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Metrics Evolution in an Energy Research & Development Program

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Abstract

All technology programs progress through three phases: Discovery, Definition, and Deployment. The form and application of program metrics needs to evolve with each phase.

- During the discovery phase, the program determines what is achievable. A set of tools is needed to define program goals, to analyze credible technical options, and to ensure that the options are compatible and meet the program objectives. A metrics system that scores the potential performance of technical options is part of this system of tools, supporting screening of concepts and aiding in the overall definition of objectives.
- During the definition phase, the program defines what specifically is wanted. What is achievable is translated into specific systems and specific technical options are selected and optimized. A metrics system can help with the identification of options for optimization and the selection of the option for deployment.
- During the deployment phase, the program shows that the selected system works. Demonstration projects are established and classical systems engineering is employed. During this phase, the metrics communicate system performance.

This paper discusses an approach to metrics evolution within the Department of Energy's Nuclear Fuel Cycle Research & Development Program, which is working to improve the sustainability of nuclear energy.

I. Introduction

All Research & Development (R&D) programs need a way to judge the value of research and the potential performance of products derived from that research. Metrics are often used for this purpose, taking program goals and breaking them down into measurable components. They are particularly useful when a program has multiple objectives and the strength of a particular potential product may be determined by its ability to achieve a balanced performance across these objectives. A system of metrics allows for assessment of performance potential across a range of objectives while weighting the importance of each objective based on a decision maker's values.

Metrics have been employed in the area of nuclear fuel cycles since at least the 1960s [1]. The performance of a nuclear fuel cycle is typically assessed in multiple objective areas, including resource utilization, nuclear waste management, safety, security, proliferation risk, and economics.

Nuclear power is unique among the major sources of energy. It is highly compact with a single reactor able to generate 8 billion kilowatt-hours of electricity per year while consuming (fissioning) only a ton of uranium. However, it also has a very inefficient fuel cycle - in the current commercial fuel cycle less than 1% of the potential energy from mined uranium is actually generated, with the rest discarded, either in processing to create fuel or when the fuel is "spent" and removed from the nuclear reactor. Fuel cycle R&D examines alternate approaches to management of nuclear fuel and develops associated technologies.

The Fuel Cycle Technologies Program (FCT) is the current title of the program within the Office of Nuclear Energy in the U.S. Department of Energy (DOE) responsible for research on advanced fuel cycles to support commercial nuclear power generation. Recent predecessor programs include the Advanced Fuel Cycle Initiative (AFCI) and the Global Nuclear Energy Partnership (GNEP).

In 2002, an international effort was completed to develop a technology roadmap for "Generation IV" Nuclear Energy Systems, a new generation of advanced reactors [2]. Most of these advanced reactors would require advances in the fuel cycle while enabling improved fuel cycle performance. Several countries, including the U.S. had associated ongoing advanced fuel cycle R&D efforts. In 2003, the U.S. Congress requested quantitative goals for the DOE AFCI R&D program. In 2005, the AFCI program responded to this request by submitting a report to Congress [3] that described the program goals and a set of objectives, each with performance targets (metrics) that would be used by the program. A subsequent report to Congress [4] reorganized and restated these goals and metrics. The GNEP statement of principles signed by the Secretary of Energy in 2007 [5] included language consistent with the AFCI goals. The GNEP program was directed by the Assistant Secretary for Nuclear Energy to focus on rapid deployment of demonstration facilities in the early 2020s for a specific advanced fuel cycle including the recycle of used nuclear fuel and the introduction of a fast spectrum "burner" reactor to reduce long-term waste burdens.

With the change of administrations in 2009, the fuel cycle research program was directed by the new Assistant Secretary to step back from the rapid deployment approach of GNEP and instead assess a much broader range of fuel cycle options, adopting a science-based program to determine the range of potential performances possible. The target date for demonstration facilities was moved back to 2040 to allow more time to assess the broader range of options and develop necessary technologies.

The current Fuel Cycle Technology Program is an outgrowth of the AFCI and GNEP programs. However, the science-based strategy of the FCT and the timeframe for demonstrations is somewhat different from the prior programs. For these reasons, it was felt that the existing objectives and metrics should be reviewed to determine if they adequately represented the FCT mission or if changes were needed. An Options Study [6] initiated this effort by listing the primary issues with nuclear energy, examining the root causes for these issues, and deriving a set of qualitative fuel cycle performance measures. This was followed by a metrics review [7] that assessed the purpose of a metrics system, how metrics could best be applied to the current phase of the FCT program, and how the metrics could then evolve with the program as it progressed.

This paper summarizes information from the fuel cycle metrics review report and then examines related activities in the FCT program since the issuance of the metrics review. These activities include completion of an R&D roadmap for Nuclear Energy R&D [8], efforts to gather and organize existing information on a wide range of fuel cycles to better understand what performance is possible, and preparation for transitioning to identification of the more desirable options based on the sponsor's performance priorities.

II. Phases of an R&D Program

This section describes metrics systems generically, discussing considerations in their development and use. A metric is simply "a standard of measurement". Metrics systems are part of the tool set used for scoping and management in the initial phases of an R&D program.

The development and application of new technologies starts with an idea and culminates with a deployed product. The proper organization and management of research and development is key to the successful completion of this process. All technology programs progress through three phases: Discovery, Definition, and Deployment [9].

- During the discovery phase, the program determines what is achievable. A set of tools is needed to define program goals, to analyze credible technical options, and to ensure that the options are compatible and meet the program objectives [10]. A metrics system that scores the potential performance of technical options is part of this system of tools, supporting screening of concepts and aiding in the overall definition of objectives. During this phase performance potentials are only understood in general terms. The "rulers" provided by the metrics system help refine this understanding and help to establish what is achievable.

- During the definition/development phase, the program defines what specifically is wanted. What is achievable is translated into specific systems and specific technical options are selected and optimized. A metrics system can help with the identification of options for optimization and the selection of the option for deployment (both examples of down selection). As options are optimized, what is achievable comes into focus and specific performance requirements can be established (points on the rulers which must be met).
- During the deployment/demonstration phase, the program shows that the selected system works. Demonstration projects are established and classical systems engineering is employed. Starting from the performance requirements, a full set of system design requirements are derived sufficient to construct demonstration facilities. During this phase, the metrics are primarily communications tools.

Under GNEP, the DOE nuclear fuel cycle program was moving from a primarily research-focused effort in the early definition phase to an effort focused on moving forward toward demonstration facilities. The FCT program is returning to the discovery phase to assess a broader range of options.

III. Development of Metrics Systems

All development programs start with a vision and high level "goals", "objectives", or other general definitions of success. These high level statements are typically qualitative and vague; they provide direction and a general desired outcome, but lack the specifics necessary to conduct day-to-day activities. This initial direction is then further defined by mission statements and the derivation of more specific objectives (criteria and metrics). As the program matures, specific development and demonstration projects may be established with formal requirements derived from the objectives and metrics.

Considerations in the development of a metrics system include how far down to drive the breakout in creating metrics from goals, whether the metrics can be quantitative of must remain qualitative based on the information available, and finally how to roll the metric values back up to obtain an overall "score" for the option being evaluated.

In the following discussion, the metrics system developed for the Generation IV technology roadmap (Gen IV) is frequently used as an example. That system started with eight general goals (objectives) covering the areas of resource utilization, waste management, proliferation resistance, safety and reliability, and economics. From these goals, a system of 17 technical criteria and 26 metrics was identified. The metrics were a mixture of quantitative and qualitative measures weighted to roll up to the goal level. The system also featured a probability distribution method for addressing information uncertainty.

The roadmap final report [11] best summarizes the evaluation methodology used:

> "The use of a common evaluation methodology is a central feature of the roadmap project, providing a consistent basis for evaluating the potential of many concepts to meet the Generation IV goals. The methodology was developed by the Evaluation Methodology Group at an early stage in the project. The basic approach is to formulate a number of factors that indicate performance relative to the goals, called criteria, and then to evaluate concept

performance against these criteria using specific measures, called metrics."

III.a Derivation of metrics from objectives

The first step in developing a system of metrics from a set of objectives is to assess how to break each objective down into measurable technical parameters. Depending on the breadth of the objective, this may involve first identifying the different technical areas addressed (criteria development), then identifying the specific parameters to use in each area (metrics development). This breakout requires input from experts in the objective area to understand what division is logical and easy to explain while also covering all of the important areas across the full breadth of the objective. During this derivation, the experts need to understand how the metrics will be applied as some areas of high general importance may be expected to generate identical values for all possible options. In this case the experts may choose to leave out that area as not being discriminating or to include it for communications purposes only.

For example, in the Gen IV area of waste management three technical areas were identified: waste minimization, environmental impact of waste disposal, and stewardship burden. Collectively, these three areas were felt to sufficiently cover the goal of minimizing both the waste produced and the long-term burden it represented.

The next step is identification of the specific parameters to measure. Care must be taken at this step to address all of the key technical properties of an area while not developing excessive metrics measuring additional minor properties. Because something can be measured is not sufficient reason to include it. Care must also be taken that the specific means of measurement are not biased toward or against any of the likely options. This is usually achieved by keeping the parameters general enough to cover the full range of options space. Each metric should also measure different properties which are independent (orthogonal) with respect to system performance. If a positive measurement on one metric always results in a similar value on another metric, they are probably coupled rather than independent and only one needs to be measured (and including both results in double counting).

In the Gen IV sub-area of waste minimization, separate metrics were developed for mass of waste, volume of waste, long-term heat output (from the atomic decay of radioactive isotopes), and long-lived radiotoxicity (a measure of the radiation energy from isotopic decay that can cause tissue damage). The focus was on reactors, and these factors were all properties of the isotopic transmutation behavior of the reactor and the recyclability of the fuel form used in the reactor.

The third step is development of the specific measurement units (quantitative) or scale (qualitative values) for each metric. At this stage, an assessment is made of the information that is likely to be available for each option and whether or not that information will be sufficient to support a quantitative metric. Quantitative values are almost always preferable because they are less subjective, but the potential added cost to develop the data necessary for quantification may not be justifiable, especially if there are a large number of options to assess. Consideration must be given to how the assessment will be used, including the cost impact of associated decisions (budget allocations, etc.) to determine how much effort is appropriate for generating evaluation data.

The Gen IV metrics system addressed this concern through the use of successively more rigorous measurements [12]. In the initial screening of over 100 reactor concepts, all metrics were only addressed qualitatively with valued determined by expert judgment. This supported a rapid assessment across a large number of options without incurring significant costs to evaluate each option. The final roadmap screening then used a mixture of qualitative and semi-quantitative measures for the metrics to evaluate each of 20 concepts carried forward from the initial screening. The roadmap final report summarized this process:

> "Two evaluation stages were employed, screening for potential and final screening. The screening for potential evaluation was designed

to eliminate concepts that lacked sufficient potential, based on the Technical Working Group's judgment of their performance against the evaluation criteria. The final screening evaluation was performed for concepts that passed the screening for potential and was designed to support selection of a small number of Generation IV concepts. This final screening employed a more detailed and quantitative set of evaluation criteria than the screening for potential. Numerical scales were employed for a number of the criteria, and weights were assigned to the criteria associated with each goal. The scales were established relative to a representative advanced light water reactor baseline. To complete the selection process, the Generation IV International Forum (GIF) members considered the evaluations and eventually selected six to become the basis for Generation IV."

A third set of fully quantitative measures was planned to be used against the 6 selected concepts after a period of roughly a decade of research, during which time it was expected the data for measurement would be generated.

III.b Weighting Systems

The previous section addressed breaking down the objectives for identification of specific metrics, including cautions on avoiding metrics that are not discriminating or are not independent. While the resulting metrics are designed to be measurable, they are typically only useful for comparisons between options for the specific properties they measure. This is often sufficient during the discovery phase, as it shows what is possible in each area. However, as the program transitions to the definition phase, a composite "figure of merit" is needed to support optimization. To do a general comparison of potential performance, the results of the individual metrics must be combined to provide this composite value. A weighting system is employed to achieve this value roll up, reflecting the relative importance of each objective as determined by the decision/policy maker.

In the simplest version of a weighting system, each metric is assigned the same weight. For example, in a system of 10 metrics, each would contribute 10% to the composite value. In a real system, the number of metrics developed for each objective varies, so the roll up needs to first be performed local to an objective, then globally by rolling up the objectives. The importance of each objective may also vary; impacting how the global roll up is performed.

The weights used to roll up one objective's metrics need to reflect the divisions that occurred in the development of those metrics. If multiple technical areas were identified, was each of equal importance (breadth), or do some deserve less weight? Within a technical area, was each parameter measured of equal importance? Were any of the metrics coupled? If so, their combined weight can be used to adjust for that coupling. If there were non-discriminating metrics that were kept for communication purposes, they can be given less weight (or even no weight) so the discriminating items are emphasized.

Weights of the metrics within an objective should be developed by the same technical experts who developed the metrics, since they best understand the relative importance of each. Rolling up objective weights presents a different issue. Program goals/objectives are usually provided or at least endorsed by the program sponsor. The definition of the "optimal" system depends on the importance the sponsor places on each objective. For this reason, the program sponsor needs to be involved in how to weigh the objectives. These weights may change over time, reflecting the changing importance of the different factors they represent. An extreme example of this was the change in weighting of proliferation risks from civilian uses of nuclear power after the Indian nuclear weapons test in 1974.

A final consideration is whether to treat cost the same as other objectives or to use it separately in a form of cost-benefit analysis. This addresses the situation where a higher cost system is expected to provide higher performance. In this approach, all of the performance measures are consolidated, with the composite performance value divided by the cost value. The Gen IV system had development cost as a separate metric which was not combined with the performance score, but did not take the additional step of a full cost-benefit comparison. In other metrics systems developed by the Idaho National Laboratory (INL) for the Department of Defense (DoD), the decision maker (sponsor) decided how much performance gain was necessary to justify a unit of cost increase. This value varied by decision maker, with field commanders wanting top performance while those closer to the budgeting process were more cost adverse.

III.c Go/no-go criteria

Metrics systems need to consider some measurement parameters that for technical or policy reasons must achieve a minimum threshold performance level, but otherwise are not discriminators. An example in the nuclear fuel cycle is the U.S. policy against separation of pure plutonium due to the potential to use it in weapons. These considerations generate go/no-go criteria that must be met or an option is disqualified. Go/no-go criteria are applied before other metrics, but are not included in the roll up process. Disqualified options receive no performance value because they are not viable candidates.

In the evolution from initial idea to final system, a go/no-go criterion is an early version of a performance requirement, used when it is understood the performance must be at least so good, but before there is enough information to establish a specific value. Care must be taken in establishing go/no-go criteria, as too stringent a criterion in one objective area may profoundly impact other objectives. The policy against separation of pure plutonium has its roots in the Indian nuclear test, which initially resulted in a ban on domestic recycling of used nuclear fuel issued by President Carter (later relaxed by President Reagan). This ban could be considered a go/no-go criterion in the non-proliferation area that eliminated whole classes of fuel cycle options, independent of how they may perform against other objectives. The current policy against separation of pure plutonium is a more focused form of the criterion which allows these classes of options to be considered within this constraint.

III.d Handling uncertainty

R&D programs involve the creation of new data, information and knowledge. Until all of this material is created, there is uncertainty about how an option may perform. This presents several issues for a metrics system. These include how to identify and communicate uncertainty, how to compare options with different levels of uncertainty, and whether to consider the effort necessary to reduce uncertainty as part of a cost-benefit system.

Uncertainty can be addressed through the use of qualitative measurement or banding/ranging of quantitative measurements (making them “semi-quantitative”). Both approaches support a coarse metrics system where the actual property measured is replaced with a numerical value for weighted roll-up. The same approach is often used on surveys using “much better” = 5, “better” = 4, etc. The semi-quantitative equivalent replaces “much better” with a numerical range for the measurement property. One problem with this approach is it does not differentiate the degree of uncertainty. In a fully quantitative system, high and low values can be used to indicate uncertainty ranges. When rolled up, this approach can exaggerate the uncertainty by summing all the high values versus all the low values. In a real system it is likely that some of the realized values will be on the upper end of the uncertainty band and some on the lower rather than all being at one extreme or the other. If the data is available to generate probability distributions, this problem can be avoided by sampling the distributions using a Monte Carlo method to form a composite distribution.

The Gen IV metrics system used a combination of the semi-quantitative approach along with a probability distribution, as shown in Figure 1. This approach allowed for scoring without having exact values while also capturing the degree of uncertainty in the measurement. The discrete nature of the distributions allowed a mathematical roll up to be employed that preserved and combined the uncertainty distributions while accounting for weighting of the metrics.

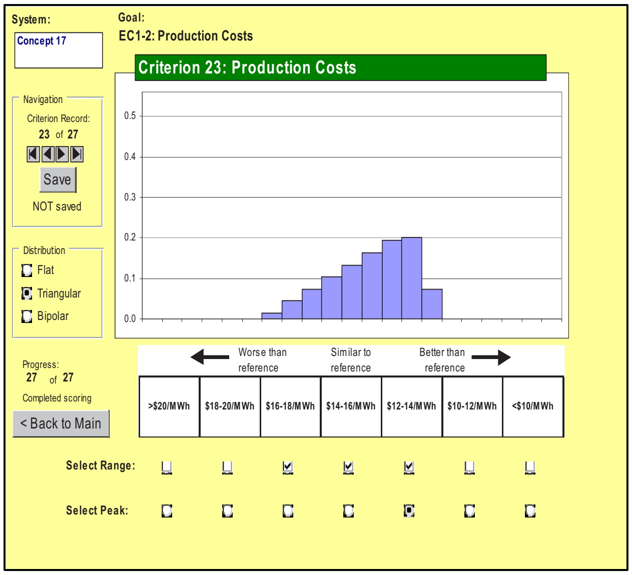

Figure 1 - Gen IV metric showing example of semi-quantitative probability distribution

The Gen IV system allows for comparison of options with varying levels of uncertainty. However, most metrics systems do not employ probability distributions. When two options are to be compared and only one has been significantly investigated, another approach is to measure both using a qualitative set of metrics appropriate for the system with the least information. In this approach, expert knowledge is used for scoring both systems, even though more exact information may be available for the better know system. Care must be taken to ensure a fair comparison by ignoring the shortcomings of the better known system that were uncovered when it was investigated in depth, since the lesser known system likely would be found to also have such blemishes if it were similarly examined.

One application of a metrics system is as a tool to help manage and prioritize R&D activities. The reduction of uncertainty is key to such a system, where each research activity is assessed by comparing its cost to the information expected to be gained from its execution (and therefore the uncertainty reduction expected). The concept of technical maturity can be used to measure uncertainty reduction.

IV. Use of Metric Systems

There are three primary applications of metrics systems in R&D programs. The first is in helping to establish what performance is possible by breaking the performance into different areas of consideration. The second is in comparing technology options for their future performance potential as an aid in focusing the program. This includes formal down selection of options where technologies with less potential receive reduced funding or are eliminated from further development. The third is in prioritizing R&D activities to maximize the uncertainty reduction achieved. This can be a tactical approach supporting down selection, where a certain level of uncertainty reduction is desired before a down selection is performed to ensure an informed decision.

IV.a Down selecting options

Concurrent with the development of technologies is the improvement in understanding of how these technologies will perform in target applications. Thus, uncertainty reduction is a meta-goal of research. A well-run R&D program should demonstrate the efficient use of resources to develop technical knowledge and reduce uncertainty. Pure research for the sake of new knowledge can achieve this objective through investigation of the areas of greatest uncertainty. Applied research focuses the investigation process on those areas with the most promise to achieve application objectives. This process of focusing including the elimination of less promising options from further development is referred to as down selection.

Figure 2 demonstrates the concept of using down selection to focus an applied R&D program based on performance potential versus uncertainty. (The comparison could also be performance versus cost or versus time to deploy, depending on program needs):

- In the first frame, the estimated potential of a number of options is plotted, along with estimated uncertainty. A cut line is drawn through the plot, showing how the decision maker has valued performance versus uncertainty. The slope of the line reflects the expectation that less mature (or lesser known) options should have greater performance potential to be retained by the program.

- In the second frame, a period of research occurs and the uncertainty of the retained concepts is reduced (movement to the left). At the same time, the improved information allows for an updated estimate of potential. Since better information often reveals previously unidentified (or unquantified) shortcomings, the potential of some options has declined.
- The third frame shows a second round of down selection. The performance bar has been raised, and an uncertainty cutoff has been added. This cutoff would be included as a program gets closer to a deployment date, reflecting the need to end work on less mature options and focus on those which will likely be ready in time.
- The final frame shows the movement due to additional research and a third cut line. This is the final cut, as only one option remains.

The example from Figure 2 shows down selection based purely on performance. Another consideration is to retain a diversity of options. Much like other diversity programs, this may require "lowering the bar" for some options. This is difficult to do in a pure metrics-based evaluation, which is one reason why management usually retains an override capability in real down selection processes. In the Gen IV roadmap, 6 diverse advanced reactor options were retained even though they did not necessarily reflect the 6 options with the greatest measured potential. This allowed for flexibility in response to future developments (such as if the value of an objective area significantly changed), while also supporting political realities of existing programs in member countries.

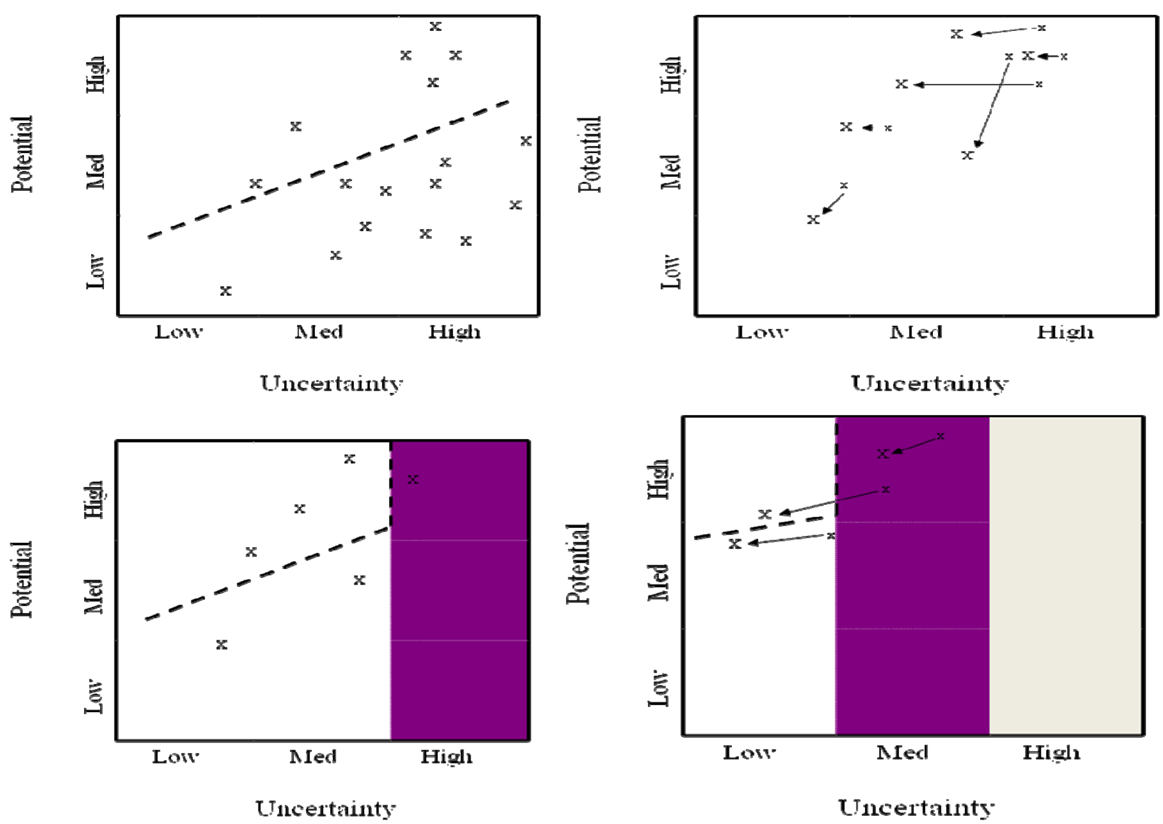

Figure 2 - Example of potential versus uncertainty and the impacts of down selection and R&D

V. Guiding R&D programs

A performance-based assessment of technology options can form the basis for management of an R&D program. Down selection can be used at the strategic level for focusing of technology options, while the compliment of uncertainty reduction can be used at the tactical level for planning prioritization.

For example, a Technology Readiness Level (TRL) approach can be used to measure uncertainty. Technology Readiness Levels (are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The systems under consideration are broken down into their components, and the maturity of technology for each component is assessed. These results are then rolled up to produce a composite TRL for the system.

The fuel cycle research program employed a TRL system as part of the GNEP program, and the GNEP Technology Development Plan [GNEP 2007] included definition and application of specific TRL scales for reactors, recycling, waste forms, fuel fabrication and fuel performance. In the development of a TRL system, it noted:

> "To be most useful the general model must include: (a) 'basic' research in new technologies and concepts (targeting identified goals, but not necessary specific systems), (b) focused technology development addressing specific technologies for one or more potential identified applications, (c) technology development and demonstration for each specific application before the beginning of full system development of that application, (d) system development (through first unit fabrication), and (e) system deployment and operations."

Uncertainty measurement and uncertainty management using a TRL system is in contrast to risk management systems used by systems engineering. Uncertainty reduction is most applicable during general program research, while systems engineering can only be fully applied when specific projects are spawned from the program, systems of requirements for those projects are developed, and technologies are sufficiently understood to determine whether they meet those requirements. The Next Generation Nuclear Plant (NGNP) project is a project spawned from the Gen IV program. Authorized by the Energy Policy Act of 2005 (H.R.6; EPAct), "The NGNP Project shall consist of the research, development, design, construction, and operation of a prototype plant . . ." The NGNP project has a formal set of requirements which form the basis for the design activities. It also has a risk management plan which assesses both the likelihood of undesirable results and their consequences on project success. The NGNP project only uses TRLs until technologies are sufficiently developed to measure performance against requirements, as described in the following paragraph from the NGNP risk management plan [13]:

> "The risk analysis method described in Section 3.3.1 is a conventional risk management methodology used to assess known risks. However, many of the NGNP technologies are less mature, leading to higher uncertainty in design parameters and risks that may not be known. To estimate the level of unknown risk associated with the performance of these technologies, a measure of technical maturity, called the TRL, will be used. An assessment of TRLs for the critical NGNP PASSCs complements the conventional risk assessment for technical risks and is an integral part of the risk management strategy."

The NGNP example illustrates the evolution of R&D management from research programs using metrics and systems analysis techniques to specific development and demonstration projects using requirements and formal systems engineering processes.

VI. FTC METRICS ACTIVITIES

Since completion of the metrics review for the Fuel Cycle Technologies Program, two parallel activities have worked to improve understanding of performance across the option space of potential fuel cycles. These activities support the general theme of the discovery phase of R&D by helping to identify what is achievable.

VI.a Systems Analysis Activities

The Systems Analysis organization within the FCT program has performed a number of assessments to identify and communicate general behavior in several of the major objective areas.

The 2009 Options Study had identified several technology areas that were not well understood. Five structured studies gathered information for these areas, culminating in an umbrella report "Filling Knowledge Gaps with Five Fuel Cycle Studies" [14].

A second phase options study was conducted to identify any nuclear fuel cycle technology or option that may result in a significant beneficial impact to any of the major nuclear issues when compared to the current commercial fuel cycle [15]. This was a broad brush approach that avoided distinctions of incremental improvements (due the uncertainties being greater than the incremental differences) and focused only on potential game changers to help inform stakeholders where major performance improvements were possible and where they were unlikely.

Another effort worked to understand the theoretical limits on potential performance of all fuel cycles imposed by the laws of physics and other hard constraints, generating the report "Assessment of Boundaries and Limits in Nuclear Fuel Cycles" [16]. This helped to define the "ends of the rulers" for the metrics system. This effort next focused on identifying performance limits by major technology type and communicating performance constraints [17]. Figures 3 and 4 provide examples of these performance patterns, both normalized per unit of energy produced.

In Figure 3, the utilization rate for uranium is shown by major classes of fuel cycles. The current fuel cycle and all other thermal spectrum fuel cycles (LWRs, HWRs, HTGRs) can achieve no better than 1% utilization efficiency even with recycling, while fast spectrum once-through systems (no recycling) can achieve up to 30% utilization and with recycling the fast systems can theoretically achieve 100% utilization.

Figure 4 shows how different technology options can be combined to reduce both the mass of the most difficult class of nuclear waste and the long-term radiotoxicity of that waste.

Collectively, these activities are supporting the Discovery phase objective of determining what is possible.

VI.b Systems Engineering Activities

While Systems Analysis has been improving the program's understanding of potential performance across the range of fuel cycle options, Systems Engineering has been structuring options space in preparation for the transition to the Definition phase of the R&D program. In the Definition phase, the sponsor (DOE) will use the information generated during the Discovery phase to identify and communicate what performance is desired, including identifying the relative importance of each objective area. This will support development of a set of weights for the metrics system that will enable calculation of an overall figure of merit for a fuel cycle option.

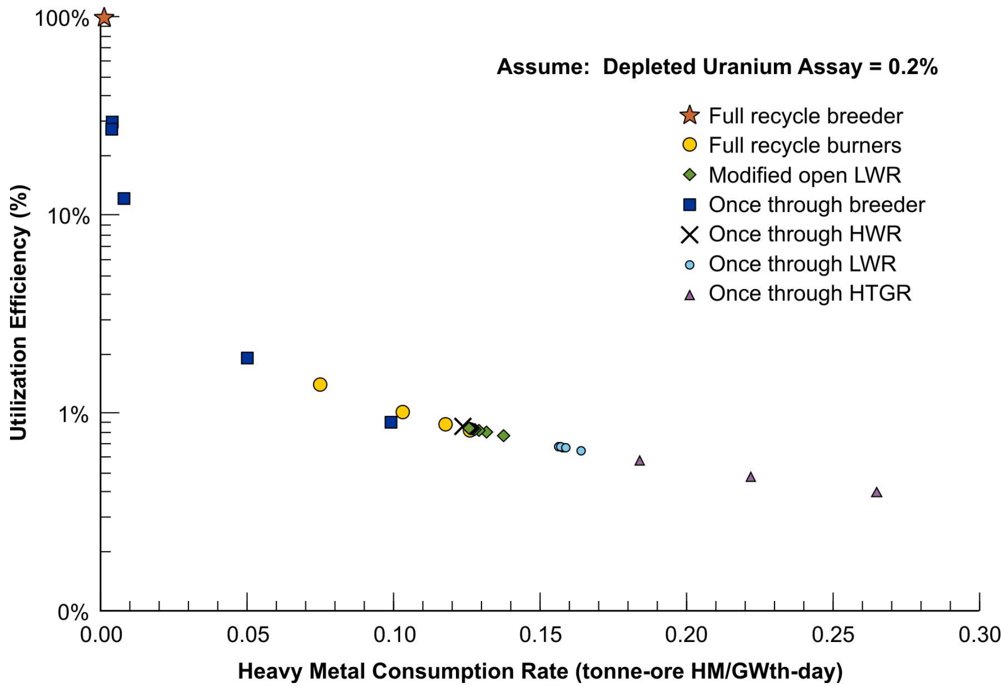

Figure 3 - Uranium utilization efficiency for major classes of fuel cycles

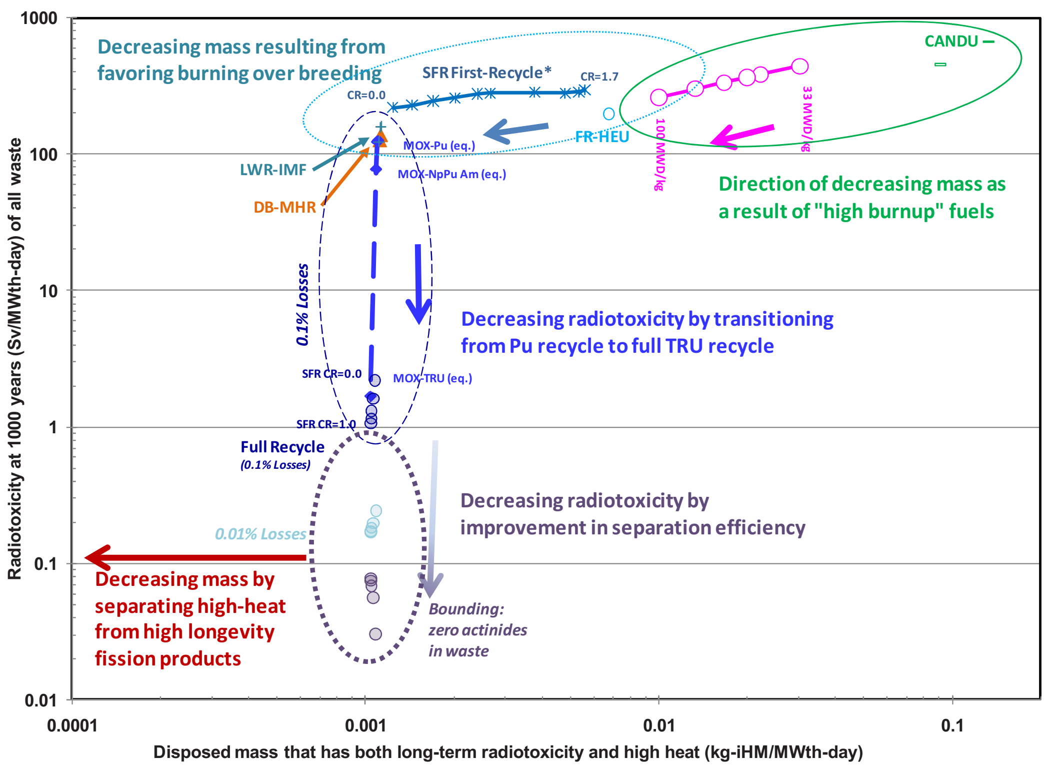

Figure 4 - Technical approaches for reducing the mass and long-term radiotoxicity of high level nuclear waste

To date, the Systems Engineering activity has drafted a structure for cataloging the numerous fuel cycle options and associated information. Each fuel cycle may employ more than one type of reactor, fuel type, fuel physical form, recycle strategy, separation technology, waste form(s), disposal strategy, etc. While some technology combinations are incompatible, there are numerous compatible combinations.

Systems Engineering has also drafted a process for screening fuel cycle options and an associated initial set of metrics [18] and is in the process of testing them. These testing activities are already providing important insights concerning the information required to evaluate fuel cycle options, the level of detail to use for the metrics system, and potential interdependencies within the initial metrics. The testing activities are also providing information on both the utility and limitations of using the metrics system as a component of managing the R&D program.

VII. CONCLUSIONS

The DOE Nuclear Fuel Cycle Technology Program is currently in the discovery phase of research and development, with the program assessing a very broad range of options to understand how much performance improvement may be achievable from the development and eventual deployment of advanced technologies and the adoption of a new fuel cycle strategy for the nuclear power industry.

Improvements in the performance of the fuel cycle in areas such as resource utilization and waste management will improve the sustainability of nuclear power, allowing it to continue to supply a significant portion of our energy needs for many more decades. It will also enable expanding the role of nuclear energy, if needed to support broader national goals of energy security and reducing greenhouse gas emissions.

Metrics are already playing an important role in the development of the FCT program. As the program evolves and matures, the application of metrics will also evolve, becoming more explicit and providing increasing influence on program direction.

ACKNOWLEDGMENTS

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