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Predicting Technology Operational Availability Using Technical Maturity Assessment

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Abstract. A technical maturity assessment method was performed by systems engineers in collaboration with an advisory panel composed of team members from different Department of Energy sites and from different engineering and science disciplines. Various stabilization technologies were assessed annually as to their relative maturity and availability for use in stabilizing nuclear materials. After three years of assessments, several of the technologies are now components of operational systems. A regression analysis of the historical assessments was performed, and it was concluded that the numerical technical maturity score produced by a team of experts can provide a powerful predictor of the time remaining until the operational application of technologies.

INTRODUCTION

On May 26, 1994, the Defense Nuclear Facilities Safety Board (DNFSB) issued Recommendation 94-1, expressing the Board's concern about the safety of DOE nuclear materials. The DNFSB recommended that DOE stabilize and repackage high-risk material within 2-3 years and the remaining materials within 8 years. DOE accepted DNFSB Recommendation 94-1 on August 3, 1994. After establishing the Nuclear Materials Stabilization Task Group (NMSTG), DOE issued an implementation plan to address DNFSB concerns (DOE, February 1995).

The DNFSB called for establishment of a research program to fill gaps in the technology base needed to accomplish the stabilization. DOE committed to a research and development (R&D) program to support the technology needs for converting and stabilizing its nuclear materials for safe storage. An R&D program plan was prepared by the NMSTG-Chartered Research Committee and published in November 1995. With that publication the Research Committee was disbanded. To ensure that technology needs for stabilization continue

to be addressed and that the R&D Plan is appropriately updated, the Plutonium Focus Area (PFA) was established by DOE in October 1995 under the DOE Idaho Operations Office, with support from Lockheed Martin Idaho Technologies Company (LMITCO) and Argonne National Laboratory (ANL). The PFA tasked its Technical Advisory Panel (TAP) composed of team members from different Department of Energy sites and from different engineering and science disciplines to update and revise the November 1995 R&D Plan in 1996 and 1997 (DOE/ID-10561).

This paper presents the technical maturity assessment method that was performed by systems engineers in collaboration the original Research Committee and its successor, the TAP. Various stabilization technologies were assessed as to their relative maturity and availability for use in stabilizing nuclear materials. After three years of assessments, several of the technologies are now components of operational systems. A regression analysis of the historical assessments was performed, and it was concluded that the numerical technical maturity score produced by a team of experts can provide a powerful predictor of the time remaining until the operational application of technologies.

TECHNICAL MATURITY ASSESSMENT METHODOLOGY

The Research Committee worked as a team to develop the 1995 R&D Plan, which included development of an assessment methodology for technical maturity. The approach was an adaptation of an aerospace systems engineering approach (PIR 91053/R1), and was completed by the committee at its first three meetings. After developing the assessment criteria, technical experts from the committee performed scoring and brought the results to committee meetings for peer review.

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Table 1. Adaptation of Aerospace Process Maturity Assessment Scale to Nuclear Engineering

LEVEL	AEROSPACE CRITERIA	NUCLEAR CRITERIA
10	No currently identified solutions meet requirements	No currently identified solutions meet requirements
9		Design concept / technology application formulated
8	Design concept / technology application formulated	Cold feasibility demonstrated
6	Analytical and experimental critical function and/or characteristic proof of concept shows solution may meet requirements	Hot feasibility demonstrated
5	Component / breadboard validation in lab environment	End-to-end design (flowsheet) complete
4	Component / breadboard validation in relevant environment	Cold prototype demonstrated at <u>end-use site</u>
3	System / subsystem model or prototype demonstration in relevant environment	
2	System prototype demonstration in operational environment	Hot prototype demonstrated at <u>end-use site</u>
1	System qualified through test and demonstration	
0	System with successful mission operations	Process integrated into operations

Technical maturity was assessed for seven individual parameters: requirements maturity (RM), process maturity (PM), hardware equipment maturity (EQ), facility readiness (FAC), operational safety

readiness (SAFT), personnel resource status (PER), and schedule status (SCH). A parameter score of 0 means that a technology is in use; and a score 10 is means that it is in pre-conceptual phase.

An example of adapting an aerospace systems engineering parameter to nuclear engineering is shown in Table 1. The progression from concept to operational readiness is a typical complete cycle; however, steps can be skipped if evidence allows developers to do so. In developing the scales for nuclear engineering, there was no specific constraint that required a criterion for each numerical level in the scale. Nuclear engineering is much more empirical in development of its chemical processes compared to the ability of aerospace designers to use simulation and analysis to a greater extent to mature a design. Thus completion of a design concept rated only a 9 in nuclear engineering, whereas it rated a more mature score of 8 in aerospace engineering. In nuclear engineering, nonradioactive cold surrogate materials often are used to perform feasibility and prototyping, such as the use of thorium or cerium in place of plutonium. The Research Committee decided that a significant advance in maturity occurs when demonstrating a prototype with hot material instead of surrogates, and arranged their scale to leap two steps when this occurred. Once a hot prototype is operating, it is the usual approach in nuclear engineering to proceed to operations with the prototype and not have any system qualification testing. This is analogous to using protflight / protqual testing in aerospace, which means that a program launches the prototype hardware to save cost and schedule while knowingly taking on the risk of potential operational failure. For nuclear engineering projects, the risks of skipping the system qualification step are less, because they are ground-based systems that are much more easily repaired than orbiting satellites. The clarifying emphasis on requiring prototyping to be complete at the end-use site was added by the TAP in 1996 as a result of application of the Technical Maturity model by other groups in the program for trade study performance criteria. Typically, a process developed at a research laboratory requires extensive effort to be implemented at an end-use site. For this reason, the trade study teams recommended and the TAP formally accepted this added emphasis in the model.

In a similar fashion to process maturity, the other six individual maturity parameter scales were defined (DOE, November 1995; DOE/ID-10561), and a weighted average was taken to produce an overall score from 0 to 10. Again, an overall Technical Maturity of 10 means that the process is in a pre-conceptual stage. A score of 0 represents an operational system that meets all requirements. The weightings used were 1, 3, or 9 following the standard low, medium, or high correlation

to success model used in Quality Function Deployment. Although it would seem an anathema to a top-down, requirements-driven aerospace systems engineer, the weighting for requirements understanding was a medium, or 3, instead of a high, or 9. This is because nuclear materials stabilization processing is an unsolved chemical problem, and much of the effort is experimental.

DETERMINATION OF SCHEDULE-DRIVEN PROGRAMMATIC RISK

Having completed the technical maturity assessment scale to yield a score from 0 to 10 for each technology, the TAP needed to relate the results of the assessment to the risk being faced by the overall NMSTG mission of completing nuclear materials stabilization according to the commitments outlined in the program plan (DOE, February 1995). The method selected was to follow the general principle of programmatic risk calculation used in aerospace (PIR 91053/R1), where the Overall Programmatic is:

$$\text{Programmatic Risk} = \text{Probability of Failure} \times \text{Consequence of Failure.}$$

In aerospace the technical maturity is converted to the probability of failure using various techniques that range from nonlinear equations to simple linear

interpolation. The TAP decided to use a simple linear transformation in which Technical Maturity is related to the Probability of Failure as follows:

$$\text{Probability of Failure} = \text{Technical Maturity} / 10,$$

Typically, the Consequence of Failure is a function of performance, cost, and schedule consequences. Since nuclear materials stabilization commitments are basically schedule commitments against broader functional requirements, the TAP developed a quantitative Consequence of Failure calculation based on a technology's Operational Need Date, which is the date by which a particular technology must be available, including personnel, equipment, facility, and safety readiness at the end use site. The Consequence of Failure is:

$$\text{Consequence of Failure} = \text{MIN}\{1, \text{MAX}\{0, 1 - (\text{Years from Present to Need Date} / 5)\}\}.$$

This makes the Consequence of Failure increase linearly in time to 1 as the R&D Need Date is approached, with the minimum value of 0 at a time 5 years from the need date. The constant 5 years was selected because the Research Committee believed that the typical time required to move a technology from a

Figure 1. Schedule-Driven Programmatic Risk Determination

Figure 2. Correlation Results for Operational Technologies

Technical Maturity of 10 to 0 was about five years. The progression of the technical maturity of these five years was assumed to be linear in time. The example curves in Figure 1 show the overall programmatic risk scores for theoretical cases where a technology scheduled to be completed in 5 years remains behind schedule for a fixed number of years as the program progresses. An on-time project that progresses linearly from a Technical Maturity of 10 to 0 (0 years behind schedule in Figure 1) produces a parabolic overall risk that never exceeds an overall programmatic risk of 0.25.

Consequently, a project whose score does not exceed 0.25 was considered a low risk. Technologies with an overall programmatic risk of 0.40 or greater were considered a high risk. A five-year project that is making little progress in the first year is medium risk, and if it continues to not make progress in the second year, it is classified as high risk (2 years behind schedule in Figure 1).

The question often is asked why this sophisticated technique of assessing Technical Maturity, converting it to a probability of failure, and then comparing it to an ideal on-time project is required to assess programmatic risk against the schedule commitment. It appears that one simply could ask the developers what is their estimated time to completion for operational readiness to calculate the programmatic risk. Unfortunately, we

have found that (1) either the estimates to complete given by program managers have been overly optimistic for the projects of interest, since there is no contracted incentive related to profit to meet operational readiness need dates, or (2) the estimates have been overly conservative when there is a schedule incentive clause in the developer's contract. This motivated us to further develop the technical maturity score into a calibration technique for estimating time to completion using regression analysis.

CORRELATION OF ASSESSMENT RESULTS TO TECHNOLOGY OPERATIONAL AVAILABILITY

Since 1995, there have been five technologies that have progressed from the R&D phase to operational deployment. They have yielded a set of eight technical maturity assessment scores that can be correlated to the time from when the assessment was completed to the actual time that technology became operational as shown in the data in Figure 2. The technical maturity scoring was set up so that a score of 0 represented an operational technology, and the least squares fit shown indicates this with an intercept estimate that is effectively 0. The slope of the estimated line can be used to predict when a given technology will be ready for operations. Roughly, it says that technical maturity

Figure 3. Regression Through Origin Used for Forecasting Technology Operational Availability

score divided by 3 is equal to the number of years until operational availability. Using a linear extrapolation out to a technical maturity of 10, means that a pre-conceptual design would be available for operational use in about 3.3 years. This is clearly different from the initial estimate of five years used by the TAP in calculating the consequence of failure previously; however, since this extrapolation goes beyond the data values for technical maturity in Figure 2, it is likely that the straight line could curve upwards for technical maturity scores greater than 5.35 (the upper limit of the observed data in Figure 2) to come closer to the expert judgment of the TAP. This methodology will be used to collect data for several more years, and should indicate whether there is nonlinear progress for relatively immature technologies that currently have not become operational, but will do so during the life of the 94-1 stabilization program.

EXPANDING RESULTS TO OPERATIONAL AVAILABILITY FORECASTING

To use the regression approach described in the previous section, we perform the regression fit with the constraint that the regression line pass through the origin, as the model is established on the basis of a Technical Maturity score of 0 for operational

technologies. This produces the fit shown in Figure 3. For a given technical maturity, TM assessed at time t_0 , the first-order predicted operational availability date simply is:

$$T_{est} = 0.3434 TM + t_0.$$

From linear statistical model theory (Graybill), this estimate actually is the estimate of the mean operational availability date. The statistic

$$t = \frac{(T_{need} - T_{est})}{s \sqrt{1 + \frac{TM^2}{\sum x_i^2}}}$$

is distributed as Student's t with $n-1$ degrees of freedom where

T_{need} = a given need date for a technology,

n = the number of data points used to perform the regression in Figure 2,

x_i = the x -values of the data points used to perform the regression, and

s = the estimate of the standard error estimate for the observation error from the regression.

The probability of meeting the need date is

Program Stage	Technical Maturity Scores Required for Entrance							Weighted Average Score	Average Time to Operational Readiness (yrs)
	RM	PM	EQ	FAC	SAFT	PER	SCH		
1. Applied Research	10	10	10	10	10	10	10	10.00	3.56
2. Exploratory Development	10	10	10	10	10	10	10	10.00	3.56
3. Advanced Development	10	9	10	10	10	10	6	9.29	3.30
4. Engineering Development	8	9	8	7	10	7	6	7.86	2.79
5. Demonstration	4	5	4	5	9	5	4	5.14	1.83
6. Implementation	2	2	1	3	5	1	0	2.00	0.71

Figure 4. Technical Maturity Assessment of Stages of Development Model

$$F(t) = \int_{-\infty}^t f_T(z | n-1) dz$$

where $f_T(z | n-1)$ is the probability density function for the Student's t distribution with $n-1$ degrees of freedom. If there is a set of technologies indexed by $\{1, \dots, m\}$, with technical maturities TM^k assessed at times t_0^k and need dates T_{need}^k , we can calculate the probabilities of meeting each individual need date $F^k(t)$ for $k = 1, \dots, m$. If the technologies are parallel competitive alternatives for which only a single technology needs to meet its need date for success, then overall probability of success is

$$1 - \prod_{k=1}^m (1 - F^k(t^k)).$$

If the project are all components of an integrated effort and all must be successful then the overall probability of success is

$$\prod_{k=1}^m F^k(t^k).$$

The above described statistical forecasting methods that have been produced from the technology tracking to date are now in use by the NMSTG in a planning activity to predict schedule performance to select alternative paths for final disposition of the stabilized nuclear materials. It is expected that the insight into realistic technology availability dates using this approach will provide for better decision making for the completing the cleanup of our Cold War environmental legacy.

APPLICATION TO ENTRANCE CRITERIA FOR STAGES OF PROGRAM DEVELOPMENT

As is the case with most Federal technology development organizations, the Department of Energy Environmental Management Office of Technology Development has developed a program life-cycle model with criteria for entering each stage of program

development. The program stages for Environmental Management are: applied research, exploratory development, advanced development, engineering development, demonstration, and implementation. The required entrance criteria for each of these stages Criteria for DOE Technology Development have been defined by Environmental Management. The criteria for each entrance event were compared against the seven technical maturity scales to produce the technical maturity weighted average represented by a typical technology that meets the Environmental Management entrance criteria, as shown in Figure 4. This allows the technical maturity assessment process to be used as a technique to assess the readiness of technology-based programs to proceed, and applying the results of our regression analysis, it also provides an estimate of the time from entrance into a stage to operational readiness. Note that the technical maturity model did not find a distinction between the first two program phases and for assessing the readiness of technology development programs to proceed to the next phase. Also, the data collected thusfar for the regression model has a maximum observed technical maturity of 5.35, which results in a great degree of uncertainty in applying the regression model for predictions of technical progress prior to engineering development in the life-cycle model until more data is collected.

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BIOGRAPHIES

C. Robert Kenley holds a Ph.D. and M.S. Engineering-Economic Systems, a M.S. in Statistics, and a S.B. in Management. He is an engineering fellow at Lockheed Martin Idaho Technologies assigned to DOE in Washington, DC, and has 15 years experience in aerospace systems engineering. His current mission is to assist DOE and its contractors in adopting the systems engineering approach to project management. He is a member of the PFA TAP and the Washington Area Chapter of INCOSE, and is a published author of several papers and journal articles.

Terry R. Creque is completing a Ph.D. in Environmental Biology, holds a M.S. in Environmental Biology and a B.S. in Biology/Chemistry. He has 25 years of experience in DoD with 6 years of operational test and evaluation on Army combat systems. He is currently a senior systems engineer with Lockheed Martin Idaho Technologies assigned to the Department of Energy in Washington, D.C. His current work areas include assisting DOE in system engineering programs for stabilizing and disposing plutonium waste material across the DOE complex. He is a member of the Plutonium Focus Area (PFA) Technical Advisory Panel (TAP), the National Association of Environmental Professionals (NAEP), and the Washington Area Chapter of INCOSE. He has published several articles and has presented at professional meetings.