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Simple SE Methods Deployed in Revitalizing the Nuclear Post- Irradiation Examination Capability for the Idaho National Laboratory

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Abstract. The "crown jewels" of nuclear energy research facilities (i.e., hot cells, analysis systems, and scientists) have been centered at the Idaho National Laboratory for over 40 years, but in recent years, emphasis and funding for nuclear fuel research and development have declined to adversely affect the readiness and effectiveness of research facilities and equipment. Conversely, the current national nuclear renaissance forces the need for immediate enhancements in facilities, equipment, capabilities, and staff for the post-irradiation examination (PIE) of nuclear fuel. PIE characterizes the "burn-up" and structural integrity of fuel elements and defines the effectiveness of new fuels/alloys in search for optimum fuel burn-up and alloys for current and next generation nuclear reactors. This paper details how a team of system engineers adapted simple system engineering tools and techniques for a customer unfamiliar with the power and effectiveness of system engineering, to achieve project success.

Introduction

Because system engineering (SE) has its roots in the aerospace and defense industries, most textbooks related to SE are based on computer, aeronautical, and defense project test cases. As an engineering discipline, SE techniques and methods have power to aid any discipline or engineering field, but SE is largely unknown, misunderstood, and un-used in many areas or fields of study (e.g., nuclear energy). This paper explains how applying four simple SE techniques achieved project success in revitalizing the post-irradiation examination (PIE) capability to support the goals of the U.S. Department of Energy (DOE) and the nation in achieving energy independence through nuclear energy.

Project Background

Since the advent of the Three-mile Island and Chernobyl accidents, nuclear energy has been much maligned, resulting in a decline of domestic nuclear energy R&D funding relating to nuclear fuel development and the PIE of nuclear fuel and materials. PIE is the process of examining or conducting a "post-mortem" on nuclear fuel elements or rods after they have been in an operating reactor for a prescribed burn-up period. Only through extensive non-destructive and destructive examination can structural and metallurgical attributes of nuclear fuel (a uranium or uranium alloy) and cladding (the metal tube that holds the fuel) be characterized. This characterization helps define the effectiveness of new nuclear fuels, fuel element configurations, or cladding alloys in the search for the optimum configuration (larger/longer burn-up) for current and next generation nuclear reactors.

To support the development of such fuels, the nation needs comprehensive, consolidated, state-of-the-art PIE capabilities. In some cases, new capabilities beyond the current state-of-the art need to be developed and implemented to perform detailed measurements. These capabilities must encompass:

- Contemporary facilities
- State-of-the-art equipment
- Highly trained and specialized workforce
- Proper security, safety, and operations infrastructure.

A consolidated facility, where a comprehensive set of measurements can be performed, is essential for efficiently implementing fuel development programs in a cost-effective manner. The reasons are as follows:

- Maintaining multiple nuclear facilities with duplicate capabilities is expensive.
- Data obtained at different locations using different samples are more difficult to consolidate.
- Extensive shipping of irradiated fuel samples raises concerns about safety, security, and potential damage to the samples.

For decades, the PIE facilities and research staff at the Idaho National Laboratory (INL) were considered the “crown jewels” of PIE because the engineers and scientists at the INL developed the scientific basis for the nuclear fuel cycle that supported the nation’s first nuclear reactor and 50 subsequent experimental and commercial reactor fuels. The current dilemma exists because those domestic “crown jewels” are in a state of disrepair. With the rapidly increasing national energy shortage and subsequent nuclear renaissance for large base power plants, a resurgence of PIE with modern equipment, capabilities, facilities, and staffing is needed to meet the national energy challenge.

PIE Four-Step Strategy

The INL is the nation’s only DOE facility with a core mission of supporting the development of nuclear energy, with excellence in nuclear fuels R&D as one of its primary strategic objectives. A four-step approach was developed to revitalize the INL PIE capability and allow for deliberate progression to optimize funding and logistics [Idaho, 2009]. The first step is to refurbish the baseline PIE capabilities to provide basic services for projects with near-term needs. Second, existing facilities will be upgraded and new equipment procured to move into a state-of-the-art PIE capability that leads the nation in nuclear fuels analysis. The third step will be evident with the development of expertise and innovative use of equipment to allow measurements possible only at a few locations in the world. The final step is the development of capabilities that do not exist elsewhere for comprehensive irradiated fuels analysis. New modern facilities would be in place to facilitate operational flexibility, development of new equipment and tools, and consistent investment in personnel expertise. As with all technology, state-of-the-art equipment eventually becomes baseline and newly developed tools/techniques are deployed to become state-of-the art. The key to the four-step approach will be the continuous improvement cycle to remain "world-leading." The INL 4-step strategy is shown in Figure 1.

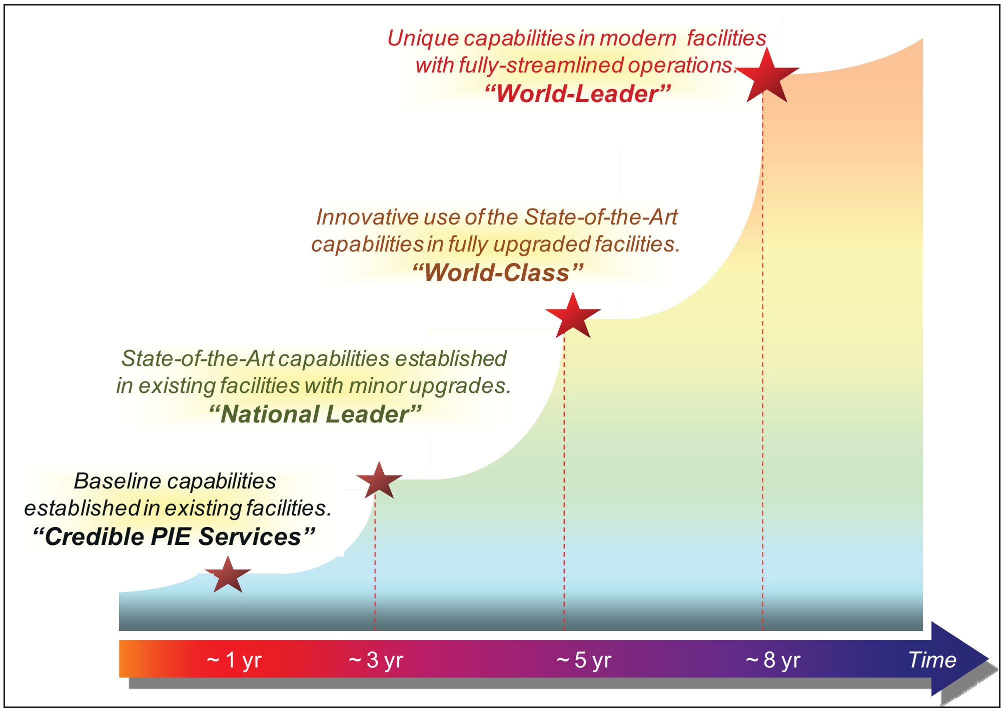

Figure 1. INL PIE Four-Step Strategy

Project Dilemma

The PIE research scientists want to purchase more electronic microscopes and a plethora of expensive detection/analysis apparatus. However, PIE capabilities, equipment, requirements, or staffing needs have not yet been defined. As such, no engineering or budget-based mission needs documents or adequate/justifiable funding requests can be submitted. Further, the existing research buildings/facilities into which the new equipment would be placed have an aging infrastructure that is not capable of meeting equipment needs (i.e., there is no more band width available for computer connections and existing equipment varies in stages of readiness).

Systems Approach

A team of SEs was deployed to investigate and remediate this problem. SE has been used at the INL for years, but the work culture using or benefiting from SE is not as mature as with an aerospace company; therefore, the SE tools and approaches are typically adjusted or modified to fit the SE maturity of the customer or end user of the data [Zirker and Hamelin, 2005]. Given this culture, the SE team detailed a systematic approach using an adaptation of four basic SE tools or methods to characterize the mission, constraints, and assortment of issues. The methods included:

1. Conduct an initial mission analysis and scoping of existing PIE systems, operational status, age, throughput of fuel and material samples, etc

2. Generate a modified functional flow block diagram (FFBD) showing a process flow of PIE functions as they are linked to each of the five PIE facilities, but color coded to reflect operational readiness
3. Develop the technical and functional requirements for PIE capabilities
4. Allocate PIE requirement/capabilities to PIE equipment, facilities, staffing, and future equipment needs with a funding estimate for out years.

The ultimate goal of the effort is to gather enough compelling data to both define a basis of PIE and to justify funding to meet current and future needs for the next decade.

Understanding the Problem. The first activity in this project was to conduct an initial assessment of existing PIE systems, facilities, staff, etc. Each of the initial (50) PIE systems was listed in the left-most column of a spreadsheet and the following headings were listed across the top of each subsequent column:

- Capability
- Equipment description
- Examination technique
- Quality of Data
- Precision/Accuracy
- Throughput
- Human Skills and Expertise
- Fuel Type
- Instrument (s)
- Location
- Status (working or not)
- Current Reliability
- Current Operability
- System Needs
- Point of Contact
- Notes

Each cell in the matrix was then populated from interviews with the PIE engineers, scientists and managers. Four separate matrices were printed, one for each of the four time periods of PIE Strategic Vision (see Figure 1):

- Baseline (~1 yr)
- State-of-the-Art (~3yrs)
- World Class (~5yrs)
- World Leader (~8yrs).

This effort took weeks to complete because of the one-on-one nature of gathering data from each of the PIE subject matter experts (SMEs) and their varying views of the extent/scope of the PIE project.

Big Picture Diagram Showing Functions Linked to Facilities. During the initial scoping phase, it became increasingly obvious that no person or program at the INL clearly understood the "big picture" of PIE capabilities or the process flow of PIE work. To further complicate the issues, the scientific nature of this unique analysis is so esoteric that few if any researchers understood all of the limitations and capabilities of the unique PIE systems or equipment. An example of this complexity is using a dual-beam focus ion beam electronic microscope system to machine ultra-thin, macro-sized test samples for analysis via a transmission emissions microscope. In short, more information was needed than just a process flow of PIE functions, so a modified FFBD, referred to herein as the "big picture graphic," was developed to show:

- The general work flow of the PIE system capabilities/processes
- The operational readiness of each process, via color coding
- The linking of the process flow to and within the five key PIE facilities
- The assignment of a unique identification number and a facility location to each functional process, regardless of duplication.

The value of this graphic became instantly apparent as the scientists, technicians, management, and customers could now see – for the first time –all of the PIE functional systems, states of readiness, and system locations on one piece of paper. This added clarity because a few of the systems are duplicated in more than one facility. An added feature, as noted above, was to numerically label each of the functional boxes with its own unique number to ensure each PIE system capability was documented and not lost because of the duplicate facility systems. The numbering was exceptionally helpful during the compiling of the subsequent budget, because each numbered facility capability was characterized and accounted for. Another benefit this one-page big picture graphic is that it provided:

- A visual tool for subsequent reviews/edits by all SMEs to capture PIE capabilities.
- Immediate understanding of the project's size and complexity for the first time.

A section of the big picture graphic (see Figure 2) shows all of the currently available PIE process activities (numbered systems) within the Hot Fuel Examination Facility (HFEF). The color codes show a relative readiness of the systems: red (boxes 1, 3, 4, and 5) shows a process with serious problems or is out of service; yellow (boxes 6–8, 10–12) shows a process that is old/slow/marginal; and white (box 9) shows a process that is operational. The large numbers to the upper left of each process are the unique identification numbers, while the small numbers on the upper right corner show the location of the process in the facility. The blue and green boxes are not PIE related.

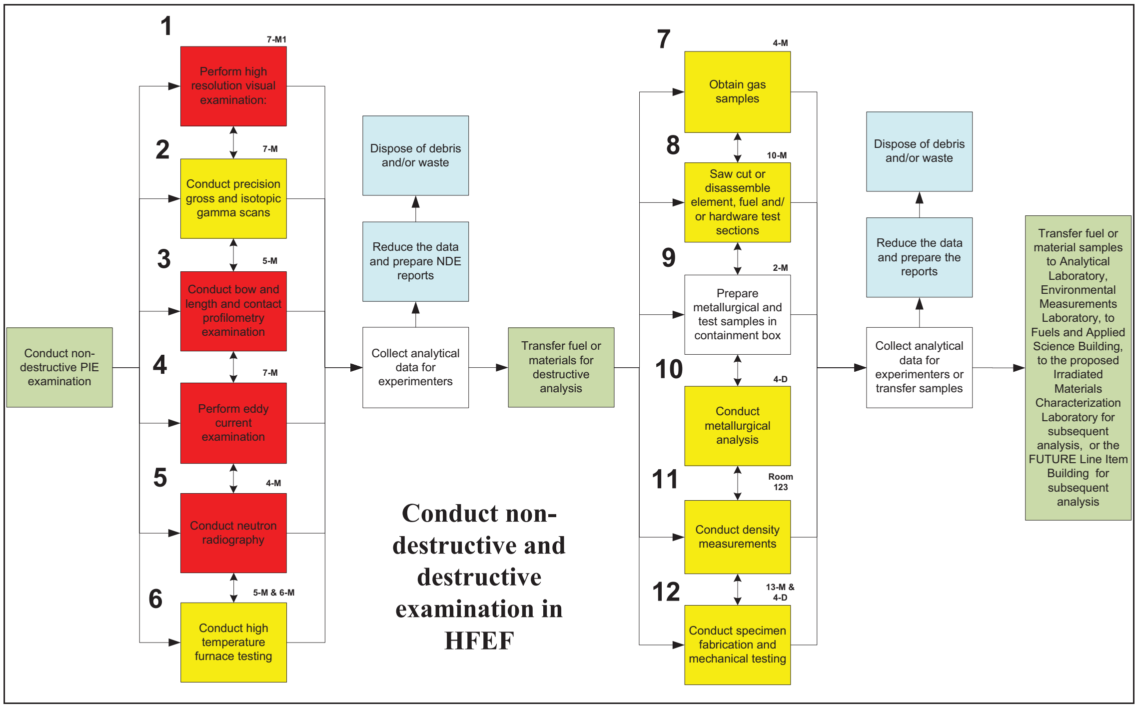

Figure 2. Hot Fuel Examination Facility PIE Processes

Technical and Functional Requirements of PIE Capabilities. The team decided it was imperative that the technical and functional requirements (T&FR) for PIE capabilities be captured since, heretofore, no one had defined the requirements or capabilities of PIE. To establish a world-class PIE capability, it is first essential to establish a baseline of T&FRs required to support the many fuel and material development efforts currently underway. This document captured the T&FRs to lead the INL to become the future world leader in PIE. Each of the four phases of the INL PIE Strategic Vision (see Figure 1) was addressed in a separate section of the T&FR document, as follows:

- Section 3, Baseline PIE (e.g., Credible Service)
- Section 4, State-of-the-Art PIE (e.g., National Leader)
- Section 5, World-Class PIE (i.e., Innovative use of state-of-the-art)
- Section 6, World-Leader PIE (i.e., unique capabilities and modern facilities).

Sections **Error! Reference source not found.** – **Error! Reference source not found.** were further decomposed into the following subsections according to the type of PIE being addressed:

- Non-Destructive Examination
- Destructive Examination
- Mechanical Testing
- Thermal Testing
- Infrastructure
- Other (Administrative).

A sample of the text is shown in Figure 3. The underlined text is a general function or task of PIE, with the follow-on sentence providing descriptive detail. The four digit number indicates a unique requirement statement. The "Justification" was added to clarify the basis for the requirement.

> 3.1 Non-Destructive Examination
>
> 3.1.1 <u>Characterize surface appearance of irradiated materials</u> – Provide a surface condition macro-characterization of nuclear cladding, assemblies, and hardware via visual examinations and photographs.
>
> 3.1.1.1 Visual examination capability shall accommodate fuel elements, plates, and/or hardware items and other irradiated materials.
>
> **Justification:** Photographs are required as part of the PIE record for visual examination of elements, fuel, or hardware items.
>
> 3.1.1.2 Macro images shall be at a magnification of ≤ 25X.
>
> **Justification:** Higher magnifications (microscopic) shall be performed after the hardware items have been sectioned.

Figure 3. Sample Requirements Text

Part of this effort was the education of the customers regarding SE methods and tools. As they would review the text, they initially asked the SE team where the equipment was listed, and then they were reminded that T&FR of capabilities is a definition on how well and to what extent, and is not about equipment. The process equipment and electronic systems would be captured in the allocation phase.

Allocation of PIE Capabilities to PIE Equipment. It was imperative to now map or allocate the functions, requirements, and capabilities to the various PIE processes or equipment systems to ensure nothing was missed or overlooked. The allocation phase began by migrating the functions, requirements, and capabilities from the T&FR into 430 rows of Microsoft® Excel spreadsheet. Although the big picture graphic had about 50 identified PIE processes or equipment systems, multiple omissions became evident and obvious as the allocation effort evolved. As a result, the big picture graphic was modified multiple times to include processes or equipment systems that were previously omitted, and the T&FR text was continuously expanded to include corresponding functions and requirements that were likewise missed during the interview process. More information was required in this allocation beyond just linking requirements and capabilities to equipment, so the columns of the allocation matrix were labeled as follows to ensure that now needed information was not missed:

- Requirement Number
- Requirement Statement
- Requirement Category
- Requirement Justification
- Chart Number (i.e., Unique process identifier from the big picture graphic)

- Function Text
- Facility Number
- Facility / Infrastructure issue
- Applicability of Function to Material/Fuel Type
- Sub-Capability Function
- System Hardware
- Location of System
- New Item
- Age of System
- Life Expectancy
- Human Capital
- Current Operational Status of System
- Current Process Thru-Put
- Current Process Scheduled (work in the queue)
- Process Backlog (behind schedule)
- Baseline Need to Meet Requirement
- State of the Art Need to Meet Requirement
- World Class Need to Meet Requirement
- World Leader Need to Meet Requirement
- Baseline Funding Approach
- State of the Art Funding Approach
- World Class Funding Approach
- World Leader Funding Approach
- Functional Point of Contact
- Notes.

The first four columns of matrix were populated with the text from the T&FR. To facilitate the manual population of the allocation matrix, the sheets were plotted onto nine E-sized sheets that could be laid out and reviewed during the interviews. The main thrust of the allocation sheets was to capture compelling data in a systematic format to show that much of the current PIE process systems and equipment were old, dysfunctional, or marginal, and that the throughput needs were increasing. The subsequent use of the allocation data will be used to develop mission needs documents that will become the initial funding documents within the DOE business process. This effort brought to light the size and complexity of anticipated PIE renovations and the extent of work required to bring the INL PIE systems up to the world-class and world-leader. Ultimately, the allocation effort defined nearly $86 million just for the facility infrastructure upgrades, much of which was previously unknown or unidentified.

Project Success

Thanks to the efforts of the SE team and the participation of the PIE scientists and engineers, the project achieved unprecedented success in the following areas:

- Generated a complete list of all PIE systems and equipment
- Compiled a (wish) list of replacement equipment with associated schedules and cost estimates
- Developed a one-page FFBD of the complete INL PIE processes within five facilities and with an operational readiness color code
- The SE department has been asked to perform an similar analysis of all of the nuclear fuel fabrication capabilities, process systems, facilities, staffing, and analysis equipment
- The SE department has been asked to develop a strategic roadmap of all nuclear R&D activities at the INL.

Conclusion

The project was extremely successful because for the first time the PIE processes, equipment, workforce, and facilities were characterized in a defensible format that could be used to justify funding to fix the problems and help the INL PIE processes achieve world-class/world-leader status. The success of this effort was achieved by using basic SE tools and techniques that were modified/augmented to meet the customer needs and to achieve customer understanding of SE process.

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Biography

Larry Zirker (MS, Welding Engineering, The Ohio State University) worked for 28 years in the energy field and is a senior engineer for Battelle Energy Alliance at the Idaho National Laboratory working both large and small projects, and worked 13 years in the System Engineering Department. Mr. Zirker works primarily the front end of projects defining project requirements, tasks, special needs, deliverables and interfaces with customers and task performers. He developed a unique circular work breakdown structure technique, Zoned

Analysis, that regularly helps customers and team members see the big picture. Mr. Zirker published three previous times at INCOSE conferences.

R. Douglas Hamelin (MA, English, Idaho State University) is a Systems Engineering Specialist and Technical Writer for the Idaho National Laboratory SE organization. Mr. Hamelin is trained in requirements management, contributes to a wide range of SE applications as a functional analyst and document specialist, and played a major role in developing a university training course entitled *Applying Systems Engineering in the DOE Environment*. Other contributions include document control, risk analysis, technology roadmapping, and decision support using a variety of software applications. Mr. Hamelin contributes on numerous DOE publications and most recently helped revise the *INCOSE Systems Engineering Handbook*, v3.2.

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