INL/EXT-21-61448
Revision 1

Application of the FaMUS Methodology to the NSUF Research Outputs Through End of 2019

January 2021

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NSUF Chief Scientist

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Idaho National Laboratory
Nuclear Science User Facilities
Idaho Falls, Idaho 83415

http://www.inl.gov

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Summary

The Nuclear Science User Facilities (NSUF) is one of a diverse group of DOE user facilities. It is focused on advancing the understanding of radiation effects in nuclear fuels and materials in support of nuclear energy applications. The NSUF has been operating since 2007 and has developed a significant portfolio of supported research. Therefore, it is appropriate to consider its achievements and to determine its successes and shortfalls. As part of this analysis of the NSUF research program, the NSUF has developed a novel and elegant formalism for assessing the current level of understanding of nuclear fuels and materials for use in nuclear environments: the NSUF Fuels and Materials Understanding Scale (FaMUS). The FaMUS methodology is being applied to the NSUF portfolio on an ongoing basis to quantify the progress made. This report summarizes the status of the assessment exercise and highlights general lessons learned.

This examination will facilitate capability balancing of future research by identifying gaps in knowledge, understanding, testing, and demonstration allowing the NSUF program office in conjunction with DOE-NE to direct resources to important aspects of the DOE-NE mission using "emphasize & enhance", "maintain", and "encourage excellence" classifications as well as providing increased transparency to researchers.

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Acronyms

ANL	Argonne National Laboratory
ATR-NSUF	Advanced Test Reactor National Science User Facility
CAES	Center for Advanced Energy Studies
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy, Office of Nuclear Energy
FaMUS	Fuels and Materials Understanding Scale
Fe-*x*Cr	iron with *x* weight percent chromium
F/M	ferritic-martensitic
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
MaCS	Microscopy and Characterization Suite
NSUF	Nuclear Science User Facilities
ODS	oxide dispersion strengthened
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
TRL	Technology Readiness Level
${}^{U,E}M_Q$	FaMUS term symbol

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Introduction

The Nuclear Science User Facilities (NSUF) is the U.S. Department of Energy (DOE) Office of Nuclear Energy's (DOE-NE's) only sponsored user facility. It is charged with advancing the understanding of radiation effects in nuclear fuels and materials to support advanced nuclear energy systems and the U.S. nuclear energy industry. Unlike most DOE Office of Science user facilities, the NSUF is not a single self-contained capability. It is a consortium of facilities distributed across the U.S. Currently 19 partner institutions and one international affiliate provide academic, national laboratory and industry researchers with access to neutron, gamma radiation, and ion beam irradiations as well as a broad range of post-irradiation examination capabilities including electron microscopy, mechanical testing, and X-ray synchrotron, neutron beam, and positron annihilation spectroscopy.

The NSUF has been operating since 2007 (originally as the Advanced Test Reactor National Science User Facility, ATR-NSUF) at Idaho National Laboratory (INL) and has supported a significant portfolio of science and engineering research. NSUF supported research answers specific questions across the whole range of Technology Readiness Levels (TRLs); however, it does not intentionally move a material system or a process up a TRL ladder.

NSUF Research Portfolio

A Clarivate Analytics "Web of Science" search shows 141 publications explicitly acknowledging NSUF support for work, i.e., as a "Funding Agency", for the period ending December 2019: a search for publications mentioning NSUF involvement in the project gives 313 hits (numbers effective January 25, 2021. A citation report on the 313 publications highlighting NSUF involvement in the study gives an *h*-index of 29 with 3477 total citations at an average of 11.11 citations per item from 2546 citing articles (this number is reduced to 2399 if self-citations are removed). The increase in the number of citations per year is shown in Table 1. The data in Table 1 (and in future analyses) refer to the calendar rather than the financial years.

Table 1. Annual number of citations of publications involving NSUF participation in the research study.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
# of citations	30	59	80	157	189	310	548	866	1141

Figure 1. Top ten focus areas for NSUF supported research. Numbers derived from the Clarivate Analytics "Web of Science" database on 25 January 2021.

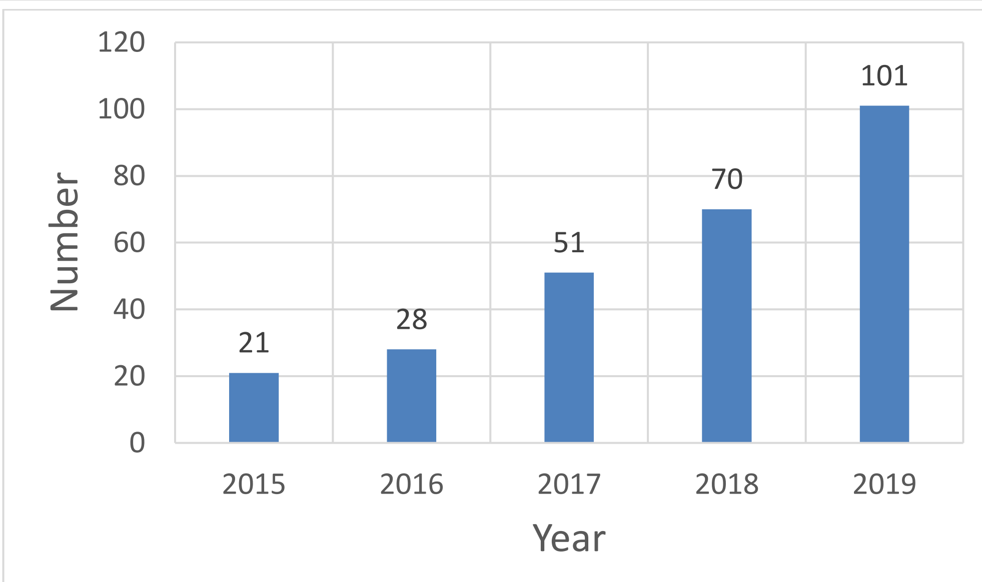

Figure 2. Growth in the number of publications acknowledging NSUF participation since 2015. Numbers derived from the Clarivate "Web of Science" database on 25 January 2021.

A Clarivate Analytics "Web of Science" analysis of the top ten areas of focus of the NSUF research portfolio and of the growth of the number of publications found are given in Figures 1 and 2, respectively.

Figure 1 shows that the NSUF supported research is primarily in the fields of Materials Science, of Nuclear Energy Technology and of Metallurgy and Metallurgical Engineering. The most popular venue for reporting NSUF supported research is the *Journal of Nuclear Materials* with 32% of the outputs, distantly followed by *Acta Materialia* and *Scripta Materialia* at 6% and 5%, respectively. These three journals have mid-range impact factors of ~2.5, ~7.3 and ~4.5.

The top ten organizations publishing NSUF supported research are shown in Figure 3. The majority of the NSUF supported publications include authors from the U.S. national laboratory complex especially staff at Oak Ridge National Laboratory (29.7%) and/or Idaho National Laboratory (27.2%). The most prolific university research institution is the University of Wisconsin - Madison, 7.7%, followed by Boise State University, 7.3%, which hosts the Materials Characterization Suite (MaCS) NSUF partner facility at the Center for Advanced Energy Studies (CAES) and has close research ties with Idaho National Laboratory.

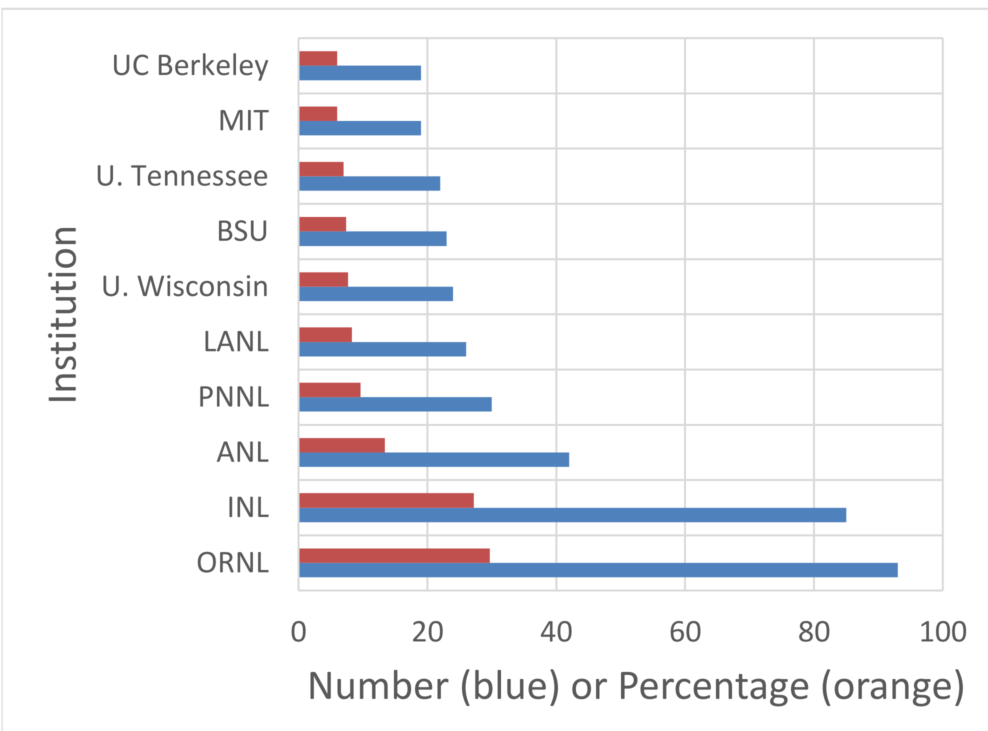

Figure 3. Top ten organizations publishing NSUF supported research. The blue histogram refers to the number of publications and the red to the percentage. Numbers derived from the Clarivate "Web of Science" database on 25 January 2021.

This Clarivate Analytics "Web of Science" analysis of the list of NSUF supported research is somewhat misleading: it highlights the heavy utilization of the US national laboratory complex in performing NSUF supported research and the impressive level of collaboration between the awarded (predominantly) university investigators and the technical experts at the NSUF partner national laboratories facilities. Furthermore, Web of Science considers all peer-reviewed outputs within the scope of the database.

NSUF sponsored outputs can be divided into six classes:

1. Overviews or reviews,
2. Articles describing the development of new scientific or engineering capabilities,
3. Articles demonstrating the application of new scientific or engineering capabilities,
4. Reports of research on the properties of materials sponsored by the NSUF,
5. Reports of research on the properties of materials utilizing capabilities provided by the NSUF,
6. Reports of computational studies utilizing HPC capabilities provided by the NSUF,

Figure 4 shows the breakdown of the 313 peer-reviewed outputs supported by the NSUF and published before December 2019 into the six classifications.

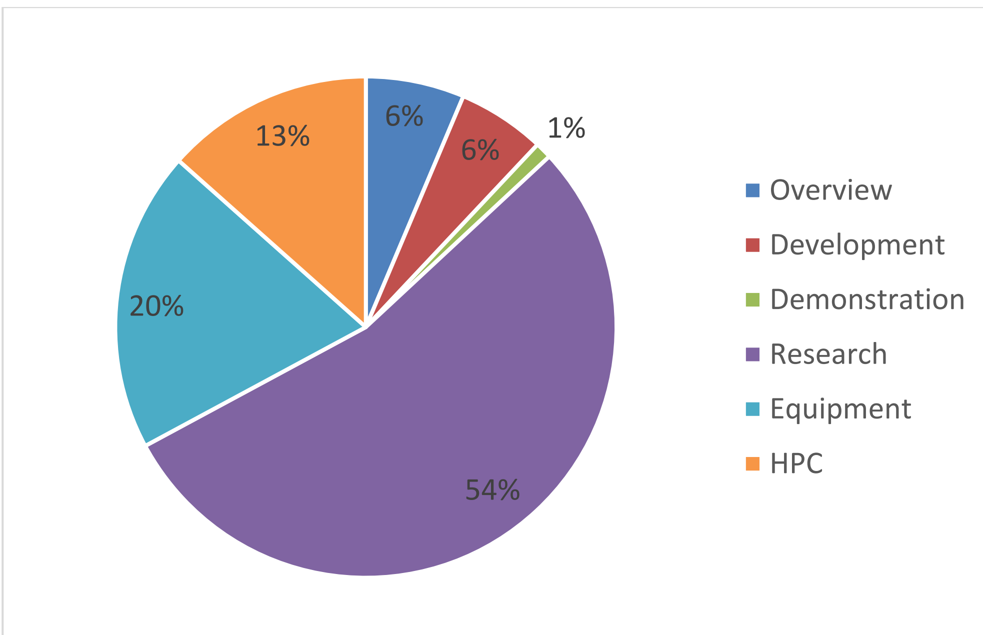

Figure 4. Breakdown by focus of the 313 peer-reviewed outputs supported by the NSUF and published before December 2019.

The following analyses and discussion are focused on the in the third and fourth classes which develop understanding of the behavior of nuclear fuels and of unirradiated and irradiated materials. The number of research outputs published year-on-year since 2010 in these three areas is shown in Figure 5 and the cumulative breakdown between the three classes as well as the breakdown in calendar year 2019 is given in Table 2.

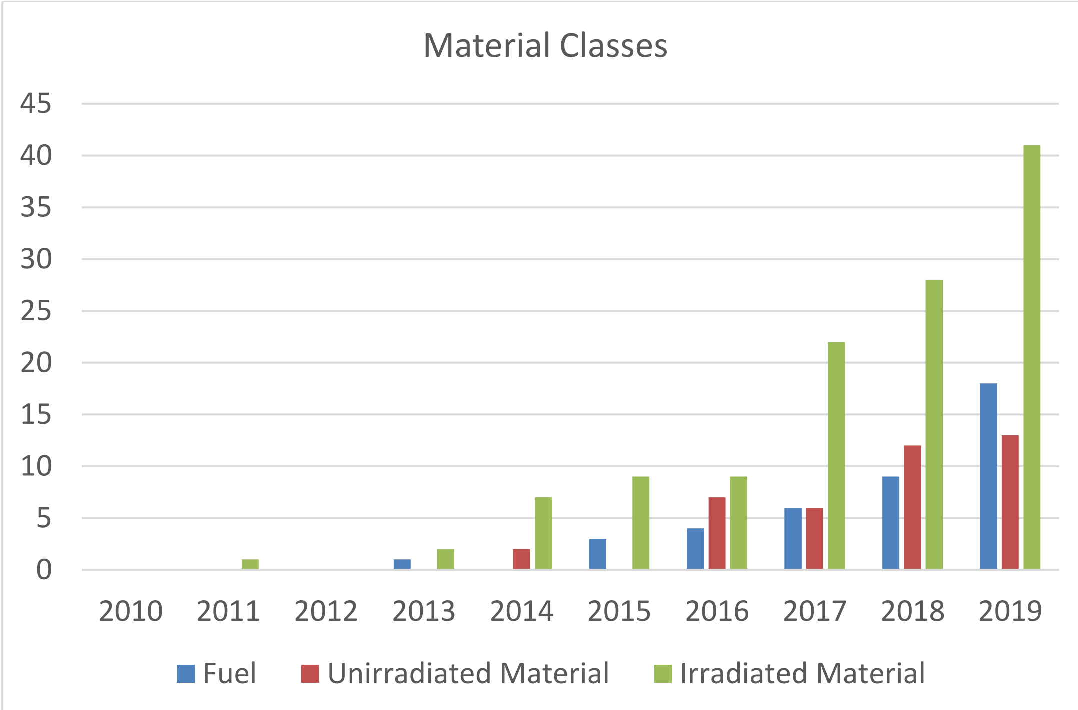

Figure 5. Number of research outputs supported by the NSUF and published before December 2019 advancing knowledge of the behavior and performance of nuclear fuels, unirradiated materials and irradiated materials.

Table 2. Fraction of research publications involving NSUF participation addressing nuclear fuels, unirradiated materials and irradiated materials.

	Nuclear Fuels	Unirradiated Materials	Irradiated Materials
Since 2007	20%	20%	60%
2019	25%	18%	57%

The NSUF research portfolio is dominated by studies of the effects of irradiation on metallic materials, primarily steels as well as silicon carbide (SiC) and SiC composites. While there are many phases in steel, there are only three structures: ferrite, cementite and austenite, with martensite being a specific ferritic phase. The breakdown of the NSUF sponsored research publications for the major metallic material types, model ferritic iron-chromium (Fe-Cr) alloys, model iron-chromium aluminum (FeCrAl) alloys, oxide-dispersion strengthened (ODS) alloys and stainless steels (SS), is shown in Figure 6. All the various materials for sensors are also included as a specific category.

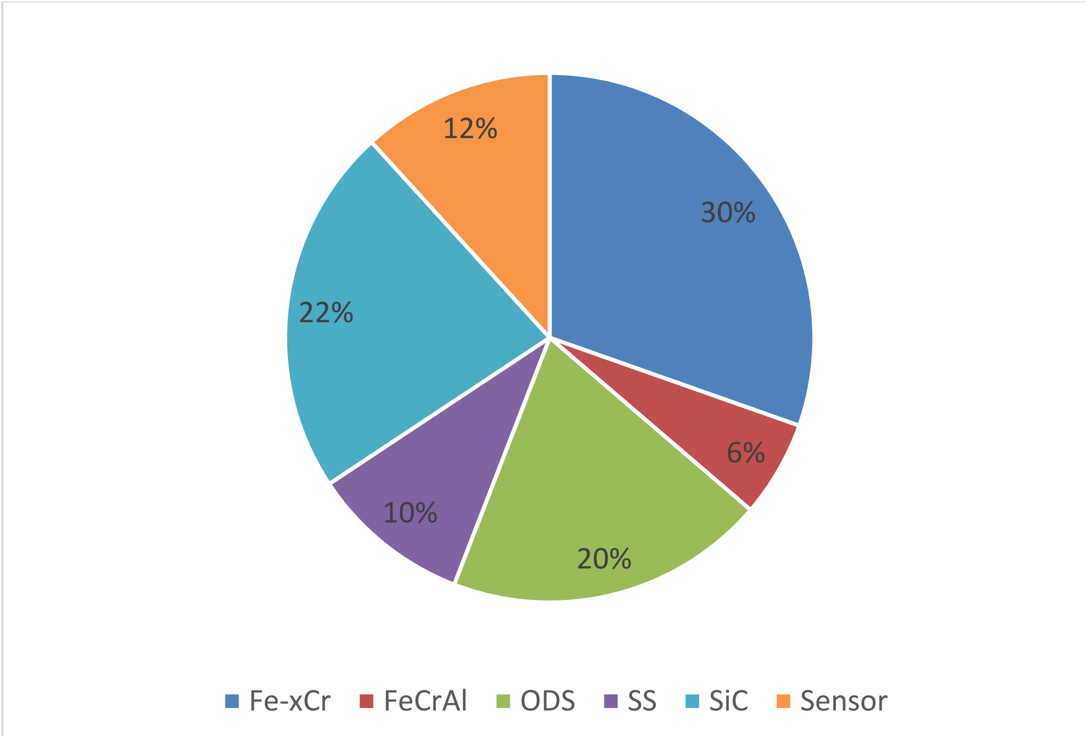

Figure 6. Breakdown of major classes of non-fuel materials studied, and reported on, by NSUF supported researchers.

The NSUF FaMUS Methodology

To assess the status of the NSUF research portfolio and to manage the future development of its research program, the NSUF is deploying and applying a new, novel and elegant formalism to determine how a research project has changed the current level of understanding: the NSUF Fuels and Materials Understanding Scale (FaMUS), which is outlined in Figure 7.

The FaMUS methodology has been described previously (1). Briefly, it expresses the level of understanding of a radiation induced modification of a material property or of a (radiation-induced) phenomenon using a term symbol, ${}^{U,E}M_Q$, where the value M denotes the total level of understanding of the phenomenon. The parameter U shows the nature of that understanding with "1" corresponding to a qualitative observational dependence, "2" to a quantitative empirical dependence, and "3" to a mechanistic understanding suitable for inclusion in a multi-physics model. The parameter Q quantifies the breadth of this understanding: the number of different experimental variables considered, such as dose, dose rate, irradiation temperature or pressure. The parameter M is the sum of superscript U and the subscript Q. A given value for M can be obtained by a variety of combinations of Q and U, reflecting different levels of information and of understanding of the phenomenon of interest. The parameter E is only employed when the term symbol refers to the radiation induced modification of a material property and there is a mechanistic understanding of the observed change. It denotes the number of microstructural endpoints that are associated with the mechanistic understanding.

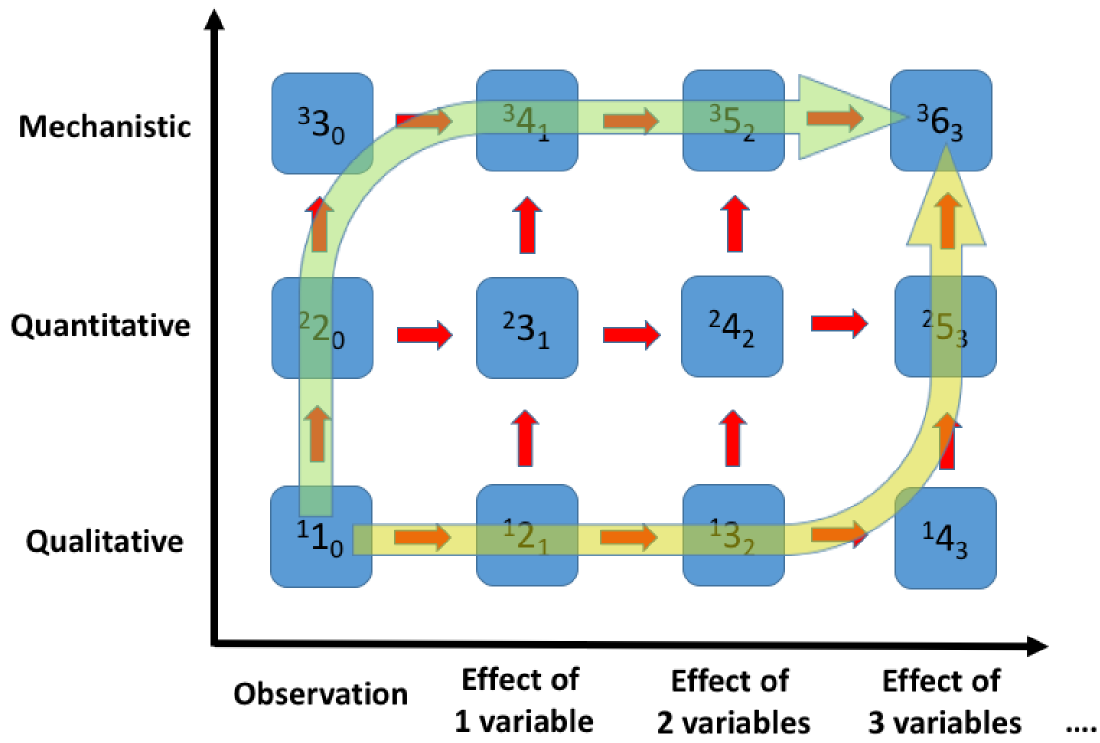

Figure 7. The Fuels and Materials Understanding Scale (FaMUS).

The objective is to reach the top right-hand corner of FaMUS as shown in Figure 7. This process can be achieved by either a predictive path (shown by the green arrow in Figure 7) in which understanding drives experimental investigation and material development or by a responsive route (shown by the yellow arrow in Figure 7) where experimental observation leads to an empirical model and ultimately to predictive understanding.

A term symbol is derived for each independent material behavior or phenomenon considered and the FaMUS rating for the material is the product of all the term symbols. Consequently, the FaMUS rating for a material with term symbols $^{U1}M1_{Q1}$, $^{U2}M21_{Q2}$, and $^{U3}M13_{Q3}$ has the form $(^{U1}M1_{Q1})(^{U2}M2_{Q2})(^{U3}M3_{Q3})$. This formulation provides a great deal of information but appears very complex. A much simpler way to show the level of understanding of a particular nuclear fuel or materials is to consider the sum of the M parameters, i.e., for the FaMUS rating $(^{U1}M1_{Q1})(^{U2}M2_{Q2})(^{U3}M3_{Q3})$ the sum (M1+M2+M2).

FaMUS Assessment of the NUSF Research Portfolio

A wide variety of different nuclear fuels and materials have been studied under the auspices of the NSUF. Figure 8 shows the number of peer review publications and the level of understanding developed in these publications for a number of popular model alloy systems and developmental commercial alloys.

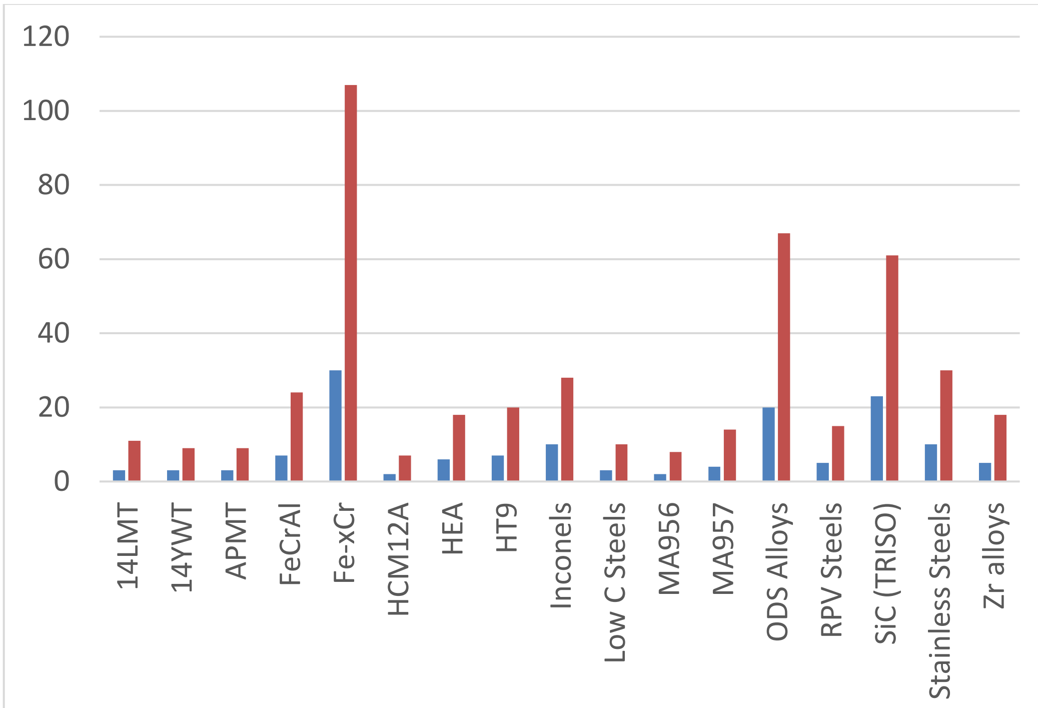

Figure 8. Cumulative level of understanding of model alloy systems and developmental commercial alloys obtained from NSUF supported studies.

To determine the evolution of the NSUF-sponsored research portfolio and to assess the health of the NSUF in supporting the DOE-NE mission, two year-on-year measures are available:

1. the increase in the "total level of understanding" developed in a calendar year, which can be quantified as the sum of the increases in M for all materials during the year,
2. the sum of the increases in the parameter M' = (U E + Q) for all materials during the year.

The first of these measures relates progress in understanding the behavior of nuclear fuels and materials. The second offers a more complete picture than the first - it includes the level of understanding for every phenomenon, i.e., microstructural endpoint, underpinning the understanding of a radiation induced material property. The FaMUS assessment of the annual growth in understanding of radiation induced effects developed in NSUF supported studies as estimated by both measures is shown in Figure 9, while Figure 10 considers each of the three specific classes of materials of relevancy to the NSUF mission: i.e., nuclear fuels (including fuel cladding materials), unirradiated materials, and irradiated materials.

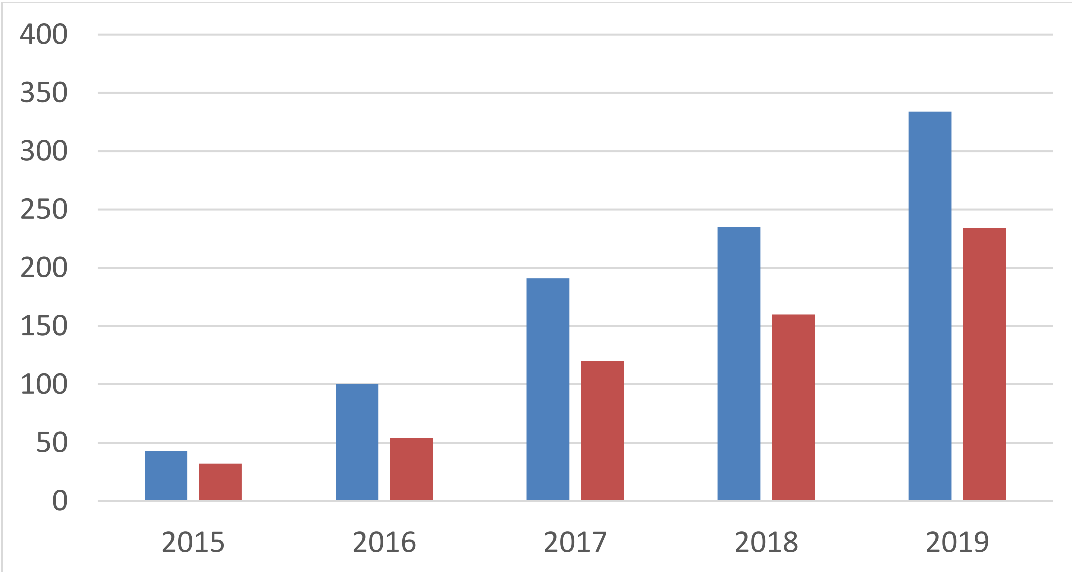

Figure 9. FaMUS assessment of the annual progress of the NSUF research portfolio - 2015 to 2019. (red) increase in "total level of understanding", M; (blue) increase in the parameter M' (U E + Q).

Figure 9 reveals a continuing steady growth in the level of understanding generated by the NSUF program, whichever of the two quantitative measures is considered. When the numbers in Figure 9 are broken down into the three focus areas in Figure 10, steady growth in knowledge is found for both nuclear fuels and irradiated materials; however, outputs of consequence on the behavior of unirradiated metallic materials is patchy. Fortunately, this area is considered of the least important to the NSUF mission.

Commentary

A complete analysis of the nuclear fuels and materials studied within the NSUF experimental program utilizing FaMUS will facilitate an assessment of the value added by the NSUF to the utility of nuclear fuels and materials commonly found in current nuclear systems and proposed for use in advance nuclear reactors. This assessment of a particular material is not expected to offer a pathway or contribute in any way to technical qualification and is not "pass-fail", rather it is intended to highlight opportunities for further future research by identifying gaps in knowledge and understanding.

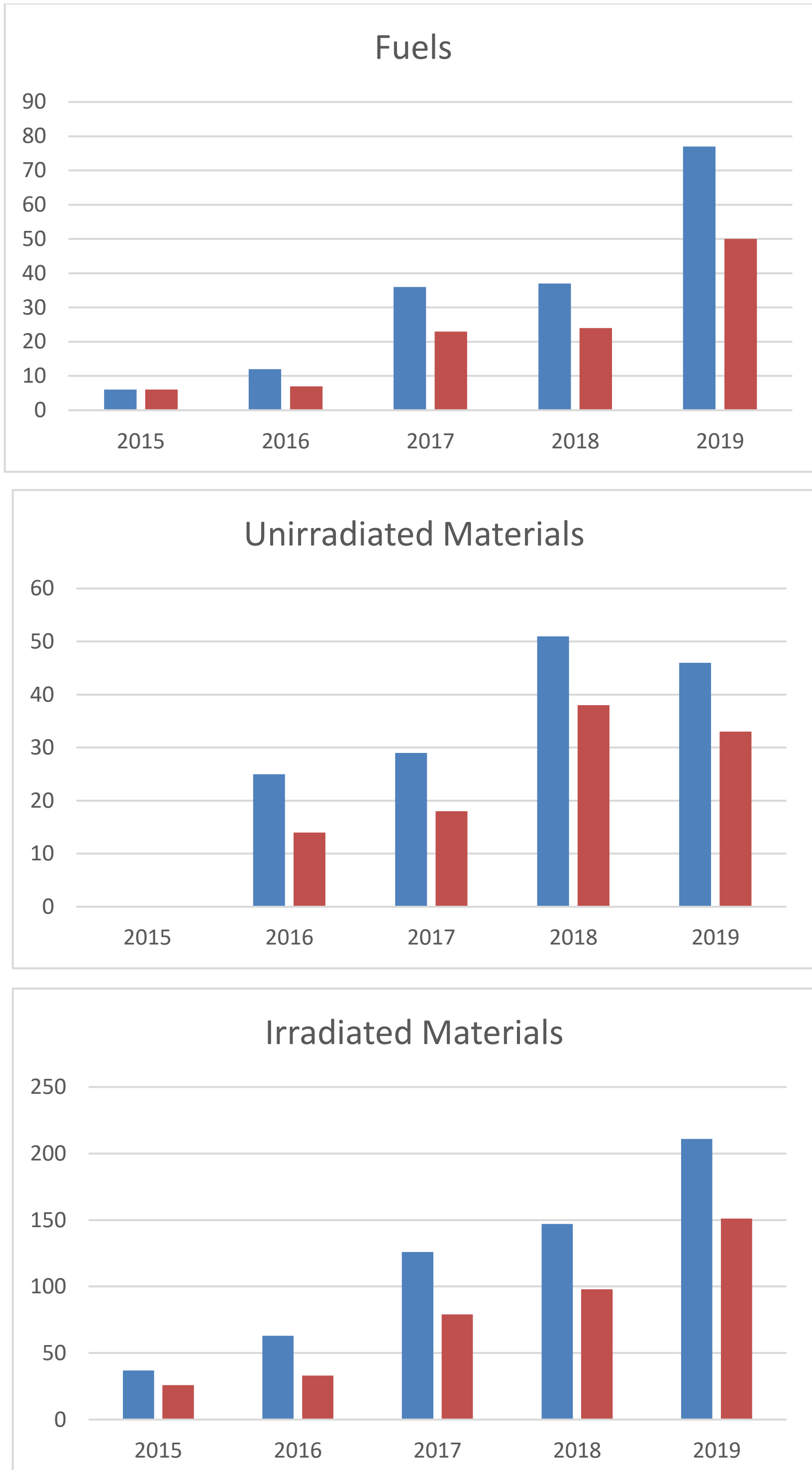

Figure 10. FaMUS assessment of NSUF research portfolio for nuclear fuels, unirradiated materials and irradiated materials - 2015 to 2019. (red) Σ M, (blue) Σ (U E + Q).

The holistic MAE of the historical NSUF portfolio will allow an ongoing "strength, weakness, opportunities, threats" (SWOT) examination of the NSUF supported research program to facilitate capability balancing of future RTE and CINR calls. The analysis will allow the NSUF to increase attention and direct resources to important fields of the DOE-NE mission using "emphasize & enhance", "maintain", and "encourage excellence" classifications as well as providing increased transparency to researchers. Such an analysis should also include consideration of the productivity of the various components of the NSUF portfolio and NSUF supported researchers.

Comparison of the Clarivate Analytics "Web of Science" compilation of the NSUF research portfolio with the self-reporting of NSUF awardees reveals significant differences, suggesting an improved and enhanced outreach plan to target user facilities and facility users that do not give appropriate acknowledgement of NSUF support in publications and presentations.

Bibliography

1. Pimblott SM; Kennedy JR. A Scale for Measuring Materials Development for Nuclear Energy Systems. idaho National Laboratory, 2018 Contract No.: INL/LTD-18-45283.