions, plotting experimental data with the evaluated cross section provides a qualitative estimate (see for example, Figure 2). Although the current EXFOR database is valuable, it contains data known to be erroneous. A "curated" EXFOR database is needed that defines the data used in evaluated ND libraries. Such a database will help users determine whether the data match measurements while simultaneously providing a foundation for future evaluation efforts. A formatted, curated database would also enable new machine learning and artificial intelligence (ML/AI) activities to improve nuclear reaction modeling.
- **Conservative covariances**: Covariances released with reaction evaluations are exploited for sensitivity and uncertainty quantification studies. These studies drive high-consequence decisions (e.g., safety margins) and are used to prioritize activities. Erroneously small uncertainties can lead to false confidence or discontinuation of important activities (like ND improvements) that are costly or impossible to restart. While significant attention has been focused on mean values, covariances must also be accurate and defensible. Uncertainties should decrease over time, not increase. Community-endorsed covariance definitions are needed.
- **Investments in method development**: Scientifically sound and statistically robust methods for identifying and prioritizing ND for applications remain a need. This activity draws on external expertise in statistics and computational methods, including ML/AI. Bayesian methods have been used to identify ND needs (e.g., neutron scattering with ^{239}Pu [12]) and inform high-impact experimental design (e.g., PARADIGM at Los Alamos National Laboratory (LANL) [13, 14]). Advanced methods require cross-collaboration across diverse teams, curated input data, trusted covariances, ML/AI algorithms, and significant computational resources. Substantial progress has been made over the past five years, demonstrating new developments and highlighting the future potential [15, 16]. Further investments to improve workflow/methods and address needs across the application space are necessary to continue the evolution of these capabilities.

2.1.2 Exploiting Emerging Technologies to Tackle Challenging Problems

For predictive capabilities to meet the deterrence mission, accurate ND and quantified uncertainties are needed across a range of stable and unstable nuclei. Advancements in theoretical and experimental

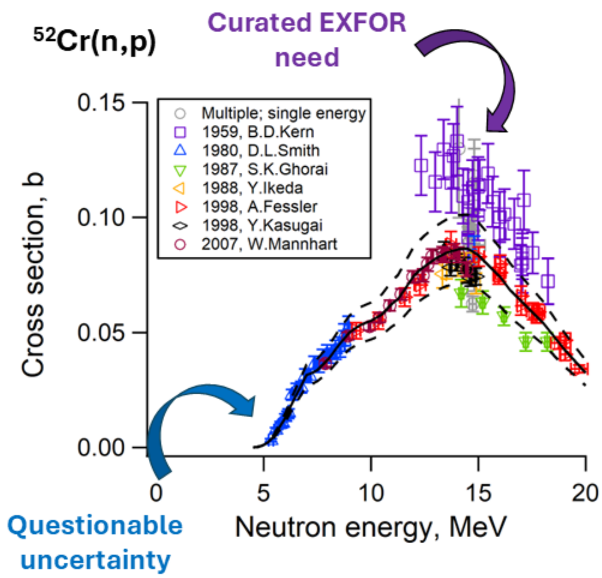

Figure 2. Evaluated and measured ^{52}Cr(n, p) cross section data. The evaluation is from ENDF/B-VIII.1 (solid black lines) with 1σ-uncertainties (dashed black lines). Measured data points are from the EXFOR database [11]. Evaluated uncertainties near 5–10 MeV appear too small; the low cross section would be challenging to measure, and there is only one experimental dataset. The 1959 Kern dataset should not be used in the evaluation or assessments. These data should be removed or flagged (i.e., in a "curated" EXFOR) to reflect this.

capabilities provide opportunities for improving challenging data needs. New data needs are also emerging for integral experiments supporting nuclear deterrence validation activities.

- **Computational platforms and advanced theoretical methods**: High-performance computing (HPC) capabilities are needed for high-fidelity theoretical descriptions of nuclear reactions. Advancements in UQ are also being employed to understand the range of calculated values. *Ab initio* methods for reaction cross sections have been demonstrated on light nuclei; these theoretical calculations can be pushed to heavier systems ($Z > 8$) with graphics processing unit (GPU)–capable platforms [17, 18]. Theory advances with density functional theory (DFT) applied to complex fission reactions are also benefiting from petascale and exascale computing capabilities [19]. New computational platforms provide significant calculational enhancements but require research investments and effort toward refactoring codes and algorithms to take advantage of platform changes.

- **Experimental platforms supporting ND measurements**: Measurements of ND often occur at dedicated facilities [20], including measurements of differential data at the Los Alamos Neutron Science Center (LANSCE) and integral experiment data at the National Criticality Experiments Research Center (NCERC). Office of Science user facilities as well as Office of Science– and National Science Foundation–funded university laboratories also provide key capabilities. New developments at the National Ignition Facility (NIF) are enabling both differential and integral measurement capabilities that are complementary to the resources for ND measurements enabled by existing accelerator and cyclotron facilities. Access to measurement facilities is limited and time is competitive, so workforce development opportunities are limited for early career students, postdocs and staff. These resource constraints emphasize the need to identify high-impact ND for improved measurements. Modern facilities designed to carry out these challenging data measurements are also being proposed by the national laboratories.

- **Detector development for ND experiments**: Measurements of nuclear properties often employ large, complex detector arrays. The use of multiple detector systems challenge data reduction analyses, but these systems capture correlations in the data that are valuable for understanding full reaction processes. New detector materials and novel capabilities, such as microcalorimeters, may provide additional improvements [21]. Exploratory investigations with new materials and detection capabilities must be maintained to ensure that new capabilities can be exploited.
- **Data supporting integral measurements for deterrence applications**: Non-nuclear activities may use diagnostics based on atomic and nuclear data compiled into a library, such as ENDF/B-VIII.1. For example, radiography is a common diagnostic tool for hydrodynamic tests exploring materials or determining their explosive properties. Experimental design and post-shot analyses use modeling and simulation tools with atomic data and ND for a variety of radiography sources (photon, proton, or neutron) [22]. Photon sources are common; there is, however, limited support for atomic data, and uncertainties are not included in the US evaluated data library. High-energy (typically $\gtrsim 7$ MeV) radiography provides a penetrating source where photonuclear effects must also be considered. Photonuclear data have received limited attention, and the necessary covariance data are lacking. An effort to improve the photon data, including its uncertainties, is needed to support UQ and experimental design activities.

2.2 UNIQUE OPPORTUNITIES/NEW CAPABILITIES

Opportunities for advancing ND and the applications they support include advanced computational and experimental methods. ML/AI is being used with increased frequency in ND production. It has clear applications to experiments (such as design and data reduction) and theory (e.g., reduced computational time and parameter determination in models). ML/AI methods have also been used to augment evaluations and perform validation activities. While large datasets are required, ND inputs are well suited for ML/AI applications. Experimental data are sparse, but theoretical efforts can create training data sets. ML/AI can be used to automate aspects of the ND pipeline, such as compiling data from published papers using large language model (LLM) technology. ML/AI methods show significant promise for improving efficiency in identifying ND needs and methods to meet those needs. Advancements require investments in nuclear theory and computing infrastructure as well as strengthened collaborations with experts beyond the ND community.

Quantum computing is an emerging technology rooted in quantum information science (QIS) that has the potential to outperform GPU-based platforms. Quantum computing utilizes quantum bits (qubits) that can exist in multiple states compared to the two (0 or 1) in current computers. Active research in experimental capabilities (qubit control, hardware) and theoretical (mathematical quantum gates, algorithm development) is growing. Although quantum systems provide no immediate impact, future systems will revolutionize computational capabilities.

Integral experiments are important in the validation of application features. These experiments, when dominated by nuclear processes, are also important for the validation of ND and have been used to adjust data or constrain uncertainties. Novel experimental platforms, such as pulsed power systems like NIF, provide new capabilities and needs for ND supporting diagnostics [23]. For example, capsule behavior can be monitored with emplacement of small quantities of pure isotopes that are activated by fusion neutrons during the laser-driven implosion. Activation cross sections and decay properties must be well known to be used as a diagnostic. Radiochemical processes must also be developed for capsule loading and post-shot separations. Activation foils are also commonly used, where activation cross sections are sensitive to neutrons above a minimum energy. Multiple foils allow one to “unfold” the neutron spectrum. Unfolding methods exist but should be improved with benchmark tests and incorporation of uncertainties. For any new facility, rapid retrieval of activation samples should be considered early in the design process. Robotic retrieval systems expand the diagnostic capabilities available as they allow assessment of shorter-lived radionuclides.

2.3 SYNERGISTIC WORK

Although motivated by the deterrence mission, the ND needs and opportunities described here are broadly applicable to other applications. Methods for improving the accuracy of ND while reducing the timeline for data delivery are desired across many US programs. ND used by nuclear deterrence programs are developed and delivered through support of the full ND pipeline. Many of these activities are accomplished through partnerships with national laboratories and academic institutions. Classification and need-to-know boundaries may exist, and methods to share data impacts without revealing controlled information have been successfully applied. Applications involving export-controlled or proprietary information face similar challenges.

Table 1. Crucial and beneficial investments for the Nuclear Data and Deterrence mission-space over the next 5 and 10 years. The NNSA Defense Program is a major supporter of the ND enterprise and has a robust mechanism for identifying needs, developing experimental and theoretical efforts to address them, and ensuring data are evaluated and incorporated into application-level efforts. Activities that improve data accuracy and reduce the timeline from experimental data collection to use in applications are needed. Data and methods that support UQ and prioritization are also needed.

Crucial in the next 5 yrs • Expanded number of reaction evaluators through training and retention programs • Conservative covariances, filling gaps and establishing common methods for determining values	**Beneficial in the next 5 yrs** • Curated EXFOR database • Exploratory research into new detector technologies and integral diagnostics
Crucial in the next 10 yrs • Advanced methods to identify and prioritize ND needs • Strengthened collaborations with experts beyond the ND community, including statisticians as well as data and computational scientists	**Beneficial in the next 10 yrs** • Investments in next-generation computational architectures and experimental facilities • Confidence in photon data for both atomic and photonuclear processes

3. NUCLEAR DATA PRIORITIZATION FOR FUSION

Recent successes at the Joint European Torus (JET) in the UK and at NIF in the US achieved, respectively, record fusion energy production [24] and the generation of more fusion power from the fuel than was input (i.e., a power amplification Q > 1) [25]. However, the levels of neutron production from JET and NIF are several orders of magnitude lower than that expected from a fusion pilot plant (FPP). There is therefore very little operational experience in the fusion energy industry compared to the fission industry. Consequently, the ND needs of this community are not yet fully defined. It is well known that the fusion energy economy needs to create, or "breed," the fusion fuel tritium since it does not occur naturally. (Deuterium, the second component of the fuel, can be extracted from seawater.) The requirement is expressed by specifying that the tritium breeding ratio (TBR) must be greater than 1.0: that is, each neutron produced in the d(t,n)^{4}He reaction must produce one triton. This is typically achieved using the ^{6}Li(n,t)^{4}He reaction. Practically, the TBR must be greater than 1.0 to compensate for tritium holdup in structures, radioactive decay, and other losses. A value of TBR> 1.05 was identified as the minimum [26] during studies of the European DEMO design. Furthermore, although a great deal of effort has been put into the design of a breeding blanket, Bernstein [27] pointed out that many of the relevant cross sections for both fertile (e.g., boron) and neutron multiplying (e.g., ^{9}Be($n, 2n$)) materials require reduced uncertainty over the entire energy range, from 14.1 MeV down to thermal energies. Additional targeted measurements that can guide evaluations can reduce the risk of costly redesign efforts "down the road."

In addition to the need for ND for the design of tritium breeding technology, there are important ND needs for shielding, nuclear heating, activation, and radiation. Given the limited experience of operating fusion experiments with significant neutron production and the variety of designs under consideration by the burgeoning private fusion industry, there is a lack of clarity regarding where the priorities for ND improvement lie. A common theme expressed in this session of the WANDA meeting was the need to bridge the gap between the users of ND and the data evaluators to ensure the latter meet the needs of the former. Loughlin pointed out that although the priority is to first establish the materials and reactions that are most important in the design of an FPP, the ability to precisely quantify the ND uncertainties in calculations is equally important. The complexity of a fusion plant compared to a fission reactor is an important consideration. The additional constraints required to maintain the proper vacuum, cryogenic, and electromagnetic conditions mean that there is little margin for error in the design. Therefore, precise nuclear analyses with well-known and minimized uncertainties are essential to ensure not only the successful operation of the plant but also the economic viability of private companies building FPPs.

The mean energy of neutrons produced in the d(t,n)^{4}He reaction is 14 MeV. It was pointed out by Sublet [28] that this high energy opens up many reaction channels that are not significant in fission reactors. There is considerable scattering of the neutrons in the FPP structure, so ND on the isotopes that make up this structure at energies from thermal to 14 MeV are of interest. Sublet pointed out that theoretical ND generated in ND processing codes (specifically average scattering angles) can significantly impact application behavior, and great care must be taken in the addition of theoretical data in post-evaluation processing. The details of the neutron spectrum vary depending on the tritium breeding concept and the depth in the blanket (see Figure 3). This means that the ND needs are not specific to fusion. As discussed by Kelly [29] and Forrest [30], there is considerable cross-cutting interest with other programs that require research in, for example, primordial nucleosynthesis (basic science), space-based radiation effects, and nuclear nonproliferation (the NA-22, NA-113, and NA-114 programs).

One nuclear data need that was articulated at the workshop by several speakers involved gamma-ray heating from (n, x) reactions induced by 14 MeV neutrons incident on the first wall materials. A 5 cm thick first

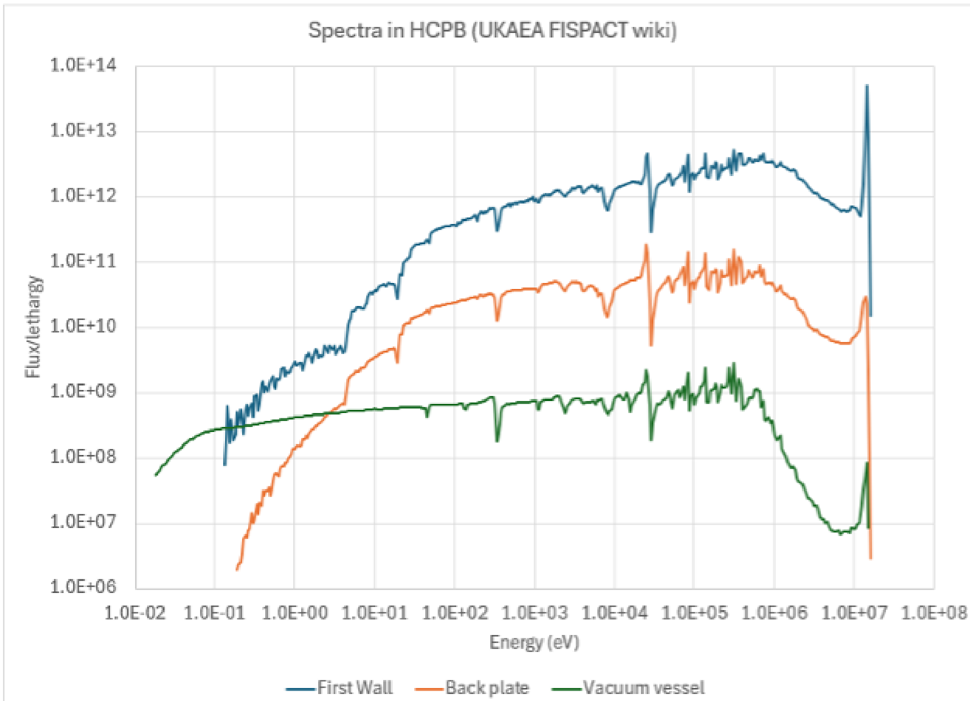

Figure 3. Neutron spectra at various depths in the structure of a helium-cooled pebble bed (HCPB) reactor [1].

tungsten wall could convert several percent of the fusion energy into extremely penetrating gammas that risk enhanced heating of both the superconducting magnet materials for magnetic confinement fusion systems and the vacuum vessel. However, very little data exist in evaluated libraries regarding the energy and multiplicity distribution of the most penetrating "statistical" gamma rays coming from inelastic scattering reactions.

As discussed by Ebiwonjumi [31], fusion plant modeling workflow complexities, the availability of computational tools, and gaps in ND make uncertainty quantification challenging. These challenges should be addressed by code development undertaken in parallel with a coordinated experimental program to address data gaps. In the absence of a Fusion Prototypical Neutron Source (FPNS) [32], it is recommended that existing experimental facilities operated by ongoing programs be utilized. This will yield value-for-return scientific benefits. More data will lead to improved ML/AI supporting the exploitation of modern supercomputers for improved radiation transport (accurate fusion predictions require very large models), molecular dynamics, and material developments. However, measurement and evaluation can take years, making advanced planning through the WANDA workshops and the NDIAWG essential.

One frequently repeated fusion ND need arises from the lack of direct measurements of displacement and gas production reactions at fusion-appropriate energies. The cross sections for these reactions are generated from elastic, inelastic, and capture cross sections in processed nuclear data combined with molecular dynamics and vacancy recombination models, creating significant uncertainties in predicting how structural materials will survive in a fusion reactor [33]. However, several speakers throughout the course of the session highlighted the possibility that some of these phenomena could be quantitatively measured by irradiating materials in a microcalorimeter using "tagged" neutrons from a deuterium–tritium associated particle imaging (DT-API) neutron generator. Data of this sort would provide a valuable constraint on both the nuclear and materials properties that are most relevant to understanding materials damage in a fast fusion field [27, 34].

3.1 GRAND CHALLENGES

The first required step is to prioritize the nuclear data needs for fusion. Doing so will require a thorough survey of the materials and nuclear reactions that are relevant to fusion, as well as quantification of the implications on the design of FPPs due to uncertainties in the ND. This is a recommendation provided in the second NSAC-ND report [35].

Then, the most important obstacle to overcome in this field is the UQ of fusion reactor behavior due to ND uncertainties. Predicting the behavior of fusion reactors as opposed to fission reactors requires detailed ND for a novel set of materials and that cover a wider range of neutron energies (from thermal to 20 MeV). Not only does fusion present a novel selection of materials for which novel ND are needed, but thoroughly validated sensitivity & uncertainty (S/U) methods are needed to reduce the economic impact of uncertainties in the design of fusion devices.

Another one of the ND grand challenges for fusion applications is shielding of the new magnets, which is complicated by the limited space available. This is one of the more exciting fields to be tackled by the next generation because it encompasses material development, advanced modeling (e.g., molecular dynamics), and improvements in ND for damage and gas production. This aligns with the US government's program for accelerated development of fusion energy to support the reestablishment of US energy independence.

3.2 UNIQUE OPPORTUNITIES AND SYNERGISTIC WORK

There is a unique opportunity to leverage new ML/AI advances in materials science for molecular dynamics modeling to improve nuclear damage modeling and determination of damage cross sections. This could significantly impact predicted maintenance for operating fusion reactors. Because damage cross sections are needed in many fields, this represents a synergistic need for improvement in the fusion science and fission science fields (among many others). Along those same lines, microcalorimeter measurements of damage cross sections represent a synergistic research space that would benefit nuclear deterrence applications. Another area of synergistic work involves measurements of statistical gamma rays from fusion-relevant nuclides because such data are of interest to the national security, nonproliferation, and space exploration communities [35]. A well-coordinated measurement and modeling campaign to address these deficiencies would ensure that shielding is designed in a safe and cost-effective manner.

Table 2. Crucial and beneficial investments for fusion energy applications over the next 5 and 10 years. In order to deploy fusion power plants on the aggressive timeline defined by the DOE, it is critical to improve modeling and S/U for shielding and damage cross sections. It will be beneficial to improve ND to accurately determine activation of reactor materials and tritium breeding to ensure economic viability of plants.

Crucial in the next 5 yrs • Damage cross sections • Covariance data for shielding materials • Shielding cross section data	**Beneficial in the next 5 yrs** • Activation and decay data • Neutron multiplication data • Tritium breeding data
Crucial in the next 10 yrs • Activation and decay data • Neutron multiplication data • Tritium breeding data	**Beneficial in the next 10 yrs** • Radioactive waste determination and classification • Data for energy conversion

4. HALEU AND NOVEL MODERATORS FOR ADVANCED REACTORS

Advanced reactor designs across the U.S. are making significant strides toward regulatory licensing. The recent prioritization of nuclear power, especially microreactors, is due to the need for reliable power and increased power demand from ML/AI. One of the attractive features of microreactors is that they offer a small footprint and low standoff space for accident mitigation [36]. Small reactors with relatively high power density may deviate considerably from current light-water reactor technology, potentially requiring both higher fissile density and improved moderator/reflector materials. Many designs use ~5–20 wt% ^{235}U enriched fuel, which is known as high-assay low-enriched uranium (HALEU). HALEU fuel and it's use with many novel moderators lack experimental validation. Reactors designed with these fuels and moderators cannot be licensed without full predictive capability, which equates to urgent needs for improved ND [7] and validation experiments. The advanced reactor landscape is shown in Figure 4.

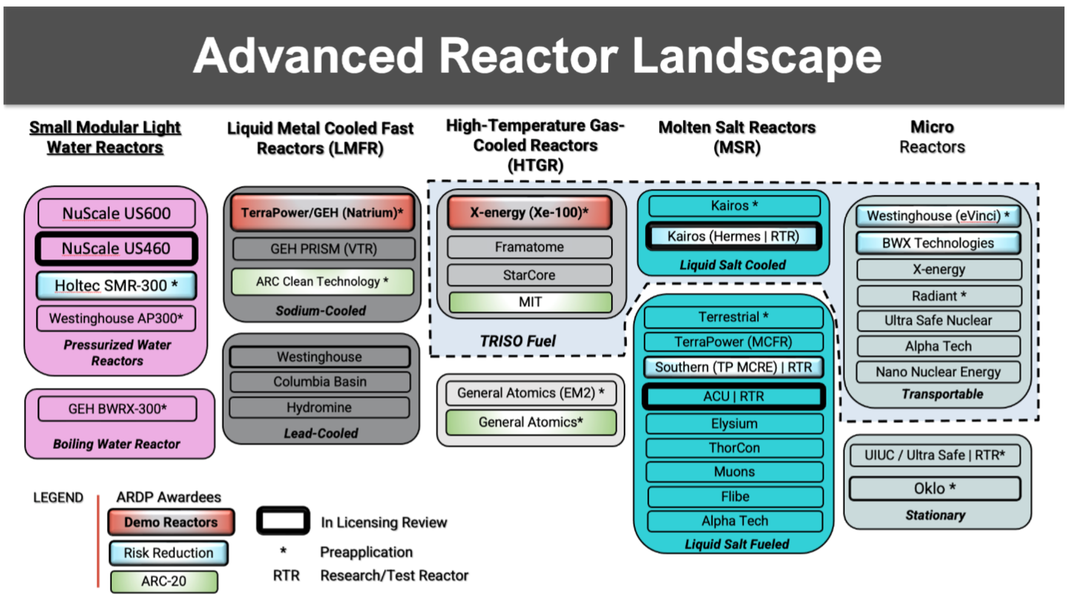

Figure 4. Advanced reactor landscape [2].

DOE and the US Nuclear Regulatory Commission (NRC) have a joint project called the DOE/NRC Collaboration for Criticality Safety Support for Commercial-Scale HALEU for Fuel Cycles and Transportation (DNCSH) [37]; this collaboration highlights the industry and NRC needs to license new designs. Industry is currently moving forward with test facilities, but they often require large margins of error to account for large or missing ND uncertainties. Although current ND are sufficient to develop and test successful prototypes, additional measurements and ND evaluations are needed to reduce margins and maximize commercial viability.

Therefore, the most important needs over the next five years are to update ND libraries with new evaluations of some key nuclear reactions as well as the pursuance of new integral experiments with HALEU fuel. The latter work will both enable ND calibration as well as code and application validation for use in design optimization and safety analysis calculations for reactors.

To comprehensively improve ND, measurements must be carefully planned to minimize experimental uncertainty and ensure that they actually fill the needed data gap. This represents a synergistic need for modern and comprehensive S/U methods as described in Section 2. This can be addressed and well documented while improving ND workflows, as noted in Section 5.1.3. Common and consistent documentation and methods are critical to maximize impact for ND users now and in the future. They also allow evaluators to reliably perform evaluations which require extensive analysis after the measurement/experiment is complete.

These complex experiments can only be performed at a small number of facilities. Major differential measurement facilities include Spallation Neutron Source (SNS), LANSCE, and Rensselaer Polytechnic Institute (RPI) in the U.S. The most active integral experiment and benchmark facilities in the U.S. include NCERC and Sandia Pulsed Reactor Facility - Critical Experiments (SPRF/CX), it should be noted, however, that other facilities exist such as RPI and University of Tennessee Knoxville, which have developed non-criticality benchmark capabilities. Fundamental physics benchmarks, a category in ICSBEP [38], cover non-criticality benchmarks and meet the same exceptionally high level of rigor and uncertainty analysis. This type of benchmark includes multiplicity, transmission, shielding, among others. Multiplicity benchmarks will specifically be essential to quantifying and thus reducing uncertainty in HALEU measurements by providing key validation sets. Multiple types of experiments are needed to quantify uncertainties and reduce margins in advanced reactor design.

Table 3 provides a list of ND availability and status of experimental data related to the most relevant novel moderators. Table 4 lists the reporting requirements in mass of various nuclides of interest. These masses drive the level uncertainty that can be tolerated in software that is used to predict radiation transport and nuclear transmutation.

Table 3. Availability of thermal scattering evaluations and measured data. Only benchmark experiments which include HALEU-relevant fuel are included in the list. [4, 5].

Material	Available TSL ENDF Files	Differential XS Measurements	Integral XS Measurements	ICSBEP Benchmark Experiments
Graphite	Yes	Yes	Yes	Yes
$ZrH_{1.6}$ & ZrH_2	Yes	Yes	Yes	Yes
YH_2	Yes	Yes	Yes	No
Be Metal	Yes	Yes	Yes	Yes
BeO	Yes	No	Yes	Yes
MgO	Yes	Yes	Yes	No
Be_2C	Yes	No	No	No
FliBe	Yes	No	No	No
SiC	Yes	Yes	Yes	No
Zr_3Si_2	No	No	No	No

Universities should play a key role in experiment design and analysis. The pace of nuclear data adoption for use in updated models and ND libraries is rarely limited by the collection of experimental data itself. Instead, the limiting factor is the staff time required to complete the analysis. Universities working closely with national laboratories have a great opportunity to fill this gap. Pursuing new reactor designs with the possibility of deployment in the real world is exciting and intellectually stimulating, making it perfect for engaging with students and early career scientists in the university ecosystem.

Representatives from Westinghouse Electric Company LLC and Kairos Power LLC were involved in the data gap discussions during the WANDA 2025 meeting to ensure that research priorities align with technology development that has real-world impact. Table 5 lists the differential and integral measurement needs that are

Table 4. Nuclear Material Control and Accountability (NMC&A) reporting requirements listed here drive the requirements for nuclear data uncertainties used in radiation transport and nuclear transmutation software [6].

Material	Domestic Safeguards	International Safeguards
Total U	whole g (for enriched U) whole kg (for depleted U)	g (for U enriched in ^{235}U or ^{233}U) kg (for natural U, depleted U)
^{235}U	whole g	g
^{233}U	whole g	g
^{233}U + ^{235}U	-	g
Total Pu	whole g ^{240}Pu isotope wt%	g
^{238}Pu	g to tenth	g
^{239}Pu	-	g
^{240}Pu	-	g
^{241}Pu	-	g
^{242}Pu	whole g	g
^{239}Pu + ^{241}Pu	whole g	g
Thorium	whole kg	kg

mentioned in literature [7] and during discussions as being crucial to reducing margin and uncertainty for advanced reactor designs. At this meeting, Westinghouse was the primary driver for YH_x measurements, whereas Kairos Power was the primary motivator for differential and integral experiments with FLiBe.

Both companies, it should be noted, stated the need for integral benchmark measurements at elevated temperatures. Thermal scattering cross sections and reactivity coefficients must be tested for all integral experiments. In these experiments it is desirable to isolate the thermal scattering effect at different temperatures, when possible. There is a need for larger experimental facilities to conduct integral experiments that better fulfill vendor needs.

The integral experiment facility should have built-in flexibility, such as that offered by the horizontal split table (HST) [39]. The integral experiments should be relevant to vendors by using prototypical fuel forms planned for current designs. There should be additional emphasis on improving modeling and simulation accuracy with validation experiments. The integral experiment should use HALEU TRi-structural ISOtropic particle fuel at varied packing fractions but within the expected needs from vendors. The integral experiments should use HALEU fuel enrichments in the range of 10–20 wt% ^{235}U. There is a need for integral experiments with HALEU fuel in combination with a variety of moderators to benchmark thermal scattering laws (FLiBe, YH_x, and large graphite moderators, at a minimum). Finally, there is a need to evaluate reactivity coefficients with various moderator configurations.

The nuclear safeguards community needs benchmarks to reduce uncertainty in safegaurds-relevant multi-physics models and detector response. The detector response benchmarks are needed to address uncertainties in novel safeguards methods. Given that this area of research is in its infancy, the specific nuclear data needs have not yet been defined. Identification of nuclear data needs for Nondestructive assay (NDA)/Nuclear Material Control and Accountability (NMC&A) and subsequent benchmarks for detector response should also be a high-priority item.

Table 5. Specific differential and integral cross section experimental needs [7].

Differential	Integral
^{9}Be(n, α)	FLiBe
^{19}F(n, n')	YH_x
^{7}Li(n, γ)	HALEU TRISO[a]
	Large graphite moderators

[a] with varied enrichment and packing fraction

4.1 UNIQUE OPPORTUNITIES/NEW CAPABILITIES

The Deimos advanced reactor testbed at NCERC went critical for the first time in September 2024. This experimental platform provides a means to test a wide range of novel fuels and moderators with representative spectra and at elevated temperatures. Additionally, the Hypatia platform for critical experiments, though smaller and driven by highly enriched uranium, provides a straightforward way to test novel moderators and fuel in a critical assembly. The Deimos and Hypatia experimental setups are shown in Figure 5. Lawrence Livermore National Laboratory (LLNL) has a newly established facility for thermal scattering law (TSL) measurements, specifically the Pulsed Neutron Die-Away (PNDA) measurements. A few have already been accepted into the ICSBEP [38] Handbook. This state-of-the-art facility should be utilized as much as possible.

4.2 SYNERGISTIC WORK

Investments in integral and differential measurements and evaluations which support advanced reactors impact many other program areas. Benchmark experiments were mentioned in the Data Preservation session, during which participants articulated the need to preserve the experimental data that are generated. This is a large component of the work needed for the HALEU and Advanced Moderators topic area. The Nuclear Data and Deterrence session identified the need for ^{235}U(n, n') differential measurements. These help understand scattering effects associated with advanced reactors, which are smaller in size and use novel moderators. This area specifically needs benchmarks for (α, n) reactions. Employment of ML/AI in the S/U and UQ space also shares synergies with the needs of the Nuclear Data and Deterrence session. Using ML/AI algorithms to determine high impact ND and to guide experimental planning for a given application is of growing interest to the ND community. The urgency of incorporating data into libraries was highlighted by the sessions on Nuclear Data and Deterrence and Data Preservation. In addition, the session on Fusion had a specific ND overlap: (n, α) reactions.

Finally, all modeling and simulation efforts tied to design optimization, safety analysis, or safeguards need reliable data that cover the relevant design space that vendors are pursuing. Therefore, these efforts complement various organizations and programs, including the US Nuclear Regulatory Commission, industry, and various government programs that aim to successfully deploy advanced reactor technology, such as Nuclear Energy Advanced Modeling and Simulation (NEAMS), Advanced Reactor Technologies, Micro Reactor, etc.

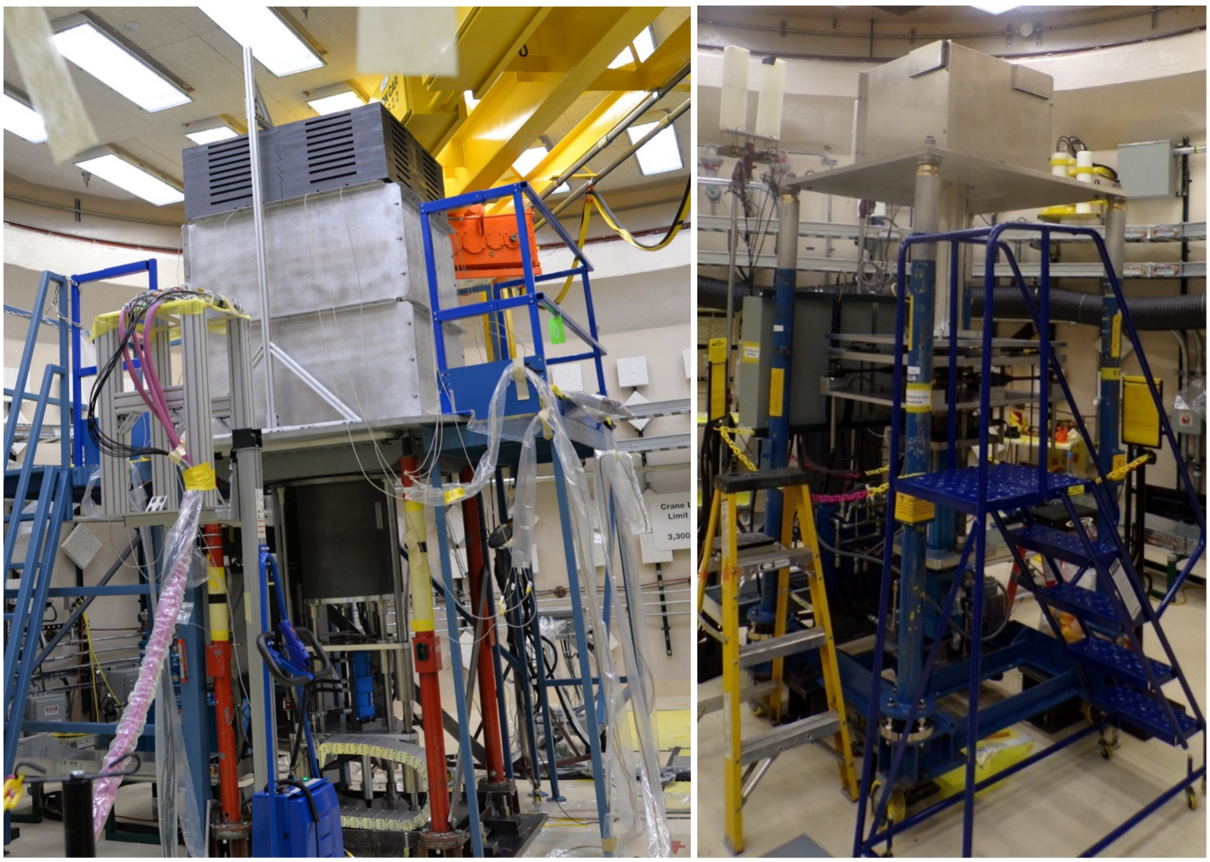

Figure 5. Left: The Deimos Advanced Reactor Testbed at NCERC. Right: The Hypatia critical experiment platform at NCERC [3].

Table 6. Crucial and beneficial investments for advanced reactors over the next 5 and 10 years.

Crucial in the next 5 yrs	**Beneficial in the next 5 yrs**
• Integral benchmark experiments with HALEU fuel & FLiBe • Evaluations of reactivity coefficients with various configurations of advanced and novel moderators • NDA/NMC&A benchmarks for detector response with novel fuels and moderators	• Differential measurements of ^{9}Be(n,α),^{19}F(n,n'), ^{7}Li(n,γ) • TSLs for novel moderators
Crucial in the next 10 yrs	**Beneficial in the next 10 yrs**
• Horizontal-split table integral experiments • YH_x critical measurements • Addition of TSL covariance data evaluations in US-ENDF/B library	• Nuclear material inventory R&D • Differential measurements of materials used in advanced reactors at extreme temperatures (both cryogenic and high temperatures)

5. DATA PRESERVATION AND DATA WORKFLOWS

Nuclear science and technology are constantly innovating; as a result, we, the ND community, are being challenged to deliver more data (both in terms of quantity and type) of higher quality to users faster and with greater efficiency. This is driving us to look at new approaches and techniques to produce ND as well as to reexamine and optimize workflows, tools, and formats. While facing these challenges, the data community is aging both in terms of workforce and tools, creating a legacy debt of codes, formats, and data. Fortunately, this legacy also provides us *generations* of experience to draw from while improving our tools and techniques. This legacy, coupled with new tools such as ML/AI, presents significant opportunities as well as concerns.

We divided this session into four Grand Challenges, each intended to facilitate the greatest amount of discussion and positive momentum. The session started with Open Data, how the community accesses, stores, and transmits information and contrasted current practices with recent guidance. This ties in with the current state of Legacy Data and how the community leverages the current landscape, with its known obstacles, to deliver ND products. Data Workflow takes a more systemic view of the ND pipeline and information sharing between different segments. Tying it all together, Data Preservation and Workflow Preservation Knowledge Management looks to past practices and future knowledge management methods as the key to best leverage past work for future endeavors. The following sections summarize each of these areas and note any opportunities we should be capitalizing on or synergistic work that we can leverage to address these challenges.

5.1 GRAND CHALLENGES

5.1.1 Challenge #1: Preserving New Data and "Open Data"

The ND community strives to make its data open and accessible and arguably has held this stance since the end of the Manhattan Project. The embrace of the Findable, Accessible, Interoperable, and Reproducible (FAIR) [40] principles of Open Data and the related FAIR in ML, AI Readiness & Reproducibility (FARR) [41] principles is a natural extension of our practices. Executive branch guidelines and policies define what information we release and how we release it [42, 43], even though many of these policies are under review by the current administration.

Meeting the basic requirements (releasing data from plots at publication) of the DOE Public Access Plan is straightforward. There is still ambiguity surrounding the plan, specifically the goal of ensuring reproducibility. For instance, the nuclear community was unsure whether this meant that experimentalists will be required to release raw experimental data, their custom tools that analyze raw experimental data, or both; whether nuclear theoreticians must release intermediate data, institutional theory codes, or both; and whether nuclear evaluators are required to release assembly scripts, corrections, or both. This ambiguity leads to many questions and concerns:

1. **Quality**: A given project consists of many steps. Results from these steps are often publishable (or required by a sponsor to be published) while the main project/product is not finished. The access plan implies that all data products, whether part of this intermediate result or the work as a whole, must be released as well. Also, often there is a reason that a result is not released (experimental hiccup, buggy code, etc.). The implementation of this policy requires consideration to allow investigators time to complete work, either with an embargo plan or some other mechanism, and let them determine what data should and should not be released.
2. **"Unfunded mandate"**: Data products, whether experimental data or theoretical codes, require a lot of work to be usable by nonexperts. Resources are also required to keep the relevant code systems functional as computers and compilers change.

3. **Ensuring credit and attribution**: Releasing low-quality or incomplete results has other implications: a nonexpert can take released data products, misinterpret the data and methods used, and publish results that contain erroneous conclusions requiring additional effort to correct later. It also raises ethical concerns: an unscrupulous expert can swoop in, take these incomplete results, "finish" the work, and take credit for it. Although there is no current evidence that this is occurring in the ND community, community guidelines and guardrails are needed to ensure correct and ethical use of data products.

5.1.2 Challenge #2: Preserving Legacy Data

The ND community has invested a significant amount of time and resources in collecting, preserving, and maintaining the published results from ND measurements and experiments. These results are the bedrock on which ND evaluators rely when constructing the next iteration of evaluated nuclear data files. Two examples of collected nuclear data are the EXFOR [11] database and the ICSBEP [38] *Handbook*. The EXFOR database contains an extensive compilation of experimental nuclear reaction data, which have been compiled systematically since the discovery of the neutron in 1932. This period of data collection has relied on reporting from a variety of institutions that have used a range of technologies and reporting standards to capture their measurement and analysis techniques. EXFOR has captured the information from all of these past experiments and compiled them into a form more easily usable by the broader ND community. Similar to EXFOR, the *ICSBEP Handbook* is a collection of mostly critical experiments, with an emphasis on the material composition and geometry that are relevant to a critical measurement. Information contained in the *ICSBEP Handbook* is used for validation and nuclear criticality safety. The EXFOR database and the *ICSBEP Handbook* are valuable as centralized locations from which to expeditiously retrieve the published results from ND measurements. However, there are direct and indirect costs associated with maintaining and preserving the EXFOR database and the *ICSBEP Handbook*.

The major takeaways from the legacy data session were that experiments must be well documented and that the easy storage and retrieval of legacy data are paramount to ensuring a continuous flow of information along the ND pipeline. A major concern for the development of integral benchmarks is the time and effort required to perform evaluation reviews. The technical expert reviewers are not currently funded, and the quality standards for these benchmark evaluations and subsequent reviews have become more rigorous. Relying on nonexperts for these reviews will sacrifice quality and is, therefore, a nonstarter.

The second takeaway involved several aspects of EXFOR:

- the retrieval of information (both data and metadata);
- additional compiler assistance;
- the need for additional information and expanded scope of reported ND;
- the backlog of legacy data,
- modernization efforts; and
- making EXFOR more compatible with ML/AI efforts.

It was noted that the Working Party on Evaluation Cooperation (WPEC) Subgroups 50 (Developing an Automatically Readable, Comprehensive and Curated Experimental Nuclear Reaction Database) [44, 45] and 54 (Continuation of Subgroup 50: Developing an Automatically Readable, Comprehensive, and Curated Experimental Reaction Database) efforts expand information and corrections, work toward making EXFOR ML/AI ready, attempt to try new compilation approaches, and simplify the EXFOR workflow. The EXFOR database serves an important role in reporting curated ND, and the community recognizes the value of having a vast amount of information in a single location. Despite its value, or because of the vast amounts of data stored within it, the retrieval of key information needed to efficiently utilize reported ND in EXFOR to create new evaluated ND libraries remains a major impediment to the flow of information along the ND pipeline.

5.1.3 Challenge #3: Workflows

A *data workflow* is a series of structured tasks for managing and preparing data for later use. In the case of ND, this workflow is often simplified using the "nuclear data pipeline" metaphor, but the full process is quite complex, as shown in Figure 6. A ND worker may only interact with a portion of the full workflow. For example, an EXFOR compiler may only interact with experimenters and their data, the curated experimental formats in EXFOR [11], and the EXFOR database itself. Similarly, an evaluator might see the compiled EXFOR data, the evaluated data [46], the post-evaluation ND processing [47, 48], and validation results using integral experiment data. There are four takeaways from this complex figure:

- Workflows, or parts of workflows, are often partially duplicated at competing institutions. This duplication is often driven by competing needs of different transport codes for different application spaces, but it also serves the added benefit of facilitating cross-checks and peer review. Many of the tools we use in ND are complex, difficult to use codes, even with good coding practices and documentation.
- Codes in these workflows need to be written well, documented well, and open-sourced when possible to remove barriers for their use. However, there are unavoidable barriers such as export control and classification restrictions that inhibit use of some of these codes.
- Workflows vary from site to site at national laboratories, universities, and private companies, but they are nearly always some combination of people and methods [49]. This means succession planning needs to be a consideration.
- The digital ecosystem is constantly changing with updates and new codebases. This implies that there is a maintenance cost (both in terms of money and expertise) that must be borne by programs. Are there best practices or tools in other disciplines that can help defray these costs?

We are working to streamline and automate ND workflows. Doing so allows experts to focus on other problems and eases entrance to the field for newcomers. That said, there are many "rate-determining" steps that are highly human dependent. These steps provide opportunities to try new techniques and tools, as discussed in Sections 5.2.1, 5.2.2, and 5.2.4. We want to highlight improvements to the EXFOR workflows that can address the "leaky pipeline" problems identified by several meeting participants.

Finally, we note that as the evaluated reaction data community moves to adopt the modern Generalized Nuclear Database Structure (GNDS) [50] common format, we face some new challenges. How do we make the transition of secondary tools from ENDF-6 to GNDS FUDGE-based workflows [51] and the GIDI+ [52] API enable ENDF-6/GNDS use in LLNL transport codes and GEANT4. What tools and investments are needed elsewhere?

5.1.4 Challenge #4: Preserving the Data and Workflows into the Far Future

The ND community's customers often work on 50- to 100-year life cycles (i.e., the Naval Nuclear Propulsion Program and power reactors [49]). Not surprisingly, several ND projects (ENDF, EXFOR, and ENSDF) are also 50+ years old. Long-term preservation requires proper strategic planning, clear goals, open communication, a readily accessible data repository, and an appropriate level of risk management. A set of well-defined, achievable goals aligned with long-term R&D programmatic objectives is the foundation for high-quality ND products and future needs and development. Institutions must monitor technological advancements and have the capacity to systematically revisit their products. This becomes more manageable when those products are stored in a common format and in a centralized location. Another key to long-term data and workflow preservation is the ability to reproduce ND products using either past workflows or modernized workflows. A strong validation basis is needed to ensure the ND product remains correct. To

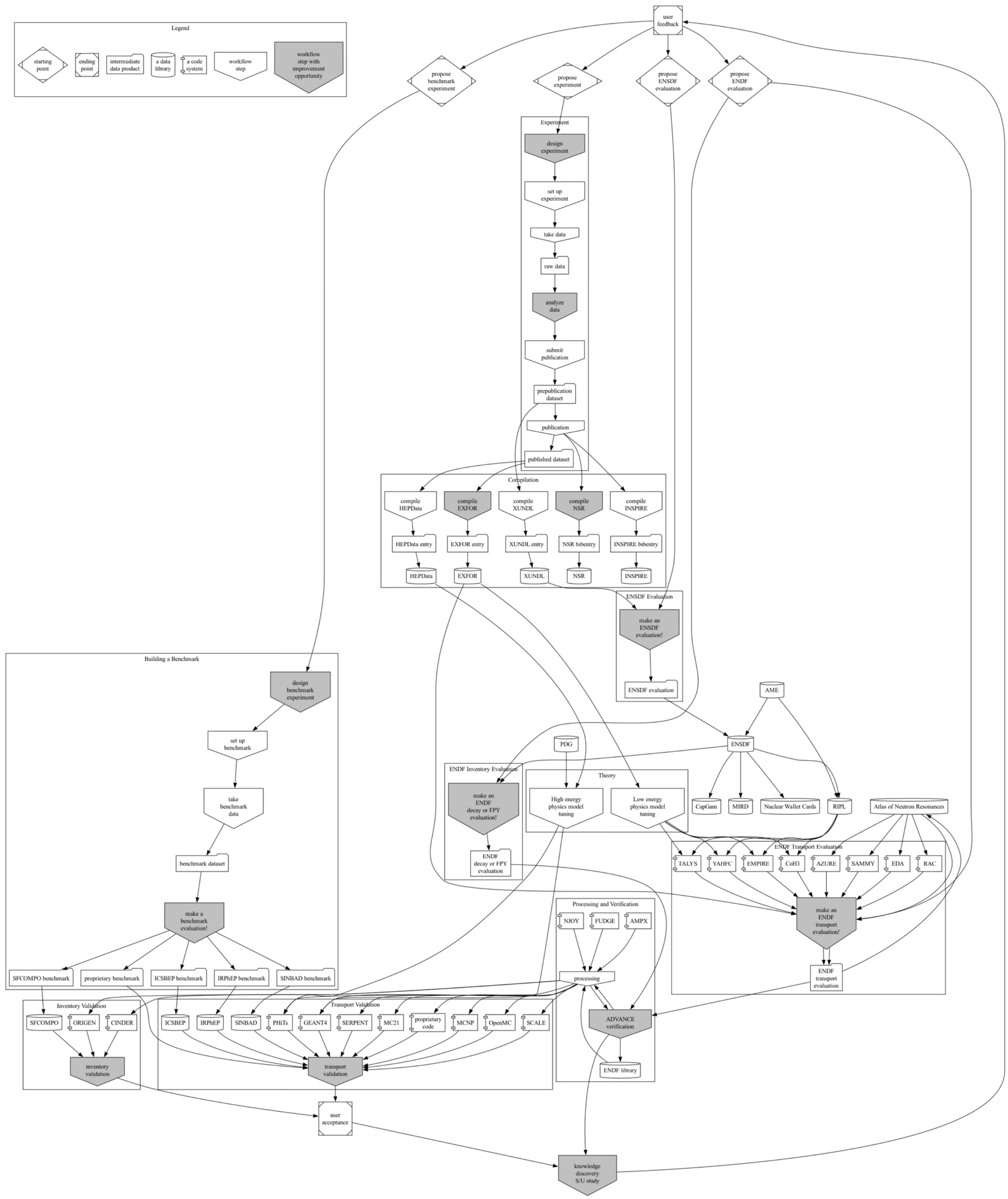

Figure 6. Full ND workflow. The full ND workflow is quite complex, touching many data libraries and user codes. We include this figure realizing that the details are almost unreadable but hope that the reader can see that user feedback drives community priorities.

achieve this, the processes and documentation describing how ND are produced, best practices for use, and lessons learned are crucial.

Many current ND projects use governance and data management, but those practices have evolved much too slowly. Advances in ML/AI can upend these unless we give forethought to data and workflow preservation on very long timescales, where the focus has traditionally been on the final files only. Saving the data and knowledge workflows requires programs with a long-term mindset, such as the existing ND collaborations. Storing the data makes it possible to find innovative ways to reuse the data well beyond the conclusion of the original work.

5.2 UNIQUE OPPORTUNITIES/NEW CAPABILITIES

5.2.1 Opportunity #1: AI

Given the ND community's size and problem scope, strategic integration of ML/AI into our daily work and workflows is essential. To take full advantage of ML/AI's promise and be ready to respond to future needs, we must continue modernizing our data sets and access tools as well as exposing the data and tools to ML/AI workflows. Also, we must begin experimenting with advanced uses of ML/AI, including data extraction from publications using LLMs and the integration of ML/AI into experimental planning and execution, perhaps with digital twins. Improvements to optical character recognition (OCR) technology will be needed to harvest information from old photocopies and logbooks. In all cases, taking full advantage of the power of ML/AI technology will require collaboration between ND subject matter experts (SMEs) and data scientists.

5.2.2 Opportunity #2: Curating EXFOR and SG-50/54

The EXFOR project is reaching a crossroads: the current compiler workforce is aging out and not being replaced fast enough. Meanwhile, evaluation efforts need more detailed information about the experimental data even as the scope of data being used is expanding. EXFOR compilation is the rate-determining step in the ND workflow, and, therefore, we need to rethink our approaches to compilation. There are many options to explore:

- Teaching students to perform EXFOR compilations. This model has been applied with some success in the collection, organization, and compilation of the high-energy physics experimental reaction data library HEPData [53]. This has the potential to grow the ND workforce but needs a simpler workflow, patience, and education.
- Leveraging existing staff. This is not cost-effective and is in fact not good for career growth.
- Citizen science. Citizen scientists are not proficient in ND and would need extremely simple workflows based on very well written user interfaces.
- ML/AI. ML/AI is not yet ready to perform EXFOR compilation work; a great deal of development is required.
- Experimenters themselves. This is the HEPData model, but a simpler workflow is needed to make it practical for EXFOR.

WPEC SG-50 and now SG-54 provide an opportunity for us to develop a "curated" EXFOR that helps evaluators learn from what past evaluators found when examining legacy experiments, integrate more information than what was available from the original publications, and make EXFOR "ML/AI ready".

Figure 7. Printouts of "Resonance Data" from the Harwell LINAC found at the former residence of Mick Moxon. The content of the boxes is currently unknown. A similar event occurred with a retired Japanese researcher, who kept a pile of papers from transmission performed at Japan Atomic Energy Research Institute LINAC at their house. Image presented by V. Dimitriou [54].

5.2.3 Opportunity #3: Data rescues

Every scientist produces an immense amount of information over their lifetime as they collect, analyze, and hone their craft. Most do not consider what happens to that data after they leave the field at the end of their careers. In a way, this is a failure of succession planning at the home institution. Setting this aside, the information must be preserved somehow because it represents a tremendous resource. A recent example was the boxes of files collected from M. Moxon's residence (see Figure 7).

Additional resources and methods are needed to extract information from legacy media (i.e., handwritten notes and institute-specific logs). Significant time and effort is needed to revisit past work and extract information needed to understand the results of an experiment, including systematic uncertainties. Incorporation of new methods to capture legacy information can prove useful for knowledge retention and data extraction.

5.2.4 Opportunity #4: "Raw" experimental data

EXFOR does not contain enough information to faithfully apply the corrections and adjustments needed to use experimental ND for generating an evaluation [45]. The ND community also cannot take full advantage of experimental efforts because our raw experimental ND are decentralized at locations throughout the U.S. This segmented approach limits cross-site sharing of experimental ND and is also hindered by lab-specific data analysis codes, methods, and procedures. To further complicate matters, in recent years, there has been a transformation where raw experimental data are now recorded in digitized form. This exponential growth in data and information has allowed some groups to extract additional information from past measurements, but only at great cost and in collaboration with site-specific SMEs [55].

The nuclear community needs a new approach to data visibility that is consistent with FAIR and FARR principles. This effort must start by first collecting all raw experimental data and its relevant metadata (e.g., experimental information, raw data formats) into a single centralized location. Data stored at a single location can be more easily accessed and analyzed. With instructions provided by SMEs, the time needed for other ND experts to be able to reproduce the results of prior experiments for validation purposes, and to begin to build on past work to extract new information, is greatly reduced. To facilitate improved data extraction, and to save significant resources, the ND community could adopt a standardized experimental ND format: that is, experimental ND analyzed by SMEs and that contain significant information on individual events, files, etc., including metadata. Having all the data in a common format greatly expedites the use of ML/AI with experimental ND. The benefits of a standard experimental ND format are similar to the benefits of data aggregation in a centralized repository (as noted above): significant reduction in overhead (i.e., time and resources expended by each user seeking to analyze unformatted experimental ND), easier validation and verification, and easier storage of metadata and descriptive keywords for data retrieval and parsing. Therefore, the community would benefit from:

1. The creation of a centralized experimental data repository. This data repository would contain all experimental ND and associated metadata produced from a measurement and would be linked to results provided to EXFOR, International Criticality Safety Benchmark Evaluation Project (ICSBEP), Evaluated Nuclear Structure Data Format (ENSDF), and other ND repositories.
2. The creation of a universal ND format for processing raw experimental data. Analyzing raw experimental ND takes institution-specific SMEs. A common format would allow external users to more easily leverage past work for validation, the extraction of new information, and the integration of ML/AI into their new work.

5.3 SYNERGISTIC WORK

5.3.1 Succession Planning

The ND community is built on several long-running (50+ years) collaborations delivering data to users. Every step in the pipeline requires domain expertise, and we need to ensure that expertise is preserved and grows to meet new needs. Simple apprenticeships are not enough; mentoring must start well before the retirement of the mentor and should involve the entire community. Junior staff need to assume some leadership roles and be given the space to make mistakes and learn.

5.3.2 Communicating the Value of ND and Helping Users Prioritize

ND's vital role and impact on modern nuclear applications is often unknown or unrecognized. As a result, when users encounter a problem, it is not unusual for them to "engineer" a workaround of an ND shortcoming. More advanced users may recognize the role of ND in their problem and may deliberately engineer a workaround, assuming that the ND are correct and therefore cannot be the source of their problem. We as a community must reach out to users and educate them about the role of ND and how it can be improved to benefit them. We note that it is sometimes difficult to demonstrate the financial impact of a specific data improvement, both because of the technical challenge of such studies and because user problems may be proprietary. Workflows can help with prioritization by providing tools to understand which features in the underlying ND are driving improvements and their associated costs and benefits.

5.3.3 Data Science Issues Touch Many Other Fields

We note that the ND community is not the only community facing such data challenges. Issues and themes discussed in this session were echoed in the form of similar problems by participants at the Software Infrastructure for Advanced Nuclear Physics Computing (SANPC) [56] and DOE Data Days [57] workshops; the Conference on Data Analysis (CODA) [58]; and by several other US federal and international programs

[59, 60, 61]. SANPC brought together those working in high-energy physics to discuss challenges and opportunities. Their finding was that current support promotes functionality on new platforms and novel hardware systems, and that effective stewards should cover the full lifecycle of data and software management. It was noted that forward-looking data analysis and preservation were essential to the development of robust long-term preservation of data and its associated metadata to ensure the accessibility and reproducibility of publicly funded science. DOE Data Days (D3) is a workshop series focused on advancing data management strategies across the DOE and national laboratories. The workshop also focused on complex-wide challenges in data governance, curation, and technology. Finally, the CODA highlighted data-driven problems of interest to DOE. These meetings also echoed a common theme from WANDA 2025, namely how to incorporate ML/AI into our workflows.

Table 7. Critical needs for improving workflows and data preservation that impact the timeline and quality of ND products delivered by DOE programs.

Crucial in the next 5 yrs	**Beneficial in the next 5 yrs**
• Modernizing the EXFOR workflow and compilation requirements that build on the results of SG50/54 and enable ML/AI workflows • Adoption of Open Data standards • Support for peer review of integral benchmarks	• Integration of ML/AI into ND workflows • Preserving legacy ND from experts who have left the field (i.e., Moxon) • Improved communication with sponsors and users about the costs and benefits of ND
Crucial in the next 10 yrs	**Beneficial in the next 10 yrs**
• Raw experimental ND repository to comply with Open Data requirements • Robust succession planning for ND programs in the U.S.	• Standard format for experimental ND

6. SUMMARY

The WANDA 2025 meeting covered various aspects of ND needs for nuclear deterrence, fusion energy applications, advanced reactors (especially microreactors), ND preservation, and ND workflows that support these and other application spaces. Participants in each topic area expressed the need to shorten timelines for delivering ND experiments and evaluations to ND users. Many of the topic areas had similar needs (e.g., damage cross sections, better and more complete uncertainty estimates, and improvements to experimental data repositories) that could be addressed by multi-program efforts. These synergies are highlighted in each of the topic area summaries. The inclusion of a data preservation and data workflow session in this year's WANDA was timely because it was applicable to all of the program elements involved in the workshop. Improving ND workflows in tandem with the mission-specific needs expressed in each section will be critical for progressing nuclear application modeling and integrating accurate nuclear data into the compressed timelines sought by DOE programs and US industry stakeholders.

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