Improvements to nuclear data in service of Intentional Forensics

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The Intentional Forensics (IF) venture seeks to identify and perfect tagging technologies for nuclear fuel provenance and tracking. These should highlight materials outside of regulatory control, thereby identifying gaps in safeguards, assisting law enforcement, and serving as a deterrent to future trafficking. A major consideration is the complex interaction of neutrons and isotopes. Many particle transport codes used in this development rely on the data in the Evaluated Nuclear Data Format part B (ENDF/B) library, managed by the National Nuclear Data Center at Brookhaven National Laboratory with stakeholders from government, academia, and industry in the United States and global partners. This work describes the data products provided to the IF venture by the NNDC. The first is a compilation and review of ENDF/B-VIII.0 database. This includes a quick reference and new calculations, and the analysis comprises data quality, resonance evaluation, integral metrics, fission product yields, covariances, and accompanying documentation. The review and results will be summarized here. The second product is a recommendation of proposed remediation for identified deficiencies from global sources, supplemented with a machine learning (ML) effort. ML is being used to predict poorly understood n-capture cross sections using the full slate of nuclear data collected and hosted by the NNDC. In particular, we present a neural network (NN) model with demonstrated improvement on a common mathematical model, the liquid drop model.

CONTENTS

I. INTRODUCTION

The development of a *taggant* technology for nuclear fuel is being spearheaded by NA-22's Intentional Forensics (IF) Venture. An ideal taggant is a well-characterized additive to the fuel that will encode some optimal information to facilitate tracking, such as manufacturer, location, age, fuel stage, and other datum to be decided. The goal of the first IF venture is a suite of initial candidate-taggants vetted by venture members to demonstrate proof of concept according to the varied perspectives and specialties of members, and to plan a path forward for the next stages.

A taggant should provide several benefits to global stakeholders from public and private interests. It will establish provenance and tracking, identify extra-regulatory material, highlight security lapses, aid law enforcement, and deter future trafficking [1]. The ultimate selection of ideal taggants will be a complex, detailed process, involving many considerations, and relying on the cooperation of many specialties. This venture, in short, is a development working group meant to identify materials for addition to nuclear fuel, and to standardize processes to uniquely identify aspects of the manufacturing chain and nuclear fuel life cycle. An active nuclear reactor enforces some of the harshest requirements found in engineering, with high temperature, and extremely high neutron fluence. The neutron spectrum can be complex

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FIG. 1. A 3M/Microtrace Taggant. Trade name: Microtaggant® Identification Particles. The website refers to the product as "The original taggant technology" and the "origin of the commonly used word "taggant". (Microtrace, 2022).

and detailed depending on fuel, design, and operation. Several methods to incorporate taggants in the nuclear fuel have been proposed, including coating, homogeneous mixing, and strategic doping or deposition. When reviewing the suitability of an isotope as a taggant, many considerations affect the conclusion. These range from radiochemistry, to cost, to ease of machining. Although there are many competing considerations when downselecting taggant candidates they are judged on two primary qualifications. First, the cross-section must be predictable in the high neutron fluence environment. Detection and quantification of taggants will be entirely dependent on this predictability. Second, and perhaps most important, fuel performance must not be impacted significantly [1]. Taggants will influence fuel performance in both thermochemical and neutronics ways. Thermo-chemical reactivity is outside the scope of this report, thus we will focus on the neutronics aspect as it relates to both detection and fuel performance. Taggants are developed for many applications, from luxury goods, to proprietary technology, to chemical explosives [2]. Actual nuclear tagging technology will be difficult to visualize, as it will likely be chemical, elemental, or isotopic in nature, so Figure 1 shows a plastic taggant for modern engineering applications to add context.

Taggant neutronics impacts fuel performance in two primary ways. First, the taggant's elastic cross section and angular distribution can influence neutron leakage. Second, the taggant can absorb neutrons via a large capture cross section, changing the reaction flow of the system. We assume a large system and/or homogeneous distribution in which leakage is a small effect, thus the data focus for this exploration will be neutron capture. The details of this assumption should be tested as part of a robust and rigorous taggant selection process, but are outside the scope of this report. In summary, n-capture reactions dominate the nuclear data considerations for materials chosen as taggants for nuclear fuel provenance.

Given this situation, we have presented several data products, each of which will be reviewed here. First is a compilation, summary and review of relevant data in Section II. This comprises a quick reference table and description, spanning from eV to MeV (Section II B)), and an assessment of capture cross sections for nearly all stable isotopes in the upcoming ENDF/B-VIII.1 release (Q1 2024)(Section II C), The plots and full text used for the assessment are voluminous (> 800 pages) and can be provided upon request from the authors of the present document. We finish this section with a discussion of implications and deficiencies II D,

Second, we explore a set of high-impact short and long-term remediation sources, that are sensitive to the financial considerations. Global libraries, recent experiments, possible future experiments, and Machine Learning are discussed (Section III). We conclude with an outlook in Section IV that summarizes next steps.

II. COMPILATION, SUMMARY, AND REVIEW OF RELEVANT DATA

A. Scope

At the early stage in taggant selection it is important to take a broad view of the list of possible candidates. However, some isotopes can be immediately eliminated. We exclude H, due to its ubiquity in a commercial reactor, noble gasses (He, Ne, Ar, Kr, Xe) as they are inert and difficult to incorporate, and incredibly rare/man-made elements like Tc and Pm as they are easy to detect.

Monoisotopic elements (Be, F, Na, Al, P, Sc, V, Mn, As, Y, Nb, Rh, I, Cs, Pr, Tb, Ho, Tm, Au, Bi, V, Rb, In, La, Eu, Lu, Re) would not be useful under a perturbed isotopic scheme, but we include them in the report for rigor and other tagging methods. Minor actinides and fission products are bred during operation and might be difficult to distinguish as a dopant but we include these as well.

B. Summary and Compilation

As discussed in the previous section, the primary consideration for taggants is neutronics, or the impact of and on a material in a high neutron fluence. A summary of the neutronics discussion is therefore useful when synthesizing this among the many concerns of the various stakeholders. A handy quick reference collection of useful metrics for naturally occuring isotopes in column tabulated data in pdf and spreadsheet form is available in report [3]. These spectrum integral quantities act as a good stand-in for n-capture cross-section over the full range of relevant energies. These are: thermal cross section, resonance integral (RI), Maxwellian averaged cross section at 30 keV, and ^{252}Cf spontaneous fission spectrum. These metrics will be described in detail in Section II C. The isotopes are listed in order of Z, then A, with the elemental symbol also reported. Values for this table are taken from ENDF/B-VIII.0 [4] and the development library for ENDF/B-VIII.1, with abundances from Nuclear Wallet Cards [5].

C. Isotopic Data Review

The National Nuclear Data Center (NNDC) maintains many different data libraries, software, and other resources for nuclear structure and reactions (see the website `https://www.nndc.bnl.gov/`). For this data review, we will focus on two main sources maintained by the NNDC. Abundance data is drawn from the same source as the compilation in Section II B, while the remaining quantities are from version VIII of the NNDC's evaluated nuclear reaction data library and associated format, designation B (ENDF/B) [4]. The ENDF library is developed by the Cross Section Evaluation Working Group (CSEWG), a collaboration consisting of representatives from governmental and industrial laboratories in the U.S. The review considers all evaluations included in the upcoming ENDF/B-VIII.1 database which will be the official release version of the NNDC's flagship nuclear data library at the conclusion of this venture. Global sources used for comparison are listed in Table I.

A single metric to assess the quality of every relevant evaluation would not be sufficient. The assembled data is the result the subjective application of a confluence of experimental, theoretical, and analytical methodologies. Also, while it is common to presume that captures happen at thermal energies simply because of the strong $\sim 1/\sqrt{E}$ asymptotic trend of a typical cross section, this assumption is not universal with isotope or timescale. A set of typical reactor spectra are shown in Figure 2, taken from Bostelmann, *et al.* [6]. The neutron flux from notional light water reactor (LWR), high temperature gas cooled reactors (HTR), and sodium fast cooled reactor using MOX fuel (SFR MOX) or metallic fuel (SFR MET) are overlayed under the weight function for the spectrum integral quantities discussed later in this section. The dips in the spectra are caused by n-capture events on the various fuel and structural elements. In this figure, one can clearly see the variation throughout the full energy range. The data presented below is intended to support a rapid assessment of n-capture cross section data quality. Therefore, this review considers a mix of qualitative and quantitative metrics, over the entire span of incident neutron energy relevant for reactor operations. The scale is "Very Poor" (0), "Poor" (1), "Acceptable" (1), and "Excellent" (3). In general, a 0 rating indicates the metric has no data. A table of this rubric is available along with the full review from the authors by request. The metrics are:

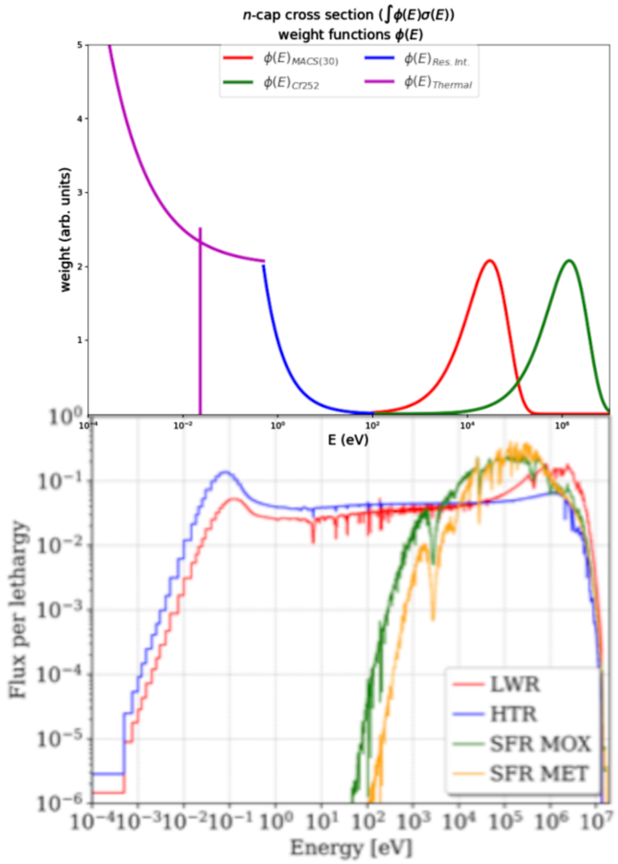

FIG. 2. Top: Comparison of the spectra used in the integral metrics portion of the cross section review. Bottom: From Bostelmann, *et al.* [6]. This figure depicts the neutron flux from a notional light water reactor (LWR), high temperature gas cooled reactor (HTR), and sodium fast cooled reactor using MOX fuel (SFR MOX) or metallic fuel (SFR MET). The dips in the spectra correspond to n-capture events on the various fuel and structural elements in the reactor model. The intention with the overlay is to demonstrate how well the metrics discussed in this work reflect regions of interest to various reactor fuels.

- **Experimental Data Quality (EXP)**: An important tool for evaluating experimental data quality is the plot of cross sections, with all available experimental data. Ratings are based on experimental source, data quality and volume, agreement with itself and evaluations, and whether or not they facilitate R-matrix analysis. "Unpopular" isotopes can be expected to lack experimental data. Where available the plots include current values from other nuclear data libraries to emphasize consensus, or lack of, and to signify the quality and trustworthyness of individual experimental datasets. Experimental data from EXFOR is tricky to interpret, so it is useful to look to other libraries, especially the *Atlas of Neutron Resonances* [7] and KADoNiS [8, 9] which have carefully considered the experimental data used in their recommendations.

- **Resonance Evaluation Quality (RES)**: The plot of cross sections mentioned in the EXP description is also useful to asses the quality of the resonance region evaluation. There are some expected behaviors regarding reasonable density and quantity of resonances, with a small count of resonances unlikely, except for the lighter nuclei. Analytical predictions undertaken without incorporating experimental data can also result in non-physical behavior. If the plot depicts a large amount of capture data in the resonance region, this can be an indicator of a high-quality capture cross section evaluation. This metric considers several things. Number and source of resonances dominates, that is, theory or experiment, with those from TEFAL (In TENDL) rating 1. Incomplete information or treatment, such as those in the Atlas of neutron resonances generally rate 2. Resonances backed by experiment with documentation of direct capture treatment and impact of missing or distant resonances receives a 3 rating.

- **Integral Metrics (INT)** Also known as spectral averages, these metrics focus on three main energy regimes: thermal energies, 10-30 keV and fission spectrum. Together they provide a summative view of the quality of the cross section in a way that more closely aligns with the reactor application of the taggants. They are often simple to calculate and average over various areas of interest in the cross section. Two of these averages, the thermal cross section and RI are thought to most strongly impact reactor performance and can be measured quite accurately, so there is plenty of data in EXFOR. In principal MACS(30) and ^{252}Cf(sf) can be measured accurately as well, but the coding in EXFOR makes use of these data problematic. This metric is primarily based on data quantity and consistency. If the covariance is provided, the uncertainty will be computed for these metrics. Consider these metrics in more detail:

  - **Thermal cross section**: This is the cross section at room temperature

$$\equiv 293.15K = 20C = kT \sim 0.02353eV = v_n \sim 2200m/s \tag{1}$$

    and sets the overall amplitude of the asymptotic 1/E behavior.

  - **RI**: The epicadmium dilute resonance integral (RI) measures captures from just above the thermal region using a filter to eliminate thermal neutrons, and extends to the resonance energy region.

$$RI = \int_{E_{cut}}^{\infty} dE\sigma(E)/E \tag{2}$$

    Where $E_{cut} = 0.5$ eV is taken to be the Cadmium cut-off energy (see S. Mughabghab, Atlas of Neutron Resonances [7]).

  - **MACS(30):**

$$MACS(kT) = \frac{2}{\sqrt{\pi}} \frac{a^2}{(kT)^2} \int_0^{\infty} dE_n^{lab} \sigma(E_n^{lab}) E_n^{lab} \times \exp\left(-aE_n^{lab}/kT\right) \tag{3}$$

    Where E_n^{lab} is the incident neutron energy in lab frame and $a = m_2/(m_1 + m_2)$. In many isotopes (particularly near closed shells) this region contains a large cluster of resonances and is best probed with the Maxwellian Averaged Cross Section (MACS) at 30 keV.

  - ^{252}**Cf(sf):** The high-neutron fluence in a reactor is the product of fission reactions. The neutron spectrum peaks in the 1-2 MeV range, depending on the fissioning isotope. This is the pointwise representation of the ^{252}Cf spontaneous fission spectrum evaluated by W. Mannhart [10, 11] now considered a nuclear data standard. The spectrum is a linearly interpolatable table of mean values and a covariance matrix, extending from 15keV-20MeV.

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The generalized weighting for the spectra are plotted in Figure 2. In our assessment, we compared the values computed using ENDF/B-VIII.1 with other data sources including those detailed in Table I and Pritychenko compilations [12–15].

- **Covariances (COV)** This metric assesses of the quality of the associated covariance data (if any). Modern evaluations often rely on *R*-matrix fit of available resonance data using a code such as SAMMY [16]. In that case, high quality capture covariance data will be available. However, many older evaluations, as well as those for "unpopular" isotopes, have at best schematic data. Notable are the low-fidelity evaluations generated using the kernel approximation [17] and even LoFi or COMMARA [18, 19]. Misclassified covariances cannot be parsed by NJOY/FUDGE, and this is considered in this metric, while a top score will have been converted to reaction MT33. It is impossible to overstate the rising importance of uncertainty quantification (UQ) in modern nuclear technologies, as engineering is heavily reliant on tolerance values, and it is difficult to assess the trustworthiness of an evaluation if no or poor quality covariances are given. This metric will guide UQ studies of these isotopes as taggants.

- **Fission product yields (FPY).** Irradiation is known to result in fission products which can ultimately change the structural, elemental, and/or molecular composition of the material during a single assay and/or over time. Due to variation in interaction time and position-sensitive temperature differentials, chemical gradients and dispersal differences result in non-uniformity of the fission contaminants. Different forms of these products, such as metals, gases, and oxides, as well as elemental groups, are expected. These adulterants can affect fuel quality and efficiency, drive temperatures up, inflict structural damage, and confound attempts at assay, thus impacting their use as a taggant. This metric is quantitative and measures only the *actual* fission yield of the isotope.

- **Evaluation documentation and associated meta data.** The age and source of the evaluation is an important qualitative metric. The documentation is considered very poor unless the resonance region is discussed and conclusions supported with a list of sources. SG-23 evaluations are generally rated "Acceptable". An excellent rating indicates that the evaluation was well documented and experimental issues were highlighted.

D. Implications

The results of quality assessment are collected in a table available from the author along with the full assessment. It should be combined with the expertise of other stakeholders in the down selection of isotopes. To summarize the results, the average rating was 14/30. However, the distribution of scores was binomial, with a smaller peak at around 20. This reflects a concerted effort to improve quality, with promising results. The highest quality isotopic data is expected from those with the greatest abundance as those are easiest to study experimentally, requiring little to no enrichment for a measurements with high-signal/ low-noise. The inverse is also true: "unpopular" isotopes, namely those with low natural abundance, are expected to be poorly studied for traditionally engineered/commercial applications, barring exceptional circumstances/utility, as they are often prohibitively expensive. Figure 3 depicts this relationship.

III. OPTIONS FOR REMEDIATION

A. New Evaluation Discussion

In the near-term there are other sources of high-quality capture data. This section will explore these resources in more detail. The relevant isotopes and sources discussed in this section are summarized in Table II.

1. *US Nuclear Criticality Safety Program*

In the United States, the Nuclear Criticality Safety Program (NCSP) supports fissionable material operations in the Department of Energy ([38], ncsp.llnl.gov). As implied by their name, the focus is on evaluations that impact criticality safety in a variety of applications. As part of this program, the NCSP fund experimental campaigns within the US and elsewhere and synthesizes these measurements into evaluations. The (NCSP) efforts are of the highest quality, and they provide many of the best resonance evaluations in world. The NCSP collaborates domestically with the Naval Nuclear Laboratory (NNL), Los Alamos National Laboratory (LANL), and Rensselaer Polytechnic Institute (RPI), and with several European labs such as the French Institute de Radioprotection et de Sûreté Nucléaire (IRSN), and the Atomic Weapons Establishment (AWE) in the United Kingdom. They have a slate of upcoming measurements and evaluations outlined in the 2023 Five Year Plan [38] which will be welcome additions. The results of this 5 year plan are included in Table II, with NCSP1 and NCSP2 indicating the experimental campaign. In the notes section is the lab sponsor, and the proposed fiscal year (FY). Of the listed isotopes, two deserve additional mention. The ^{54}Fe(n,γ) measurement and the ^{204,206,207,208}Pb evaluation, both at RPI, are the thesis work of students funded through the NEUP program and will be very useful for perturbed isotopics.

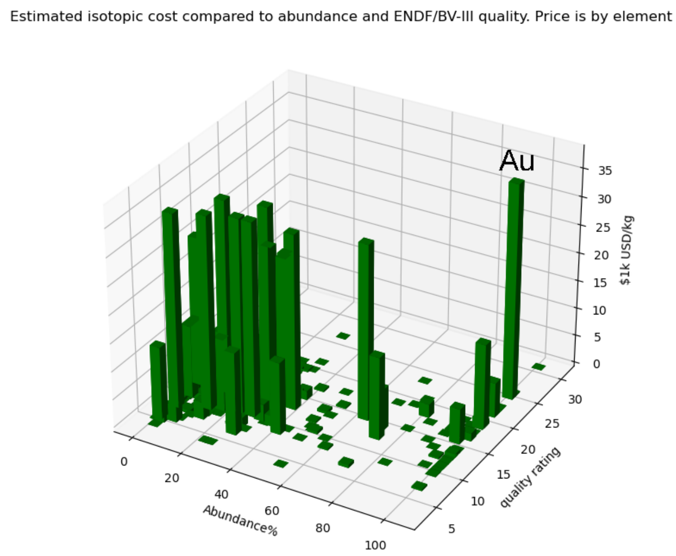

FIG. 3. This image depicts the quality rating of isotopes in this review with abundance and elemental cost from global markets within 10 years. Au is identified for context. The most common isotope is the basis for pricing, actual price for lesser isotopes should be assumed higher. The important trend is the clumping of low quality ratings, for high cost, low abundance isotopes. This highlights one of the main challenges in improving evaluation: cost of acquisition.

Atlas of Neutron Resonances[20]:, previous and latest release, viewed as the definitive source and adopted by ENDF/B. [21](2006) [7](2018)
CENDL-3.1: Chinese Evaluated Nuclear Data Library [22].
EAF-2010: European Activation File, from EASY project. Derived from ENDF/B-VI.8, JEFF-3.1, JENDL-3.0 and others, with an additional internal review [23].
ENDF/B-VII.1 and -VIII.0: domestic general purpose library[24](2011) [25](2018). MCNP [26, 27] and SCALE [28] are based on this. ENDF/B-VIII.1 version is expected early 2024. (`https://git.nndc.bnl.gov/endf/library`)
EXFOR: Experimentally measured quantities related to cross section: total, average, differential and isotopic abundance weighted, as well as resonance integral [29, 30]
IRDFF-v1.05: [31]
JEFF-3.12 and 3.3: Joint European Fission/Fusion File[32](2011) [33](2020).
JENDL-4.0, -4.0u, and 5.0: previous and current release of the Japanese general purpose library [34](2012) [35](2021).
k0 Database: Highly regarded dosimetry database of capture cross sections derived from activation measurements, more precise but limited applicability [36](2019).
KADoNiS-0.3: [8] (not KADoNiS-1.0 [9])
ROSFOND-2010: Russian evaluated library, often duplicates other libraries [37].

TABLE I. Table of global nuclear data libraries consulted for an ENDF evalution. Each provides an alternate "viewpoint". In well characterized isotopes the evaluation process has "converged", while in poorly studied isotopes the "best" (sometimes only) evaluation is adopted. When libraries disagree evaluators incorporate different experimental data and/or theory and rely on subjective judgment. Determining the best evaluation requires a detailed time-consuming, and often expensive study. The IF venture can can help guide these limited resources based on community- and venture- determined needs.

2. *CERN n_TOF*

The CERN neutron time-of-flight (n_ToF) facility is a state-of-the-art experimental center with scientists mostly representing the European Union. The method is discussed previously in Section III B. The 6 ns pulses of 20 GeV/c protons impinge on on a Pb spallation target, resulting in approximately 300 neutrons slowed to the MeV to the GeV region. The focus is on materials relevant for basic science, astrophysics, nuclear technology, and novel fuel and reactor designs. Some important quantities measured include level density in the neutron binding energy region.

CERN has an institutional commitment to open data, which promises full access to data results. The n_ToF facility has completed 137 experiments since Phase-I in 2002, with 82 in a release version. Of these, 29 have been used to develop a full Resolved Resonance Region (RRR) evaluation to resonance parameters in ENDF format using their high quality data. See Table II for details on experiments converted to the relevant ENDF Resolved Resonance Region (RRR) data files. All entries are hosted at both the IAEA and the NEA Janis system `https://twiki.cern.ch/twiki/bin/view/NTOFPublic/DataDissemination`

3. *JENDL-5*

Isotopic evaluations from the Nuclear Data and Reactor Engineering Division, Nuclear Data Center, Japanese Atomic Energy Agency (JAEA) have been released as part of the Japanese Evaluated Nuclear Data Library (JENDL). Begun in 1977, the library current version is the 5th, released in December of 2021 [39, 40]. As with any of the global nuclear data efforts, the focus is on Japanese national priorities, especially nuclear waste and burn up issues. To this end, they produce special purpose files on topics such as dosimetry and transmutation of long-lived fission products, in addition to the standard library. Energy is extended from the standard ENDF/B limit of 20 MeV up to 200 MeV, and the neutron sublibrary includes $\sim$ 200 additional nuclides beyond ENDF/BVIII.0. Included in the V5 update is ToF data from the Accurate Neutron-Nucleus Reaction Measurement Instrument (ANNRI) [41], at Japan Proton Accelerator Research Complex (J-PARC) [42], which uses a 3 GeV proton beam on a mercury target, and a .04 s pulse width. The resulting neutron cross-section data is fit using the specialty R-matrix neutron-capture fitting code REFIT [43], which relies on a multi-level formalism that can analyze many sets of data simultaneously. Isotopes of particular relevance are those recently measured by the J-PARC n_ToF facility, as they are either light actinides or fission products. They are identified in Table II with the source JENDL, and the corresponding journal and year is in the notes.

4. *IRDFF-v1.05*

The International Reactor Dosimetry and Fusion File (IRDFF) [31] library contains cross sections for dosimetry reactions commonly used in nuclear physics. In addition to their intrinsic value as high quality evaluations, they are "radiochemically interesting" for activation experiments and may provide the venture an indicator of a forensic signature to take advantage of. The full list of stable (n,γ) capture cross sections found in IRDFF that may be of interests is indicated in Table II with the source indicated by "IRDFF".

B. Possible New Measurements

In addition to the HFIR radiations currently underway, new measurements can supplement the nuclear data. Predicting the behavior of isotopes in the environment of a nuclear reactor requires a fluence of neutrons that reproduces various fuel-stock spectra. There are two general options for this: a research reactor and a neutron-source beam line. Research reactors exist at the University of Massachusets at Lowell (UMLowell), North Carolina State University (NCSU), and the National Criticality Experiments Research Center (NCERC). They have turnaround of months- 1-2 years, and cost from 0-10k\$.

For neutron beam lines, neutron-capture cross sections are measured directly wherever possible, energy threshold and back ground permitting. Alternatively, total cross-section derived from transmission experiments can indicate the level spacing, total width, and neutron resonance widths, which are useful for analysis using R-matrix, a common method for estimating cross section when only partial information is known.

The Time-of-Flight (ToF) technique correlates the incident velocity, and hence energy, of the neutron to the time it takes to traverse a beam pipe with known length. A range of facilities exist to take advantage of the TOF method and should be considered for future venture activities. Domestically, the Gaerttner Linear Accelerator (LINAC) Center at Rensselaer Polytechnic Institute (RPI) accelerates electrons up to 60 MeV, with 10^6-10^9 sec. pulses and peak neutron production greater than 4 $\times$ 10^{13} / sec. The Los Alamos Neutron Science Center (LANSCE) produces neutrons via a pulsed proton-beam impinging on a W production target. Neutrons up to 500 MeV, with beam pulses >.01 ns are available. Both RPI and LANSCE, have a wait list of 6 mo. to 2 years, with possible cost sharing with collaborators such as the NCSP or the Naval Nuclear Laboratory. The LANSCE program advisory committee (PAC) meets annually for the following year, and closed the next round in March of 2023.

C. A Machine Learning approach

A new Machine Learning (ML) contribution is also in progress at the NNDC. This is an attempt to use ML to predict important n-capture cross sections in effort to supplement the previously discussed remedies for isotopes whose data was identified as "poor" in our assessment, until new measurements can be completed.

We attempt to improve estimates of Maxwellian Averaged Cross Section (MACS) over the full range of energies in the neutron sublibrary, 2.3×10^{-5} keV-20 MeV. This work focuses on regression rather than classification, with a KERAS-based Neural net (NN) [44]. The feature dataset includes all physical quantities available in the NNDC database, with >30 intrinsic and measured values from Z,A,N to S_{2n} and $Q\beta^-$. Many are expected to be coupled and may be eliminitated in a pure regression method, however they could be useful to implement Bayesian improvements.

The most promising result currently studies the residual of the calculated MACS and the Liquid Drop Model (LDM), with shell closure. The results shown here depict the LDM residual fit with a toy-model NN using keras.sequential. A more sophisticated NN using the KERAS functional api has begun. The currently used method should be considered unsupervised, as very limited mathematical relationships are provided to the fitting. Figure 4 demonstrates the improvement in absolute residual.

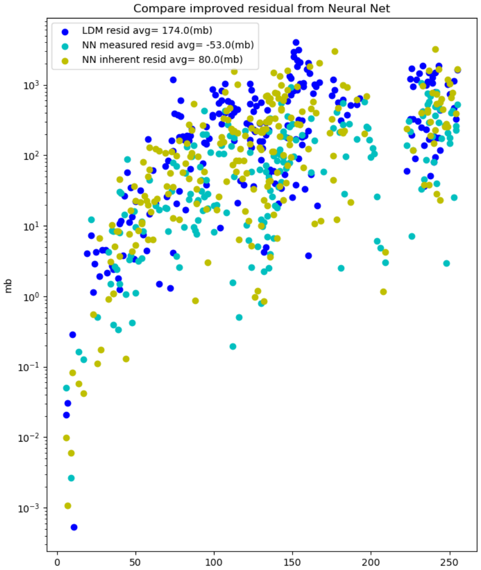

FIG. 4. Plot residuals of MACS at 30keV from the LDM: actual value compared to improved predictions using a neural net for intrinsic and measured quantities. This allows the original dataset to be reconstructed for training, and ultimately, predict isotopes with poor quality data. Note that the information found in the single-isotope formulation could be recreated from this dataset if necessary. Validation with train-test is not depicted in this image for clarity, but is implemented in the model.

IV. OUTLOOK

This final section provides a summarized review of important conclusions and suggestions for subsequent work

Table of possible new data

Isotope	El	Source	Source	Source	Notes
^{19}	Fl	NCSP1	NCSP2		ORNL, IRSN FY'24-'26
^{23**}	Na	IRDF			
^{24,25,26}	Mg	CERN$^+$			23163
^{35}	Cl	NCSP1	NCSP2		ORNL,LANL FY'23-'25
^{45}	Sc	IRDF			
^{50,53}	Cr	NCSP1	NCSP2		ORNL,BNL FY'25-'26
^{51}	V	NCSP1	NCSP2		ORNL FY'23-'25
^{54}	Fe	CERN$^+$	NCSP1	NCSP2	23734 : RPI, ORNL, IRSN, BNL FY'23-'25
^{55**}	Mn	IRDF			
^{56}	Fe	NCSP2			ORNL, IRSN, BNL FY'23-'25
^{57}	Fe	CERN$^+$	NCSP2		23734 : ORNL, IRSN, BNL FY'23-'25
^{58}	Fe	IRDF			
^{59**}	Co	IRDF			
^{63}	Cu	IRDF			
^{63,65}	Cu	NCSP2			ORNL FY'23-'24
^{86,87}	Sr	NCSP1	NCSP2		ORNL FY '23-'27
^{89}	Sr	NCSP2		ORNL	FY '23-'27
^{90,91,92,94,96}	Zr	CERN$^+$	NCSP1	NCSP2	23329,23194,23117,23330,23331 : ORNL, RPI,NNL,BNL,FY'23-'27
^{93}	Nb	IRDF	JENDL		J. Nucl. Sci. Technol.(2021)
^{95}	Mo	NCSP1	NCSP2		LANL,IRSN, FY'23-'25
^{99}	Tc	JENDL			EPJ Web of Confferences (2017)
^{103}	Rh	NCSP2			ORNL,NNL,IRSN, FY'23
^{108}	Pd	JENDL			Nucl. Data Sheets (2014)
^{109}	Ag	IRDF			
^{113,115}	In	IRDF			
^{133}	Cs	NCSP1			LANL FY'24-26
^{135}	Cs	JENDL			Nucl. Sci. Technol. (2020)
^{139}	La	CERN$^+$	IRDF	NCSP2	23259 : ORNL,LANL FY'23-'25
^{143}	Nd	NCSP1			LANL FY'23
^{149,151}	Sm	NCSP1	CERN$^+$		LANL FY'23-?
^{151,153}	Eu	JENDL			wwwndc.jaea.go.jp/jendl/j5/j5.html
^{155,157}	Gd	CERN$^+$	JENDL		23400 : Nucl. Sci. Technol. (in prep)
^{171}	Tm	CERN$^+$			23460
^{176,177,178,179,180}	Hf	NCSP2			ORNL,IRSN,NNL, FY'23-'25
^{181}	Ta	IRDF	JENDL		Nucl. Sci. Technol. (2022)
^{186,187,188}	Os	CERN$^+$			22796,23027
^{186}	W	IRDF			
^{197**}	Au	IRDF			
^{204,206,207}	Pb	NCSP2			RPI FY'23
^{208}	Pb	NCSP2			RPI FY'23
^{209}	Bi	CERN			22944
^{232}	Th	IRDF			
^{237}	Np	CERN			23069
^{241}	Am	CERN	JENDL		23237 : Nucl. Sci. Technol. (2022)
^{243}	Am	JENDL			Nucl. Sci. Technol. (2022)
^{242}	Pu	CERN			23368

TABLE II. Nuclear data activities of interest to the IF Venture. Mass numbers marked with ** are monoisotopic elements. The National Criticality Safety Program NCSP are marked † if the evaluation is performed by the International Nuclear Data Evaluation (INDEN) collaboration. CERN n_TOF entries indicated with $^+$ are the most relevant for the IF collaboration, while the notes section indicates the EXFOR entry. JENDL entries list the publication and year in the notes section.

for the NNDC and the cooperative members of the venture.

The NNDC has provided data products: a compilation, summary, and review of relevant n-capture cross section data in ENDF/B-VIII. These are described and detailed in this report. Several data sources have been identified for short-term, straightforward improvement of the evaluations in the ENDF/B-VIII.1 library and collected in Table II by the NNDC as either permanent sources, or interim improvements until full evaluations and planned new experiments can be incorporated. For taggants identified after the effort has matured, the NNDC and other stakeholders should collaborate to measure and evaluate these isotopes with the exact engineering needs defined by this venture in mind. The most straightforward methods at domestic facilities are summarized.

An ML approach to fill in gaps for very poorly known or unstable nuclei, especially those relevant to the current taggant list is underway. This has particular application in cases such as those discussed in this work. For example, the technique can address the unstable isotopes in between stable isotopes or improve stable nuclei that are especially poorly known.

As mentioned earlier in the document, the full text and plots used for the assessment spans (> 800 pages). Due to its size it will be provided upon request from the authors.

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