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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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**Development of the FaMUS Methodology for Quantify Materials Understanding and its Application to the NSUF Research Portfolio.**

Simon M. Pimblott[a] and J. Rory Kennedy[b]

[a] Nuclear Science User Facilities, Idaho National Laboratory, Idaho Falls, Idaho, U.S.A.; simon.pimblott@inl.gov
[b] Nuclear Science User Facilities, Idaho National Laboratory, Idaho Falls, Idaho, U.S.A.; rory.kennedy@inl.gov

## INTRODUCTION

The Nuclear Science User Facilities (NSUF) is one of a diverse group of U.S. Department of Energy (DOE) supported user facilities. It is the DOE Office of Nuclear Energy's (DOE-NE's) only sponsored user facility and is focused on advancing the understanding of radiation effects in nuclear fuels and materials in support of nuclear energy applications. The NSUF is unique in that it is not a single self-contained capability, but is a consortium of facilities distributed across the U.S. at a number of institutions. It provides 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 (PIE) capabilities including electron microscopy, mechanical testing, and X-ray synchrotron, neutron beam, and positron annihilation spectroscopy.

The organizational vision of the NSUF is to "ensure the U.S. leads the world in nuclear energy research" by providing "access to world-class capabilities and expertise to perform high impact research that will advance nuclear energy technologies" to "produce the highest quality research results that will impact and increase understanding of advanced nuclear energy technologies important to DOE-NE." The NSUF is focused on supporting the execution of fundamental research and its operational model is to address specific challenges and questions of importance and impact.

The research supported by the NSUF answers specific questions to add value, it is not targeted at a specific range of Technology Readiness Levels (TRL) and it does not intentionally move a particular system or process up a Technology Readiness Level ladder. The NSUF funds research and obtains results at all TRLs. For instance, examples of materials of different TRLs for nuclear application on which the NSUF has supported research are:

- Low TRL: MAX phase materials as potential accident tolerant, radiation resistant cladding materials
- Intermediate TRL: oxide dispersion strengthened (ODS) alloys for reactor structural applications; and
- High TRL: corrosion resistant stainless steels such as 304 and 316.

## CHALLENGE

The NSUF has been operating since 2007 and has developed a significant portfolio of supported science and engineering 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 new, novel and elegant formalism for assessing the current level of understanding of nuclear fuels and of (advanced) materials for use in nuclear environments, especially in reactor: the NSUF Fuels and Materials Understanding Scale (FaMUS), which is outlined in Figure 1.

## APPROACH

The FaMUS methodology quantifies the level of understanding of a specific radiation induced phenomenon, such as interstitial or vacancy production, radiation-induced grain boundary segregation, fission gas bubble formation or void swelling, in a nuclear fuel or irradiated material. The level of understanding of a particular radiation response phenomenon in the material of interest is expressed by the term symbol ${}^{U}M_{Q}$. The value $M$ reflects the total level of understanding of the phenomenon and is the sum of superscript $U$ and the subscript $Q$. In the example shown, $M$ may have a value of 1 to 6 depending on the specific values of the $Q$ and of $U$. The parameter $U$ shows the level of understanding, with 1 corresponding to a qualitative dependence, 2 to a quantitative empirical dependence, and 3 to a mechanistic understanding suitable for inclusion in a multi-physics model and $Q$ quantifies the breadth of this understanding, that is, the number of different experimental variables considered, such as dose, dose rate, temperature or pressure. A given $M$ can be obtained by a variety of combinations of $Q$ and $U$. reflecting different levels of information and of understanding of the phenomenon.

As an example, consider a nuclear fuel or material with a term symbol ${}^{2}3_{1}$ for a particular radiation-induced phenomenon. This term symbol implies that the phenomenon in question has been experimentally observed as a function of one variable, say displacement dose, and has been measured quantitatively allowing empirical prediction/extrapolation. If the term symbol was ${}^{3}6_{3}$, the

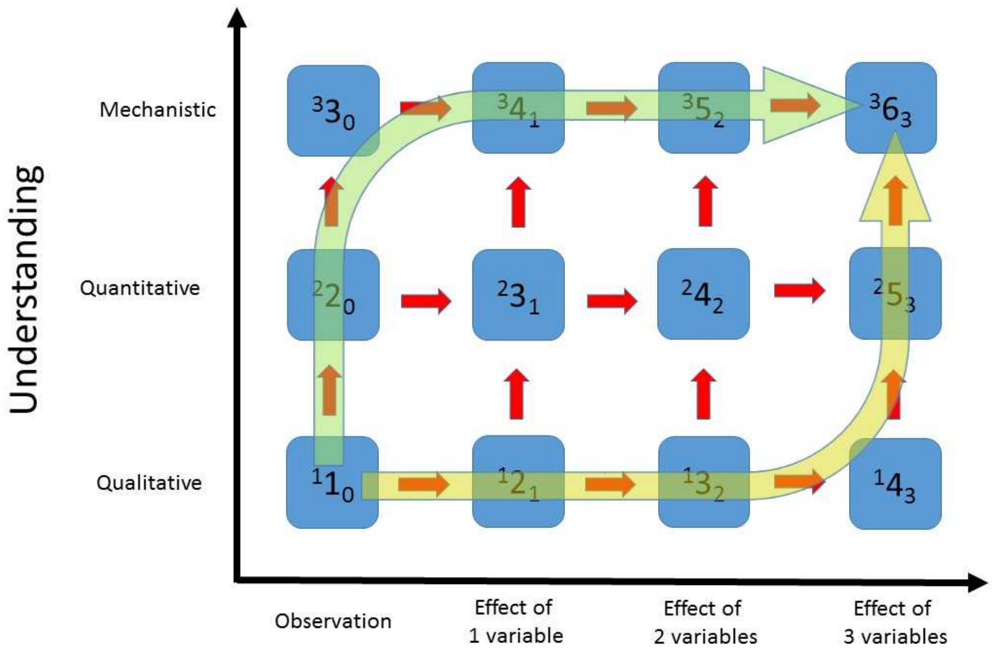


**Figure 1. Representation of the FaMUS Methodology**

phenomenon has been experimentally observed as a function of three variables, say displacement dose, dose rate and temperature, and is understood at a mechanistic level allowing inclusion in multi-physic models. A given material will have a term symbol to quantify the level of understanding of each radiation induced phenomenon that has been investigated or observed.

As a materials behavior and performance is investigated, the objective is to move from the lower left hand corner of Figure 1 where a phenomenon has been observed, but is not quantified or mechanistically understood, to the upper right hand corner where a phenomenon is understood mechanistically and measured experimentally under a large number of different experimental conditions. This process can be achieved by either a predictive path (shown by the green arrow in Figure 1) in which understanding drives experimental investigation and material development or by a responsive route (shown by the yellow arrow in Figure 1) where experimental observation leads to an empirical model and ultimately to predictive understanding.

## OBJECTIVE

The goal of the FaMUS formalism is to allow judgement of where the NSUF has added value to nuclear fuel or material development and deployment by looking at the change in the term symbols for a particular fuel or material. For instance, the increased understanding of a radiation induced effect due to a series of NSUF Rapid Turnaround Experiments (RTEs) and subsequent analysis might be described by the path:

$$^2 3_1 \rightarrow {}^2 4_2 \rightarrow {}^2 5_3 \rightarrow {}^3 6_3$$

where the starting point, $^2 3_1$, is a phenomenon that has been experimentally observed as a function of one variable, displacement dose, and has been measured quantitatively allowing empirical prediction/extrapolation. The first step, $^2 3_1 \rightarrow {}^2 4_2$, reflects an experimental study quantifying the effect of a second variable such as dose rate. The second step, $^2 4_2 \rightarrow {}^2 5_3$, represents a further experimental study quantifying the effect of a third experimental variable such as temperature, and the third step, $^2 5_3 \rightarrow {}^3 6_3$, the development of a mechanistic understanding of the effect of the three experimental parameters on the observed phenomenon.

## APPLICATION

Application of the FaMUS methodology via a material assessment exercise (MAE) to the NSUF research portfolio will provide a tool to allow qualitative and quantitative assessment of progress in the understanding of nuclear fuels and irradiated materials performance by NSUF supported research. Performing a MAE, like a TRA, will require experienced and knowledgeable technical and subject matter experts independent of the original research projects. Furthermore, the exercise should be based upon documented, publically available and peer-reviewed evidence rather than anecdotal and verbal information. Consequently, the analysis will require a “deep-dive” into the NSUF portfolio of research and the peer-reviewed and openly accessible publications that have resulted.

The NSUF's FaMUS methodology is being applied to the NSUF portfolio to quantify the progress made in the understanding of radiation effects in nuclear fuels and materials. This presentation will describe the status of the assessment exercise, and present a summary of any notable outcomes found as well as preliminary conclusions.

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