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Cover Page Footnote

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Incorporating Human Readiness Levels at Sandia National Laboratories

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Sandia National Laboratories

Abstract

Since 2010, the concept of human readiness levels has been under development as a possible supplement to the existing technology readiness level (TRL) scale. The intent is to provide a mechanism to address safety and performance risks associated with the human component in a system that parallels the TRL structure already familiar to the systems engineering community. Sandia National Laboratories in Albuquerque, New Mexico, initiated a study in 2015 to evaluate options to incorporate human readiness planning for Sandia processes and products. The study team has collected the majority of baseline assessment data and has conducted interviews to understand staff perceptions of four different options for human readiness planning. Preliminary results suggest that all four options may have a vital role, depending on the type of work performed and the phase of product development. Upon completion of data collection, the utility of identified solutions will be assessed in one or more test cases.

Keywords: human readiness level, technology readiness level, human systems integration

Technology Readiness Levels

Technology readiness levels (TRLs) represent a common tool to measure technology maturity that provides consistency within and across programs. The TRL concept can be traced back to as early as 1969, and the first published description appeared in 1989 (Sadin, Povinelli, & Rosen, 1989). At that time, the U.S. National Space Policy directed a broader role for NASA in the technology maturation process to drive technology advances for future mission capabilities. Development of the initial seven-level TRL scale was prompted by NASA's realization that the differences between success and failure in the past were directly attributable to the adequacy of technology readiness. The explicitly defined readiness levels in the TRL scale provided a precise means of describing the maturity of a technology and its readiness for operational use.

The Department of Defense (DOD) fully adopted a nine-level TRL scale in 1999 when the General Accounting Office (1999) concluded that demonstrating high maturity before including new technologies in development programs increases the chances of success. Since that time, the DOD has fully incorporated TRLs into its acquisition framework. Technology development begins upon Milestone A approval; afterwards, formal readiness assessments of the technology under development are required at Milestones B and C and as otherwise directed by the milestone decision authority (Department of Defense, 2011) (Figure 1). For major defense acquisition programs, TRL 6 is required before Milestone B approval (Department of Defense, 2012). TRLs are now widely accepted and used not only throughout the DOD but also at other U.S. government agencies such as the Department of Energy and many companies worldwide. At Sandia National Laboratories, the process and rationale for assessing a product's TRL are described in an internal document referred to as Realize Product Procedure (RPP) #22.

The nine levels of the TRL scale describe various stages of technology maturity, beginning with the initial stages of scientific investigation at TRL 1 and culminating in successful operational use of the final system at TRL 9. In general, all sites use the same basic descriptors for each of the nine TRLs (Sandia's descriptions appear in Table 1), but they may be supplemented with more specific descriptions tailored to products and missions. Each level of the scale has associated exit criteria describing the conditions that must be met before the technology can advance to the next level. For example, TRL 3 indicates that concepts have been demonstrated analytically or experimentally. In order to exit TRL 3 and advance to TRL 4, analytical models or laboratory prototypes must demonstrate the proof-of-concept for the key elements of intended applications. As part of meeting this exit criterion, descriptions of the functionality of intended applications must be developed.

Limitations of Technology Readiness Levels

The TRL scale offers many benefits. It provides a simple indicator of a technology's maturity that is readily understood. It can be used to gauge progress throughout development and manage program risks. However, the TRL scale does have limitations.

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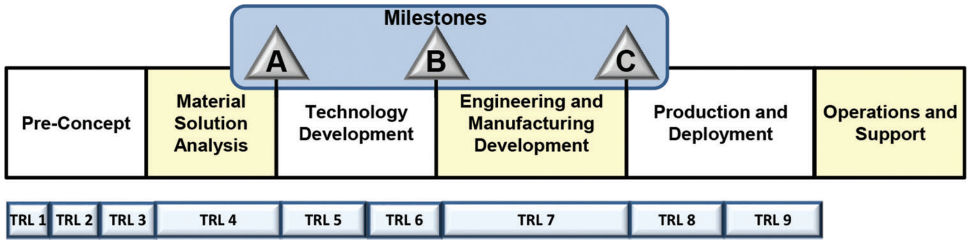

Figure 1. TRLs in the DOD acquisition framework. For major defense acquisition programs, TRL 6 is required before Milestone B approval (Department of Defense, 2012).

Table 1
Sandia National Laboratories TRL descriptions.

TRL Descriptions
9: Operational use of deliverable
8: Actual deliverable qualified through test and demonstration
7: Final development version of the deliverable demonstrated in operational environment
6: Representative of the deliverable demonstrated in relevant environments
5: Key elements demonstrated in relevant environments
4: Key elements demonstrated in laboratory environment
3: Concepts demonstrated analytically or experimentally
2: Concept and application formulated
1: Basic principles observed and reported

Namely, the TRL definitions combine several different aspects of technology readiness into a single metric; in effect, the scale represents technology maturity as a single dimension. Such limitations have spawned the development of multiple other types of readiness level scales to fill the gaps, including manufacturing, design, integration, and system readiness levels.

Another gap that has been identified in the TRL scale is its inability to capture the human-related aspects of technology development and their critical role in the readiness of a technology for operational use. A system is comprised of both technological and human components that must interact successfully within the environment in order to achieve system effectiveness. Failures originating from any one component of the system can negatively impact overall system effectiveness. While the TRL scale provides assurance that the technological components of the system will function as intended, it does not address the interactions between the technologies and the humans in the system that are necessary for success. That is, a technology may be mature in a strictly technical sense; however, if it is not ready for people to use effectively, then its overall readiness for deployment could be much lower.

Human Issues in Engineered Systems

Along with this recognition of a gap in the TRL scale is the growing realization that most of the problems in engineered systems stem from the people in the system, not the technologies. Human error is said to be a major causative factor in many domains—up to 45% of nuclear power plant accidents, 60% of aircraft accidents, 80% of NASA Type A/B mishaps, and 90% of road traffic accidents are attributable to human error (NASA Armstrong Flight Research Center, 2017; Pheasant, 1991). People typically make 3 to 7 errors per hour under normal conditions and up to 15 errors per hour in stressful, emergency, or unusual conditions—up to 15 million errors per million hours (Farris & Richards, 2009). By contrast, a toggle switch fails once per million hours (Smith, 2005).

To complicate matters, most current systems engineering approaches for product development "forget" the human—the largest error-generating component—in the system (Schatz, 2016). That is, the role of people in the system and their interfaces with the technological components receive little to no attention throughout the development lifecycle. More commonly, the human component is not considered until the system is fielded and human errors start to occur. Given that costs to fix errors escalate exponentially over the product lifecycle, it can be 30 to 1500 times more costly to correct an error at the operations and maintenance phase as compared to a design flaw detected and corrected early in the development process (Steicklein et al., 2004).

Human Readiness Levels

In an effort to address these concerns, several researchers have been exploring the utility of supplementing TRLs with another type of readiness scale—human readiness levels (HRLs) (Endsley, 2014; Kosnik & Acosta, 2010; O'Neil, 2014; Phillips, 2010). The intent is to afford equal weight to the technologies and the humans within the system and to "remember" the human early and often throughout the lifecycle. The central question underlying HRLs is whether the technology is ready for human use. In other words, have the features necessary for usability and operator effectiveness been engineered into the design as early as possible?

Acosta (2010) first introduced the concept of a HRL scale during a panel discussion at the Aerospace Medical Association annual meeting in Phoenix. Afterwards, he served as an advisor for a Naval Postgraduate School thesis in which a framework for a nine-level HRL scale was formally developed (Phillips, 2010). Mica Endsley, Chief Scientist of the Air Force from 2013 to 2015, began

Table 2
Proposed HRL scale (Endsley, 2015).

HRL Descriptions
9: Post-deployment and sustainment of human performance capability
8: Human performance using system fully tested, validated, and approved in mission operations
7: HSI requirements verified through development test and evaluation in representative environment
6: System design fully matured by human performance analyses, metrics, and prototyping
5: HSI demonstration and early user evaluation of initial prototypes to inform design
4: Modeling and analysis of human performance conducted and applied within system concept
3: Mapping of human interactions and application of standards to proof of concept
2: Human capabilities and limitations and system affordances and constraints applied to preliminary designs
1: Human-focused concept of operations defined

Note. HSI = human systems integration.

advocating the nine-level HRL scale and maintained that it should be as much of a requirement as the TRL scale for system development (Endsley, 2014). Table 2 shows the proposed HRL scale that Endsley (2015) presented at the National Defense Industrial Association (NDIA) Human Systems Conference in 2015.

Understanding HRLs

The unique contributions of HRLs for product development can be understood in part by considering how they can augment existing TRLs. Returning to an example presented earlier in this paper, TRL 3 focuses on advancing the maturity of the technical components of a system through analytical models or laboratory prototypes. If human readiness were to be addressed simultaneously with TRL 3, the development team would also concentrate on how humans interact with the technical components. For example, the team might investigate and clarify the nature of the human roles for the intended applications identified in this phase—inspector, monitor, maintainer—and the implications for the specific technical components that have been selected. Similarly, the team would examine whether the features of the laboratory prototypes that have been developed account for human capabilities and limitations. Examples might include verifying that the planned displays are compatible with human visual capabilities or that the knobs and switches on control panels are within reach of the intended users.

The contributions of HRLs can also be understood by examining the consequences of neglecting human readiness during development. The U.S. Army Stinger missile system provides one example. The shoulder-fired anti-aircraft missile system was designed to support a required probability of kill of 0.6 for low-flying enemy aircraft. The system presumably advanced through all required TRL levels, and it was initially deployed in 1981. During fielding, it was discovered that the actual probability of kill was much lower at 0.3. It became apparent that operator training and skill were critical factors in successful use of the Stinger missile. An Army study found the Stinger was unnecessarily difficult and, with 18 separate steps needed to fire it, too complicated for many soldiers (Tully, 1986). The critical error that occurred during design involved an assumption throughout the development process that soldier performance would be perfect (Booher, 2003). The issue could have been addressed early in the design process by expanding the definition of "system probability of kill" beyond the strictly mechanical components of the system to include the concept of "human readiness" for the human component.

Potential Benefits of HRLs

HRLs are intended to mitigate program risk, improve system performance (minimize failures), and reduce lifecycle costs. As described earlier, the human is the largest error-generating component of a system. Addressing the readiness of technological components of a system for human use early and often can reduce program risks, lifecycle costs, and system failures. For a typical system, approximately 90% of total lifecycle costs are determined at the end of the research and development phase, and the majority of those costs are associated with subsequent operations and maintenance (Schatz, 2016). Thus, for a typical system, total lifecycle costs are determined at a point when the human component has not been considered. As a result, a large portion of the already high operations and maintenance costs is spent to correct human error issues. Focusing on human readiness throughout the lifecycle helps satisfactorily address risk, cost, and system performance simultaneously.

Status of HRL Development

The HRL scale has been intentionally designed to parallel the TRL structure familiar to the systems engineering community to facilitate integration into current approaches for product development. While there has been interest and continued effort in developing the HRL concept, the scale has yet to be formally adopted and used (Ganey, Garcia, & Wilbert, 2017). One issue is current DOD feedback, which suggests reluctance to introduce yet another readiness scale. As a result, more recent DOD efforts have begun to explore options that retain the critical concepts embedded in an HRL scale, but focus more heavily on tools to support performance- and risk-based assessments of human readiness (Stohr, 2016). Human systems integration (HSI) risk tools like Stohr's are intended to facilitate communications regarding the program risks stemming from insufficient human readiness as well as the consequences of those risks not being addressed during development (e.g., degraded system performance, safety, cost, schedule).

Suggested mitigation strategies to address the identified risks are also incorporated. A standard risk matrix illustrating the likelihood and consequences of each risk may be used to facilitate communications with program managers.

Sandia HRL Study

Sandia National Laboratories initiated a study in 2015 to evaluate options to incorporate human readiness planning tailored to Sandia processes and products. One driver for the study involves the inherent differences between the DOD acquisition process and Sandia's product development process. Similarities between the two approaches are reflected in the general progression of activities during the development lifecycle. As in the DOD acquisition framework, development of Sandia products progresses from initial concept development (Phase 1) through full quantity production, maintenance, and evaluation (Phase 6). Given that full system production for the systems of interest at Sandia has already occurred, current development processes consist of refurbishment and maintenance of existing systems produced in Phase 6 to achieve life extension or enhanced system capabilities (e.g., design modifications for existing components). This modified development process falls entirely within lifecycle Phase 6 and is therefore referred to as the "6.X process." Figure 2 illustrates the linkage between Sandia's 6.X development process and TRLs (Sandia National Laboratories, 2015).

Study Scope

Bearing in mind these differences, the present study capitalizes to the extent possible on previous DOD research by leveraging the lessons that have already been learned to facilitate a study approach. The scope of the Sandia study includes an initial baseline assessment to understand in detail how various organizations within the laboratories conduct product development now. The intent of the baseline assessment is to explore the requirements that guide product development, the resources that are used (e.g., documents and subject matter experts), and the extent of any gap that may exist at present in addressing the human component of the system. Accordingly, the study team interviewed personnel who work in multiple different groups throughout Sandia to represent the range of development activities.

While completing the baseline assessment, the study team also gauged staff views of four different options that might be implemented to prompt human readiness assessments. Interviewees were also given an opportunity to identify other options. The study team developed and presented the following four options:

1. ***Separate HRL scale:*** this concept launched the study. The study team chose to include use of a separate HRL scale as one option, recognizing that DOD reservations about adding another readiness scale might or might not be reflected at Sandia.
2. ***TRL+ scale:*** represents a proposed modification to the existing TRL scale to incorporate human readiness concepts directly into the definition of technology maturity. The intent is to add HRL concepts to existing exit criteria for each TRL, and developers must meet both types of criteria before advancing to the next TRL level. This option would obviate the need to add a new readiness level scale.
3. ***Human factors RPP:*** a proposed Sandia document that would characterize how human factors products would be developed during HSI activities to evaluate readiness of a product for human use. References to the human factors RPP would then be incorporated into existing RPPs that govern the design and development process to ensure that HRL-type concepts are included systematically and comprehensively throughout the process.
4. ***HSI risk tool:*** a tool similar to Stohr's (2016) proposed HSI risk tool to help HSI practitioners quickly develop and communicate programmatic risks stemming from the human component of a system as well as possible mitigation strategies for those risks.

Preliminary Results

The study team is continuing to collect data from staff interviews to address the study objectives. To date, collected data suggest that current baseline approaches for Sandia product design and development tend to neglect the human component of a system. For the most part, interviewees have indicated that coordination with follow-on manufacturers early in the process constitutes HSI. Aside from that form of pre-planning and coordination, little else is routinely accomplished to manage the human component of a system. If the human component is addressed in some fashion during design and development, the engineering team rarely consults human factors professionals for input. Furthermore, only a small minority of the staff who have

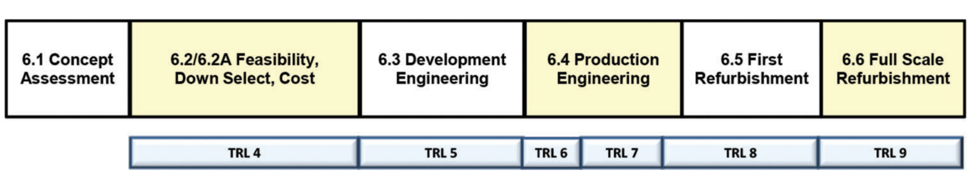

Figure 2. Recommended minimum TRLs in the Sandia product development framework.

been interviewed at this point have completed Sandia's internal human factors course or undertaken another type of human dimension training. In addition, current product requirements do not typically include specific human performance requirements for effectiveness or efficiency, though some teams actively derive them from more generic, higher-level requirements for their own purposes.

Reactions to the four options for systematic and comprehensive incorporation of the human component throughout development have shown some variability, depending on where people work within Sandia and the type of work they perform. Overall, however, a fairly consistent picture has begun to emerge. In general, all four options have proponents, but the contributions and value of each option are contingent on the phase of product development. Each option addresses different questions and provides different types of information. At this stage in data collection, responses appear to favor implementation of either a separate HRL scale or a TRL+ scale, supplemented with a human factors RPP to provide overarching guidance and requirements. Critics of a separate HRL scale have pointed out that it may not be well received due to the perception of imposing more requirements on their already extensive list of obligations. Critics of the TRL+ scale pointed out that TRLs and HRLs will not likely progress in parallel for every product, which will make it difficult to determine how to assign HRLs to existing TRL exit criteria.

Finally, interviewees who have responded positively to the concept of an HSI risk tool state that it conforms to many current risk-informed approaches used throughout Sandia. In fact, risk management is a central feature of project management. Consequently, an HSI risk tool might be readily accepted as part of common practice rather than viewed as yet another requirement that must be met.

Staff also posited some options the study team had not previously considered, primarily as secondary aids. For example, one suggestion is to add human factors training to current internal training and professional development requirements for systems and component engineers. At present, engineers are not required to complete any human factors courses offered at Sandia. Along these lines, another suggestion is to provide human factors training for personnel in higher-level executive roles to achieve a top-down understanding of the criticality of a development process that includes the human component of a system. A third suggestion is to circulate a human factors lessons learned newsletter periodically to promote more widespread awareness of the impacts of human factors throughout the product lifecycle.

Future Efforts

Future efforts for this study consist of completing staff interviews and developing a comprehensive approach that incorporates interviewee inputs and suggestions. Afterwards, the utility of this approach will be tested with up to three test cases to capture a range of early-, mid-, and late-phase development efforts. The test cases will help identify and refine the optimal approach that will be recommended to Sandia management as a path forward to achieve systematic and comprehensive human readiness planning, regardless of the specific program or product.

Summary and Conclusions

Sandia National Laboratories has identified a need for an approach to bridge the gap between the current technology-centric systems engineering approach and the desired end state of full incorporation of the human component throughout the product lifecycle. Sandia leveraged DOD research and lessons learned in this arena to inform a study approach, recognizing that solutions that work for the DOD may not be optimal for Sandia's missions. The objective is to provide a recommended path forward to ensure a balanced systems engineering approach that gives equal weight to the technologies and the humans in the system throughout the product lifecycle.

To date, the study team has collected the majority of the baseline assessment data and has conducted interviews to understand staff perceptions of various options for incorporating the human dimension throughout the product lifecycle. Collected data have confirmed a gap in Sandia's current design and development process with respect to consideration of the human component of the system. Further, all of the proposed options to fully address the human component during design and development appear to have vital contributions, depending on the type of work performed and the phase of product development. Upon completion of data collection, the study team's next task is to effectively combine the feedback into a coherent approach that can be tested for utility. Test cases will be used to finalize an approach to achieve a balanced systems engineering process that affords equal consideration to the technologies and the humans in the system throughout the lifecycle.

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