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On the Integration of Technology Readiness Levels at Sandia National Laboratories

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Abstract

Integrating technology readiness levels (TRL) into the management of engineering projects is critical to the mitigation of risk and improved customer/supplier communications. TRLs provide a common framework and language with which consistent comparisons of different technologies and approaches can be made. At Sandia National Laboratories, where technologies are developed, integrated and deployed into high consequence systems, the use of TRLs may be transformational. They are technology independent and span the full range of technology development including scientific and applied research, identification of customer requirements, modeling and simulation, identification of environments, testing and integration. With this report, we provide a reference set of definitions for TRLs and a brief history of TRLs at Sandia National Laboratories. We then propose and describe two approaches that may be used to integrate TRLs into the NW SMU business practices. In the first approach, we analyze how TRLs can be integrated within concurrent qualification as documented in TBP-100 [1]. In the second approach we take a look at the product realization process (PRP) as documented in TBP-PRP [2]. Both concurrent qualification and product realization are fundamental to the way weapons engineering work is conducted at this laboratory and the NWC (nuclear weapons complex) as a whole. Given the current structure and definitions laid out in the TBP-100 and TBP-PRP, we believe that integrating TRLs into concurrent qualification (TBP-100) rather than TBP-PRP is optimal. Finally, we note that our charter was to explore and develop ways of integrating TRLs into the NW SMU and therefore we do not significantly cover the development and history of TRLs. This work was executed under the auspices and direction of Sandia's Weapon Engineering Program. Please contact Gerry Sleefe, Deputy Program Director, for further information.

Acknowledgment

The authors would like to thank Julie Kesti and the nuclear weapons program for funding this work. We also acknowledge members of the TRWG (technology readiness working group) pictured in Figure 1. The TRWG began the process of integration and assimilation of TRLs into Sandia National Laboratories and provided the reference set of TRL definitions published in section 1.2 of this report. We would also like to thank Carol Sumpter for generously contributing section 1.3 on the history of TRLs at SNL.

Contents

Figures

Nomenclature

NWC	nuclear weapons complex
PRP	product realization process
PRT	product realization team
SNL	Sandia National Laboratories
TBP	technical business practices
TRL	technology readiness level
TRWG	technology readiness working group

1. Introduction

The main objective of this report is to discuss and propose methods for integrating TRLs into the NW SMU business practices. The TRL definitions themselves contain structure and basis sufficient to provide hints as to how and where to proceed. This chapter serves to introduce TRLs. We discuss why TRLs are important, provide a reference set of definitions and give a brief history of TRLs at SNL. In the following chapter, we discuss and propose the integration of TRLs into the NW SMU business practices.

1.1 Why are TRLs Important?

Technology readiness levels address two key purposes:

- Communication
- Risk

TRLs improve communications by creating a common understanding of the maturity of a specific technology for an intended application. They reduce the risk to project managers by enabling the project manager to make consistent comparisons between different types of technologies and to identify which program elements require more development. TRLs require the technology provider and the project manager to define at the outset of the project what constitutes achievement of each TRL. TRLs are intended to be technology independent, and therefore, the description associated with a given level will be specific to the technology being matured and will depend on the needs of the first operational user of that technology. Even identical technologies will be at different TRL levels in different applications.

1.2 Reference TRL Definitions

There are several sets of TRL definitions with slightly different wordings although very similar overall semantics. The technology readiness working group (TRWG), discussed below, agreed upon a set of definitions that make sense for Sandia National Laboratories and we present those as a reference.

TRL 1: Basic principles observed and reported
Lowest level of technology readiness; Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.

TRL 2: Concept and/or application formulated
Once basic principles are observed, then at the next level of maturation, practical applications of those characteristics can be 'invented' or identified. At this level, the application is still speculative: there is no experimental proof or detailed analysis to support the conjecture. Examples are still limited to paper studies.

TRL 3: Concepts demonstrated analytically or experimentally

At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. Examples include the study of the separate elements of the technology that are not yet integrated or representative.

TRL 4: **Key elements demonstrated in laboratory environment**
Following successful "proof-of-concept" work, the basic key technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory. Examples include integration of “ad hoc” hardware in a laboratory, such as breadboards, low-fidelity development components, and rapid prototypes.

TRL 5: **Key elements demonstrated in relevant environment**
At this level, the fidelity of the key elements being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment. Examples include “high fidelity” laboratory integration of the key elements.

TRL 6: **Representative of the deliverable demonstrated in relevant environment**
A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative of the deliverable (examples include a model or prototype system or system - which would go well beyond ad hoc, 'patch-cord' or discrete component level integration) - would be tested in a relevant environment This level, represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.

TRL 7: **Key final development version of the deliverable demonstrated in operational environment**
TRL 7 is a significant step beyond TRL 6, the development version of the deliverable is near or at the planned operational system. This level requires the demonstration of an actual development version of the deliverable in an operational environment Examples include X-planes and Advanced Concept Technology Demonstrations (ACTDs).

TRL 8: **Actual deliverable qualified through test and demonstration**
At this level, the technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the actual deliverable in its intended application to determine if it meets design specifications. This level might also include integration of the new technology into an existing system.

TRL 9: **Actual Operational use of actual deliverable**
Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true 'system development.' Examples include using the deliverable under operational mission conditions. This TRL does not include planned product improvement of ongoing or reusable systems

1.3 A Brief History of TRLs at Sandia National Laboratories

1.3.1 Technology Readiness Working Group (TRWG)

The technology readiness working group was chartered by the PDLT on May 22, 2003 as the result of a briefing on Integrated Microsystems for Future Weapons. Using a lab-wide team, the group was tasked to discuss and address the issues related to 'Successful Technology Maturation' at Sandia. This was to include:

- Metrics, Scales, and Tools
- World-class processes
- Relevance to NW SMU
- Successful and "lessons learned" Case Studies

On May 22, 2002, Doug Henson (8200) requested that Marion Scott form an additional planning team within Center 1700 "to start from a clean sheet of paper and brainstorm ways in which integrated microsystems could be used for future Arming, Firing, and Fuzing systems." After months of work, on February 19, 2003, the 1700 group presented its findings to staff and managers from Centers 8200 and 8700. Doug Henson then recommended that the 1700 team involve various component organizations, specifically 2300 and 2600 to mature the presentation and socialize the result with Center 2100.

By May 22, 2003, the enlarged group briefed its findings on the topic of "Integrated Microsystems for Future Weapons" to the Nuclear Weapons Program Development Leadership Team in preparation for their presentation to the Nuclear Weapons Leadership team on June 9, 2003.

As a result of the May 22, 2003 PDLT briefing, Carolyne Hart and Don Cook chartered a group to be co-chaired by David Myers, 1702, and Gerry Sleefe, 2614. The co-chairs were directed to include representation from both sites and across all SMUs. The original contributors included Reid Bennett, 1748; Greg Cardinale, 8245; Mike Daily, 1738; Vince Hietala, 1738, Gil Herrera, 14100; Tom Hitchcock, 15403; Scott Holswade, 2333; Ming Lau, 2338; Guillermo Loubriel, 15333; K.K. Ma, 1735; Keith Ortiz, 1011; Carol Sumpter, 1702, Barb Wampler, 2333; and Ted Wheelis, 5734; Ed Talbot, 8222. The technology readiness working group (TRWG) is shown in Figure 1. The group represented a multi-SMU, multi-disciplinary team with experience from government, industry, academia and a range of science communities. They chose to make decisions and recommendations by consensus with the result being suggestions for a possible future state at Sandia that would represent the successful development and maturation of new technologies for the Nuclear Weapons Stockpile.

The following is a list of topics and questions that the group was directed to analyze and report back on:

- How to develop unambiguous communications between customer and supplier about the appropriateness of inserting a technology into a given product or system
- Assess and recommend best practices for managing concurrent development based on a common language and understanding
- How to bridge the “valley of death” between concept demonstration and full production.

Figure 1: Technology Working Group (TRWG)

2. Integration of TRLs into the NW SMU

2.1 Process and Scope of Work

During the course of this work, we informally met with staff throughout the laboratory to discuss their engineering practices, processes, and use of TRLs. From these interactions, we gained useful information which formed the basis of our understanding (anecdotal) of the actual practices and processes that exist today at the laboratory. These staff interactions also reinforced our belief that the use of TRLs is critical to successful project management of nuclear weapons work at Sandia National Laboratories. In most cases, we met with team leads and project managers. The breadth of our interactions is indicated by the following list of staff members with whom we met. The recommendations we make in this report were strongly influenced by these discussions.

- Gerry Sleefe (Engineering Campaigns)
- Michael Cieslak (Weapon Engineering Programs)
- Marion Scott (Microsystems S&T & Components)
- Gilbert Herrera (Manufacturing Science and Technology)
- Doug Weiss (W76-1 AF&F)
- Mark Dickinson (TBPs)
- Richard Berget (W76 micro-electronics)
- Greg Wickstrom (systems modeling software)
- TY Chu (Campaign 6)
- Carla Busick & Mike Etough (neutron generator tube)
- Frank Peter (W76-1 MC4713)
- Ernie Garcia (SiRES)
- Rick Fellerhoff (Surety Components)
- Scott Holswade (Weapon Electronics and Advanced RF Systems)

In addition to the above staff interactions, we also took on the larger task of reading and understanding the formal and documented requirements associated with the NW SMU policies and processes. Our focus was on the technical business practices (TBPs).

2.2 Integrating TRLs into the Technical Business Practices: TBP-100 and TBP-PRP

The history and depth of the TBPs is quite large and well beyond the scope of this report. Our objective for this section is to very briefly introduce the TBPs with an emphasis towards integrating TRL concepts.

At the time of this writing, there are 43 TBPs listed on the "Nuclear Weapons Complex PRP online" website: http://prp.lanl.gov/documents/tbps.asp. Quoting from the website:

> *These are agreed upon practices for weapons related design and production within the nuclear weapons complex (NWC).*

Product realization and concurrent qualification are arguably the most fundamental concepts represented in the TBPs as they represent the overall engineering process associated with nuclear weapons. TBP-PRP (product realization process) [2] describes DOE/AL requirements that span the entire weapons development lifecycle, from design to disposal. TBP-100 (concurrent qualification) [1] describes DOE/AL requirements which emphasize the use of concurrent engineering and it may be considered as part of the overall product realization process. Given the fact that TBP-PRP and TBP-100 are key elements in the DOE/AL requirements associated with nuclear weapons related work, it makes sense that they may also be a logical place to integrate TRLs.

In the remainder of this chapter, we investigate and propose methods for integrating TRLs into these two documents. It is tacitly assumed that the reader is familiar with the basic stages/steps of the product realization process (PRP) and concurrent qualification as defined in TBP-PRP and TBP-100 respectively. Every effort has been made to minimize redundancy between the current document and TBP-100 and TBP-PRP. We only reproduce figures and text here where it is absolutely necessary in order to clarify or define key concepts.

2.2.1 On the Relationship Between TBP-PRP and TBP-100

The product realization process spans the entire engineering lifecycle and concurrent qualification is one of its key elements. Concurrent qualification maps directly into steps 1 & 2 of the PRP, as shown in Figure 2, and it adds rigor to the PRP. Opportunities exist to integrate TRL concepts into the definitions and processes of both the PRP and concurrent qualification although it is our view that it is more straightforward and transparent to integrate them into concurrent qualification rather than the PRP. The PRP has a very broad scope and attempting to integrate TRLs into it amounts to adding footnotes and appendices to existing documentation (TBP-PRP). TRL concepts are fundamental and must be given a higher profile than would be possible with that approach. However, TBP-PRP does give important rank and relevance to concurrent qualification which is separately defined in TBP-100. It is our opinion that integrating the TRL concepts into TBP-100 provides sufficient visibility and opportunities for rigor in the existing TBP system.

In the remainder of this chapter, we demonstrate two approaches for integrating TRLs into the TBPs – one for TBP-100 and the second for TBP-PRP.

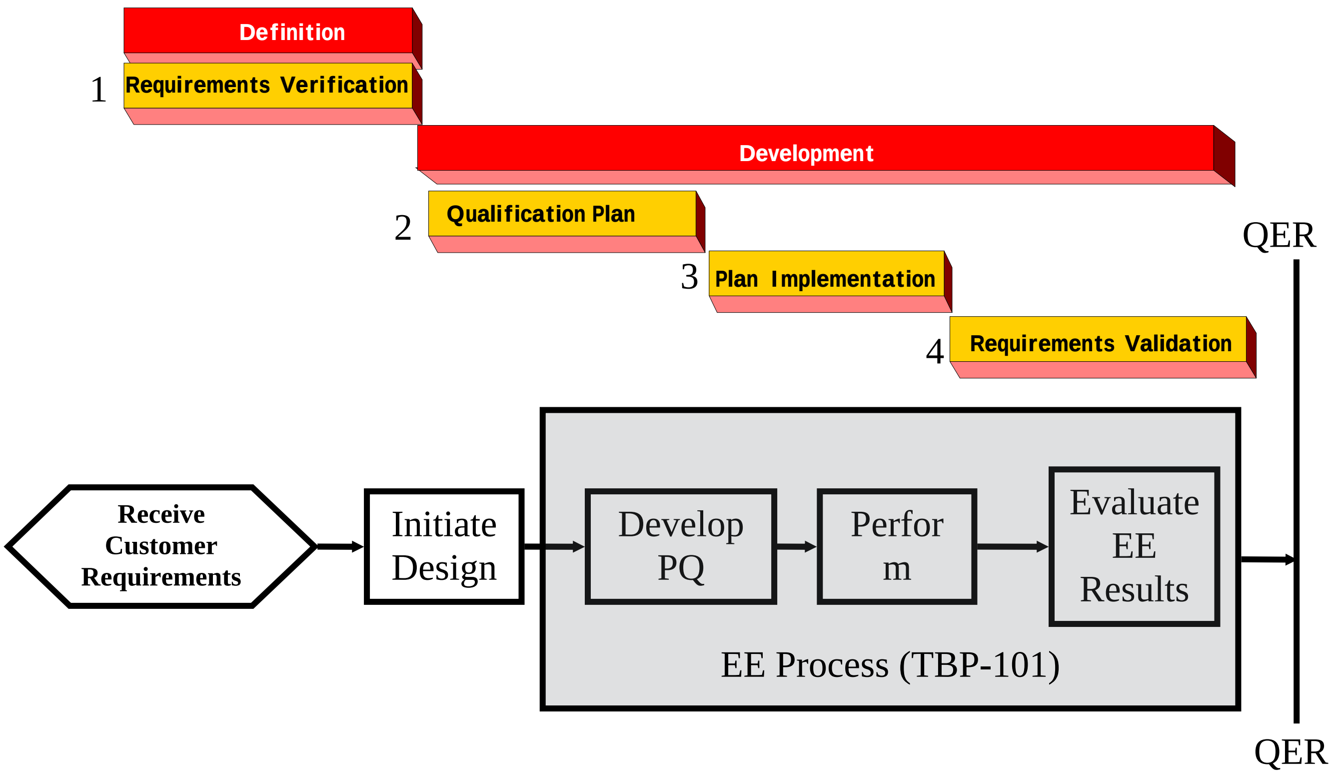

Figure 2: PRP Steps 1 & 2; Concurrent Qualification

2.2.2 TRLs and Qualification (TBP-100)

In this section we explicitly integrate the TRL concepts into concurrent qualification (TBP-100).

The four stages in concurrent qualification are 1) requirements verification; 2) qualification plan; 3) plan implementation; 4) requirements validation. All of these stages are shown with respect to the PRP in Figure 2. We integrated the use of TRL concepts directly into TBP-100 using the semantics and exact definitions provided therein. In the following 4 sections, *black text* refers to the original stage definition provided in TBP-100, *blue text* is text that was added to reflect the TRL concepts and requirements, *green text* is text that was slightly changed to enhance and increase the readability of the new TRL text in blue.

2.2.2.1 Requirements Verification

At the start of concurrent qualification, it is important for the customer/supplier to communicate in very clear terms. The relevant TRL concepts related to communication at this stage require that together the customer and supplier shall identify the following:

- Operational/environmental requirements
- Integration requirements
- Key elements and technology options
- Technology readiness level as an exit criteria for stage 4

The following text taken from TBP-100 is augmented in color as described earlier to reflect the above concepts.

"During stage 1, the customer requirements are obtained and the conceptual design is verified to meet identified customer requirements. Processes shall be in place to identify, document, validate, control and maintain customer requirements. Key elements, operational environments, and technologies used in the conceptual design as well as its integration within the customer's processes and or products shall be identified. Working with the customer, the PRT shall establish acceptable technology readiness levels for key elements and products to be delivered. As the product definition begins to evolve, it should be placed under configuration management. The product definition will continue to evolve through Stage 3. The attributes prescribed in TBP-PRP should be addressed and the rationale for excluding any attributes should be documented. Project plans, risk plans and budget/costs shall be documented and appropriately managed."

2.2.2.2 Qualification Plan

The next stage in concurrent qualification is to develop a qualification plan. To buttress the TRL concepts established in stage 1, the qualification plan must include:

- tests and procedures for establishing technology readiness levels

The following text taken from TBP-100 is augmented in color as described earlier to reflect the above concepts.

"During stage 2, the PRT develops and releases a qualification plan using the Engineering Evaluation Process described in TBP-101. The PRT also establishes methods for demonstrating that the project meets all stage 1 requirements. This includes verifying and identifying specific methods for demonstrating technology readiness levels of products delivered by the project. Measurable success criteria are established to determine when the PRT has successfully reached all goals and requirements established for the project. The qualification plan is updated as requirements are changed."

2.2.2.3 Plan Implementation

Given the qualification plan, the PRT implements the plan that must include:

- Establishing the technology readiness levels of products

The following text taken from TBP-100 is augmented in color as described earlier to reflect the above concepts.

"During stage 3, the PRT ensures that the planned qualification activities are conducted and completed using the Engineering Evaluation Process described in TBP-101. These activities shall be verified against the qualification plan and must include integration and operational assessments while concurrently exposed to identified environments. Overall technology readiness levels of products and processes to be delivered must be established. Quality evidence and performance verification data shall be collected and used to verify adequacy of planned qualification activities versus the acceptance criteria in the qualification plan. Documents (product definition and production work instructions) are recorded, by issue, at the time of the

quality evidence review. The requisite product definition for production is set at the end of Stage 3."

2.2.2.4 Requirements Validation

Once the qualification plan has been implemented, qualification is completed by validating that the requirements established in stage 1 have been satisfied. To reflect the TRL concepts this must include:

- validating the technology readiness levels of products and processes are in accordance with requirements defined in Stage 1

The following text taken from TBP-100 is augmented in color as described earlier to reflect the above concepts.

"During stage 4, the PRT ensures that the processes and/or the product yielded by these processes meet the customer requirements. The PRT ensures that the final outcome of the EE has satisfied the requirements verified in Stage 1 and validates with the customer the technology readiness levels established in Stage 3. The PRT validates that required data, quality evidence, and documentation are available and will be appropriately maintained in accordance with established record retention requirements. This documentation becomes part of the product realization report, which is a required part of the Product Realization Process per TBP-PRP. At this stage, the product realization process has achieved the requisite state of readiness and must be capable of producing Mark Quality material."

2.2.3 TRLs and the Product Realization Process (TBP-PRP)

In this section, we utilize the flow charts and definitions provided in Appendix B of TBP-PRP to integrate technology readiness levels into the PRP.

The PRP is documented through the use of four flow charts with each chart depicting the flow, process and concurrency within a step. As indicated in the previous sections on concurrent qualification, TRLs integrate most readily into the first two steps (definition, development) and we continue with this approach. The flow charts for steps 1 (definition) and 2 (development) are shown in Figure 3 and Figure 4 respectively.

Following the approach taken in TBP-PRP, each box in the flow chart is labeled alphabetically which can be used to cross reference with a list of expanded definitions, action items and semantics. Based upon our reading and judgment of Appendix B in TBP-PRP, we expand (add bullets) only those entries where TRL concepts are relevant. The integration concepts we propose here strongly depends upon our view and understanding of the flow charts as a whole.

In summary, our approach is to highlight boxes in the flow chart with red where we have added TRL concepts. We list the box subject headings including the list of bulleted items that the PRP associates with the box. Only boxes that are highlighted in red (see Figure 3 and Figure 4) are included here and we use *blue text* when we have added TRL concepts. *Black text* corresponds to existing text.

2.2.3.1 Definition

In this subsection, we integrate TRL concepts into the flow chart shown in Figure 3. Following the approach that we used for TBP-100, our aim for the definition step is for the customer and supplier to identify the following:

- Operational/environmental requirements
- Integration requirements
- Key elements and technology options
- Technology readiness level as an exit criteria for stage 4

There are two entries in Figure 3 that provide opportunities for integrating the above key ideas:

c. Identify Customer Requirements

- *Interact with customer to determine requirements that include: rigorous definitions of environments, key elements, and elements of integration*
- *Work with the customer to establish acceptable technology readiness levels for key elements and products to be delivered*

g. Feedback to customer

- *Review and verify environments, key elements and elements of integration with customer*

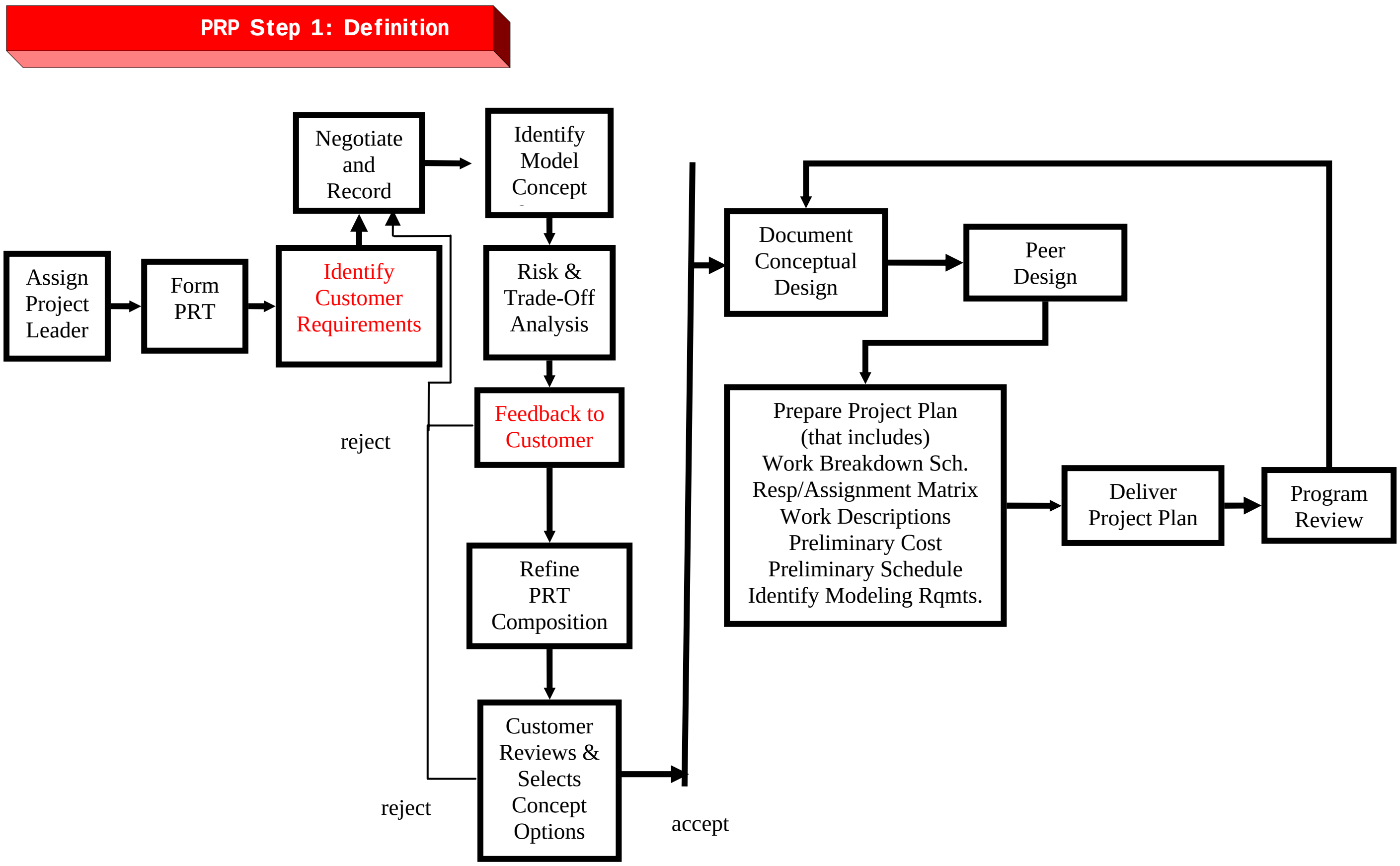

Figure 3: PRP – Step 1: Definition Flow Chart

2.2.3.2 Development

In this subsection, we integrate TRL concepts into the flow chart shown in Figure 4 for the development step of the PRP. Following the approach that we used for TBP-100, our goals for the development step are to:

- Develop test plans and procedures for establishing technology readiness levels of all products
- Establish technology readiness levels of products developed
- Validate with customer that technology readiness levels of products and processes are in accordance with requirements established during step 1(definition)

b. Conduct/Simulate Tests

- Develop test plans and procedures for establishing technology readiness levels of all products

d. Finalize Design

- Establish technology readiness levels of products

e. Qualify Final Design

- Validate with customer that technology readiness levels of products and processes are in accordance with requirements established during step 1(definition)

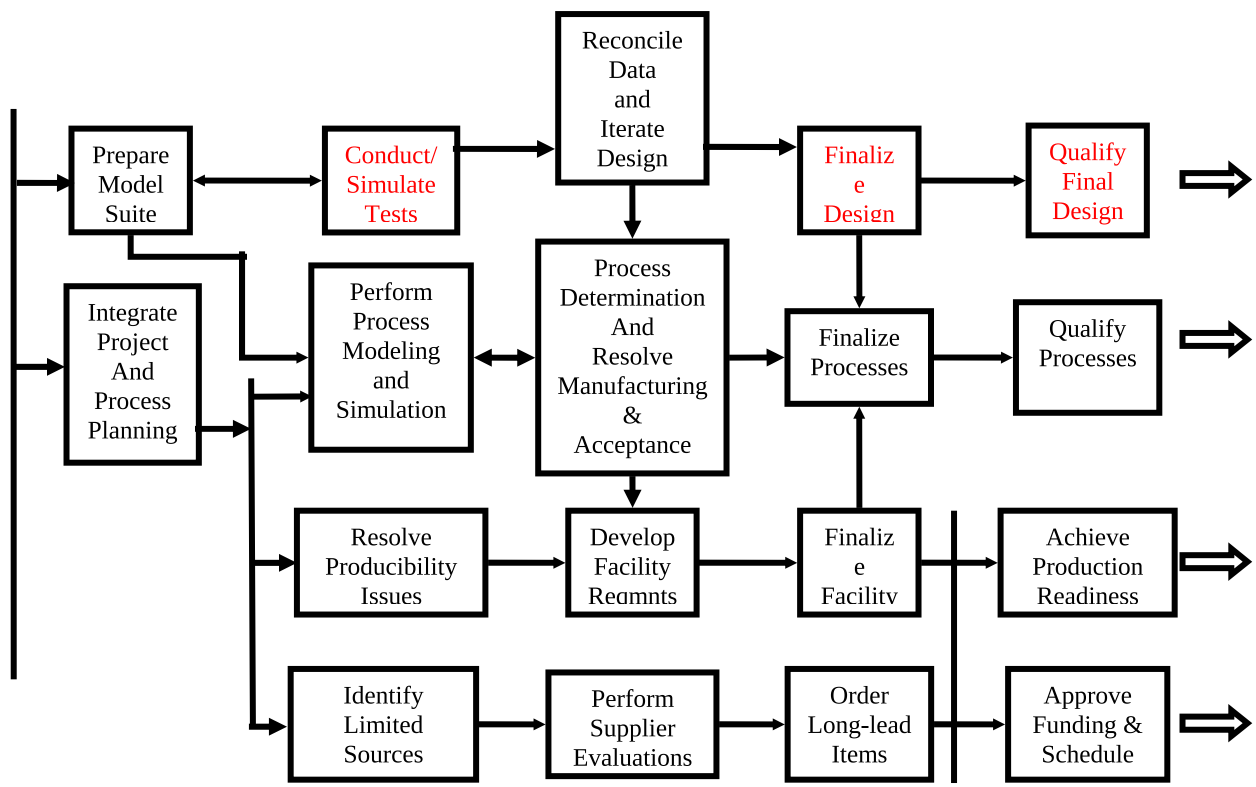

Figure 4: PRP – Step 2: Development Flow Chart

3. Conclusions

3.1 Summary

In this report, we have described technology readiness levels and proposed two approaches for incorporating them into the NW SMU through the TBPs. We have described the technical details for integrating TRL concepts into the product realization process and concurrent qualification, and have included examples of specific language for this approach.

3.2 Status and Path Forward

To successfully complete the integration that is proposed here, several additional activities should be undertaken. These include:

- Acceptance that TRL concepts be formally integrated into the TBPs. There is apparently a consensus on this within SNL at both the staff and executive management levels. A consensus throughout the NWC (nuclear weapons complex) and at NNSA must also exist (this may exist – the authors are simply unaware of work to integrate TRLs throughout the NWC and NNSA).
- Specific language and structure (such as that presented here) for incorporating TRLs into the TBPs must be agreed upon by working groups and committees that oversee the TBPs. In FY06, the NWC System Team worked to restructure the TBPs, offering an opportunity for integrating TRLs into the newly structured TBP system of documents. Using the present work as a starting point, Mark Dickinson (SNL Org. 00514) is working with the NWC System Team to get acceptable TRL language into the TBPs.
- Training/Education on TRL concepts and use must be widely available to laboratory staff. Most notable progress on this front is the TRL website which is available via the SNL IRN at: http://www-irn.sandia.gov/trl.

4. References

[1] TBP-100, “Concurrent Qualification,” Issue G, Sept. 16, 2005.

[2] TBP-PRP, “Product Realization Process,” Issue E, May 4, 2001.

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