Technology Advancement and Insertion into Operating Nuclear Facilities

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ABSTRACT

Key challenges in the NNSA modernization effort are centered around the selection of new processing / production technologies to deploy in existing, operating, and oftentimes, aging nuclear facilities. New uranium processing technologies may offer significant improvements in worker and environmental safety, material control and accountability, and production efficiencies, but adaptation of these technologies into existing facilities presents unique (and usually, difficult) engineering solutions for each new technology. This presentation discusses approaches utilized at Y-12 to mature and demonstrate new processing and production technologies for deployment into nuclear facilities. The technology advancement lifecycle (from concept to deployment) of uranium electrorefining technologies will be reviewed, as a prototypical example, to describe steps and approaches utilized at Y-12 (and NNSA Sites) to (i) mature technologies and manufacturing strategies, (ii) establish testbed capabilities for full-scale process demonstrations, and (iii) reduce risks associated with operational disruptions when commissioning new uranium processing technologies.

BACKGROUND

The National Nuclear Security Administration (NNSA, a semi-autonomous agency within the U.S. Department of Energy) is modernizing facilities and operations to support U.S. nuclear security needs. At Y-12, modernization of production infrastructure has involved a combination of refurbishing existing / legacy uranium processes, establishing new processes in aging facilities, and planning for new facilities. This paper concentrates on approaches that have been employed to establish new processes in existing and new facilities at Y-12, which require significant investments to ensure the most appropriate technologies are deployed in the right locations to minimize risks associated with budget and schedule. With existing facilities, deployment of new processes must also consider legacy operations that will either be removed or continue operating during and after process deployments.

All of the modernization activities at Y-12 today utilize a readiness level approach to gauge the level technical, manufacturing and programmatic maturity. General definitions of technology, manufacturing, and program readiness levels are provided in Table 1. In many cases, technology maturation of manufacturing approaches is performed and assessed by multi-site interdisciplinary teams across the DOE and NNSA Enterprise of laboratories and sites. Recent reliance and rigor applied to the technology maturation approach across NNSA has resulted in improved R&D, deployment project management, and ultimately, the transition of technology into the manufacturing environment.

Table 1: Technology, Manufacturing, and Program Readiness Levels (Adapted from Ref. 1)

Level	Technology	Manufacturing	Program
1	Fundamental research. Scientific principles are studied analytically or experimentally.	Concept team to identify design; process; materials; and manufacturing options, needs, and risks.	Identification of basic scientific concepts and performers with preliminary planning schedule.
2	Practical application concepts and assumptions identified, potentially without proof or detailed analysis.	Options, gaps, and risks identified and evaluated for scope, strategy, and requirements.	Establishment of program (1) identifying customer and (2) forming program/project team.
3	Applications are still speculative, but R&D validating predictions of key elements of technology. "Proof-of-concept" validation of the applications / concepts formulated at TRL 2.	Initial manufacturing options down-selected. Manufacturing development needs and strategies identified. Costs are estimated for the point designs	Establishment of formal program/project planning documentation. Work scope, schedule, and cost have been formally identified.
4	The key elements of technology integrated to verify key elements - consistent with requirements of potential applications. Relatively low-fidelity when compared to a final product.	Initiating manufacturing system capability and producing component/subsystem proof-of concept development builds.	Program/project planning are updated to reflect the results of the conceptual design development and requirements.
5	Fidelity of the key elements increases significantly and are integrated to test and demonstrate in simulated or actual environments.	Development builds have successfully met requirements. Product Definition and Documentation Review and Final Design Review completed.	The design requirements have been baselined and documented. Cost and schedule updated to fully represent what is need to implement/produce.
6	Prototype technology demonstrated in simulated or actual environment.	All resources demonstrated and approved, with formal procedures completed.	Technology design demonstrated to requirements. Production engineering drawings finalized.
7	Development version of deliverable demonstrated in operational environment. In almost all cases, this TRL coincides with the end of research.	Successful producibility, Production Readiness Review and production prove-in achieved.	Technology design *and production* verified and validated to meet requirements. Funding in place to begin production / construction.
8	The technology proven to work in its final form under expected conditions.	Manufacturing processes are qualified and initial production metrics are achieved. The First Production Unit is delivered.	Technology is designed, produced, or constructed and the customer agrees to accept product.
9	Application of the technology in its final form and under operational conditions.	Steady State Production - The ability to consistently meet cost, quality and schedule targets has been demonstrated.	N/A

Uranium Electrorefining (ER) Process was first employed in an R&D setting in 1953 and showed great promise for the purification of uranium metal [2] – significantly reducing the concentration of impurities in uranium metal. Since that time, ER has been studied more extensively for separation of uranium and plutonium from higher-actinide isotopes and fission products in spent nuclear fuel [3]. The Mark-IV electrorefiner [4], as well as prior Argonne and Idaho National Laboratory (ANL and INL, respectively) designs and prototypical systems, was developed over the course of the past three decades through collaborations between INL and

ANL, as well as university and international partners. This highly optimized design utilizes three separate working electrodes: (i) spent fuel is loaded into a steel anode basket assembly, (ii) uranium is collected on a steel electrode, and (iii) plutonium with low weight-% uranium is collected in a molten cadmium electrode. In addition, this system contains a molten pool of cadmium that is utilized to capture metals considered more noble than uranium and plutonium.

The production of highly purified uranium metal on the industrial scale is quite distinct from recovery of uranium from spent nuclear fuel – both in electrochemical cell design and uranium product requirements. Electrorefining at Y-12, ANL, and INL (for the purpose of purifying uranium metal) is performed in a similar manner, but with an electrolytic cell that with slightly different design. However, the safety, material control and accountability, and environmental improvements for adopting this technology for enriched uranium purification are quite similar:

i. All operations are performed in a non-aqueous environment, thus reducing the risk of a criticality accident,
ii. Material control and accountability can be instituted for the complete ER glovebox system, and
iii. Waste from the process is greatly reduced from aqueous processes that have been utilized for uranium purification.

A full description of the ER process technology is outside the scope and focus of this session, which concentrates on technology maturation. However, the technology maturation of the uranium electrorefining process at Y-12 provides an excellent case study for negotiating the challenges of deploying new technologies into existing (and operating) nuclear facilities.

ER Technology Maturation Lifecycle

Electrorefining technologies at Y-12 began with a collaboration lead by James Willit (Argonne National Laboratory, ANL) and David Cecala (Y-12 National Security Complex) and was sponsored initially by internal funding at Y-12 (Plant Directed R&D, PDRD) to explore the possibility of utilizing electrorefining to replace solvent-based uranium purification technologies. After initial studies at ANL and validation studies on prototypical electrorefining equipment at Y-12, the ER project was initiated. The ER project was unique (at the time) for new technology deployments at Y-12, where its success was critical to the supply of EU products for U.S. and international partners. This drove NNSA (Uranium Modernization Program) and Y-12 to sustain technology advancement by establishing the Uranium Electrorefining Technical Exchange (ERTE) and rely heavily on a rigorous implementation of technology readiness assessments and stage gates. These two central actions were considered part of a necessary strategy to reduce technical and programmatic risks associated with adopting a new technology at this scale.

The ERTE was comprised of members from Argonne, Idaho, Los Alamos, Livermore, and Savannah River National Laboratories and the University of Utah to foster collaboration across the DOE and NNSA Enterprise and advance the technologies from prototypical scale to full-scale operations through routine technology readiness assessments (TRAs) and review of R&D and deployment plans at Y-12. The implementation of TRAs (during this timeframe, ca. 2015) was governed by procedures developed at individual sites, following general guidance developed by NASA, DOD, and other U.S. government agencies typically tasked with development and deployment of new technologies.

ERTE provided an independent evaluation that provided feedback to the technology proponents at Y-12 and to the NNSA program management funding the R&D and deployment of the technology. This was central to advancing the technology through the, so-called, 'valley-of-death', in which a new technology has been shown to be successful, but adaption of the technology languishes due to lack of clear customer support and implementation plans.

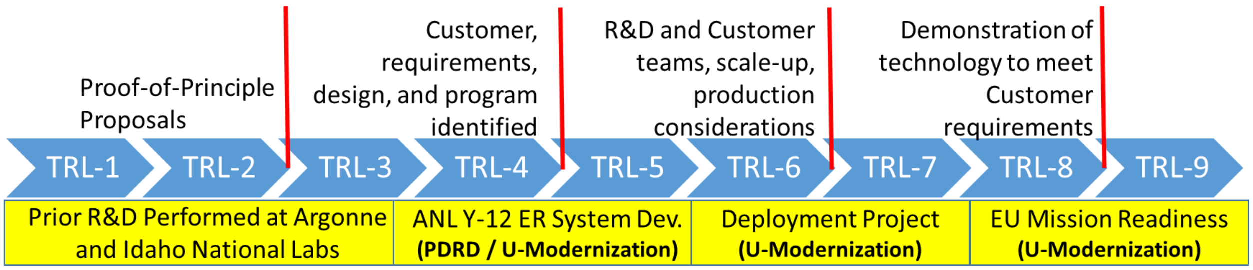

Figure 1: Schematic showing the stages of technology maturation lifecycle for the Y-12 Electrorefining System

To reduce potential risks associated with starting a new enriched uranium process in an operating production area, multiple steps were taken as the Y-12 electrorefining system matured to TRL-6:

- Production prototype equipment was designed and procured from a set of vendors well ahead of the fabrication of the production equipment. The production prototype system allowed for testing the functionality of the system, developing potential process improvements, and training of future chemical operators for the plant. This full equipment set was installed in an R&D facility that could process depleted uranium and contained all key subsystems.
- Continuous process improvement R&D was conducted (e.g. investigation of potential changes to process steps or design to improve effectiveness or efficiency) that served two purposes: (i) testing the functionality of all subsystems, and (ii) identification of potential design flaws in the procured system.
- The ER system design was placed under configuration management control at TRL-6 by establishing a configuration management board, comprised of the project engineer, program manager, and lead technology developer. This board and engineers with expertise in specific disciplines (e.g. safety, mechanical design, etc.), depending on the type of technical improvement, evaluated any potential improvement for its impact on the production equipment design.

While it is unavoidable that late-stage design or operational changes occur with new technologies (especially those never deployed previously), the combination of early full-scale prototype procurement, continuous improvement R&D, and a configuration management approach served to reduce the risk to project schedule and budget by identifying design flaws and challenges that would have normally been realized during start-up and commissioning of the system in enriched uranium operational areas.

Current Technology Maturation Lifecycle

With an emphasis on modernizing nuclear operations over recent years, multiple Offices within NNSA (specifically, Technology Maturation, Strategic Materials, Uranium Modernization) have made a concerted effort to establish a more rigorous and consistent system to evaluate technologies and gauge the effectiveness of new systems and processes, compared to legacy processes within the U.S. Nuclear Security Enterprise. First, NNSA has adopted a technology readiness assessment approach [5], [6] similar to other U.S. agencies that are routinely tasked technical research, development and manufacturing missions [7], [8], [9], to include evaluation of the technical, manufacturing and programmatic readiness associated with new technologies (with descriptions provided in Table 1):

- Technology Readiness Levels measure the maturity of a technology to perform the intended function,
- Manufacturing Readiness Levels measure the maturity of an organization to manufacture the technology, and
- Program Readiness Levels measure the maturity of program management to accept the responsibility of maturing the technology to final deployment

While this more rigorous approach to assessing technologies improved an understanding of technical, manufacturing, and programmatic risks, implementing technologies still faced the common challenge of overcoming the TRL 5-7 'valley of death'.

The second improvement to modernization efforts has been the establishment of Technology Realization Teams (TRTs) [10], which serve a similar purpose to the ERTE, but was codified and implemented – with defined roles and responsibilities to members of the TRT. Initially, TRTs were a singular construct for the Office of Technology Maturation, but in recent years, the TRT function has begun to span across multiple offices, with the specific goal of providing a clear advancement and transition strategy (from one NNSA office to another), to address technology maturation from TRL 3-9.

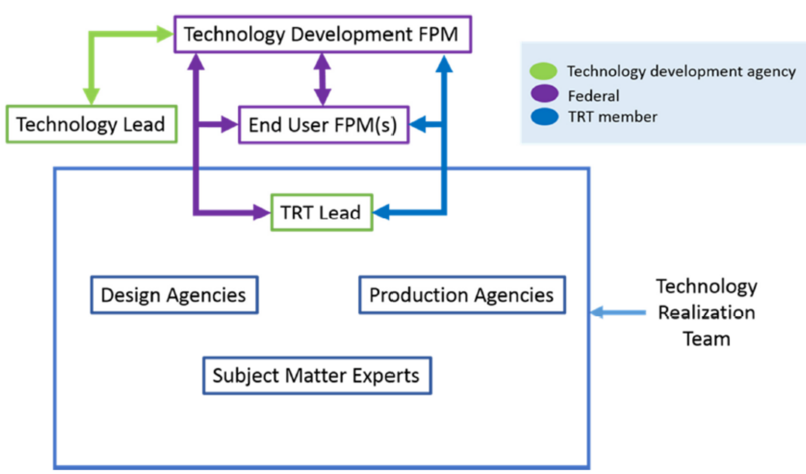

Figure 2: Technology Realization Team structure with the arrows indicating information flow.

At this time, Y-12 is currently involved in maturing six technologies, which range in maturity from TRL-3 to TRL-7, following the technology readiness team approach. Nearly all national laboratories are involved in one of the 6 activities – providing support through evaluations, and routine reviews of R&D and project plans associated with advancing the TRL, MRL, and PRL of the technology. For those technologies spanning support from multiple NNSA programmatic offices, TRT Charters have been developed that clearly define the scope of support from each office and the transition of technology from R&D to implementation.

Challenges, and Potential Improvements

Within the constraints of DOE and NNSA guidance and regulations for program and project management principles, additional improvements may be realized when maturing technologies – especially those related to manufacturing and processing technologies. Areas for potential improvement revolve around assessment approaches for intermediate manufacturing technologies, definition of product requirements at early stages, and early implementation of TRT functions.

In general, the technology and manufacturing readiness level definitions (Table 1) and NNSA Calculator were developed to assess a specific final product that will be produced by NNSA to meet customer requirements. However, intermediate manufacturing technologies – i.e. processes that produce raw materials or do not produce a *final* product – can be difficult to assess under the current approaches. Under the current structure, the definitions and NNSA Calculator questions can be customized for each technology, however, this can lead to varied assessments of manufacturing technologies and could also lead to unrecognized risks at higher readiness levels. Development of tailored questions and assumptions related to the intermediate product and manufacturing technologies has been necessary for addressing this challenge and integrating new technologies into broader modernization strategies.

The clear and early definition of product requirements (whether final or intermediate) represents a challenge to maturing technologies at all readiness levels within NNSA due to the dichotomy of highly constrained nuclear operations design space and dynamic / evolving customer requirements. This gives rise to significant challenges associated with maturing manufacturing technologies beyond TRL-5 / MRL-3, because (i) final definitions and requirements may not be fully developed, and (ii) testing to those requirements cannot occur. Advancement to TRL-6 and higher typically requires well-defined requirements and testing, which can occur too late to advance a manufacturing technologies effectively. For that reason, large modernization projects (e.g. requiring retrofitting of existing facilities or construction of new facilities) face challenges with incorporating new manufacturing technologies. Some technologies being advanced today have defined general requirements through collaborations between design and manufacturing entities within the NNSA Enterprise. This requires routine review and updates to account for evolving needs/requirements, but the establishment of requirements, outside of the normal product lines, has allowed for independent maturation of manufacturing technologies.

The TRT structure developed to help guide the research, development, and deployment of new technologies for either specific product lines or intermediate manufacturing processes is an ideal construct for addressing these two areas, but requires early implementation to (i) establish the scope of a technology and (ii) define the envisioned requirements for manufacturing technologies. Establishing a TRT (or a TRT-like) establishment early in the technology lifecycle addresses the two challenges discussed above by improving the communication lines between the technology proponents, the ultimate end user of the product (either final or intermediate), and ultimately, allows the NNSA and customer stakeholders to make well-informed decisions.

CONCLUSIONS

While new product development and modernization of operational processes and facilities present unique challenges to the DOE and NNSA Enterprise, the development (and improvement) of R&D, project, and program management systems are necessary for realizing significant gains in capabilities over the past 20-30 years. NNSA sites have realized significant improvements in transitioning technologies to operational status in recent years by codifying technology maturation and implementation approaches across the Enterprise.

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