# Manufacturing Readiness Level (MRL) Deskbook

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**Prepared by the**

**The Joint Service/Industry MRL Working Group**

**Chartered by the Joint Defense Manufacturing Technology Panel**

*This document is not a DoD directive and is being offered as a "best practice."*

*V2.2.2: This version has changes made to the Criteria Matrix in the appendix to agree with version 11.4 dated 15 December 2014.*

*V2.3: This version has adds changes from the 2014 Workshop to address the new DoD 5000.02 and user comments.*

*V2.4: This version has corrections in the Matrix to version 11.5.*

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*2020: Updated MRL Criteria Matrix to incorporate enhanced MRL 1-4 criteria (2020); updated Section 6, "Applying MRLs in Contract Language;" and Deskbook updates for clarity and current policy and guidance.*

*2022: Updated section 1 to current documents, Section 2 to reflect refined relationship of MRLs to TRLs, Section 3 to DoD AAF guidance, Section 6 to AS6500A, and addition of Cybersecurity appendix.*

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# Executive Summary

Manufacturing status and risk evaluations have been performed as part of defense acquisition programs for years in a variety of forms. These evaluations, while often highly structured and well managed, did not use a uniform metric to measure and communicate manufacturing risk and readiness.

Department of Defense Instruction (DoDI) 5000.88, *Engineering of Defense Systems*, states, "The production, quality, and manufacturing (PQM) lead, working for the [Program Manager (PM)], will ensure manufacturing, producibility, and quality risks are identified and managed throughout the program's life cycle."[1] This instruction establishes general maturity criteria for each life cycle phase leading to the production decision.

Assessments of manufacturing maturity utilizing the Manufacturing Readiness Level (MRL) criteria have been designed to identify and manage manufacturing risk in acquisition, decreasing the risk of technology transition for new technology to weapon system applications. MRL criteria and metrics create a measurement scale and vocabulary for assessing and discussing manufacturing maturity and risk. Using the MRL criteria and metrics, an MRL Assessment is a structured approach for evaluation of a manufacturing processes, procedures, and techniques for technology, components, items, assemblies, subsystems, and systems. A MRL Assessment, *aka* Manufacturing Readiness Assessment (MRA), is performed to:

- Define current level of manufacturing maturity
- Identify maturity shortfalls and associated risks and costs
- Provide the basis for management of manufacturing maturation and risk

This document provides "best practices" for conducting assessments of manufacturing maturity and risk using the MRL criteria. It is intended for those tasked with conducting MRL Assessments, as well as acquisition program managers, system engineers, manufacturing managers, and managers of technology development and pre-systems acquisition technology demonstration projects.

[1] DoDI 5000.88, *Engineering of Defense Systems,* November 18, 2020, Section 3.6.c.

# 1. Introduction

## 1.1 Manufacturing Risks Recognized in DoD Policy

Manufacturing status and technical risk evaluations have been performed as part of defense acquisition programs for years in a variety of forms (*e.g.*, Production Readiness Reviews, Manufacturing Management/Production Capability Reviews, etc.).[2] These reviews, while highly structured and well managed, did not use a uniform metric to measure and communicate manufacturing risk and readiness.

Studies by the Government Accountability Office (GAO) cite a lack of manufacturing knowledge and maturity at key decision points as a leading cause of acquisition program cost growth and schedule slippages in major DoD acquisition programs.[3] Consequently, DoD policy has been developed to strengthen the way in which manufacturing issues and risks are considered in the defense acquisition system.

There is long-standing law on manufacturing-related content of acquisition strategies. Defense Federal Acquisition Regulation Supplement (DFARS) Section 207.105, *Contents of Written Acquisition Plans*[4] mandates specific National Technology and Industrial Base (NTIB) considerations are included in acquisition strategies for Major Defense Acquisition Programs (MDAP) as follows:

- An analysis of capabilities of the NTIB to develop, produce, maintain, and support programs, including consideration of factors related to foreign dependency
- Consideration of requirements for efficient manufacture during the design and production of the systems to be procured under the program
- The use of advanced manufacturing technology, processes, and systems during the research and development phase and the production phase of the program
- To the maximum extent practicable, the use of contract solicitations that encourage competing offerors to acquire, for use in the performance of the contract, modern technology, production equipment, and production systems (including hardware and software) that increase the productivity and reduce the life cycle costs

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[2] Manufacturing risk is one element of overall technical risk to the program.

[3] *Defense Acquisitions: Assessment of Selected Weapon Programs* (GAO-19-336SP), Government Accountability Office, May 2019. Similar conclusions were made in prior GAO reports issued annually since 2004. These reports may be accessed at https://www.gao.gov/reports-testimonies.

[4] PGI 207.105, *Acquisition Plans*, Defense Federal Acquisition Regulation Supplement (DFARS), revised Jan 2021; https://www.acq.osd.mil/dpap/dars/pgi/pgi_htm/PGI207_1.htm#207.105

- Methods to encourage investment by U.S. domestic sources in advanced manufacturing technology production equipment and processes through:
  - Recognition of the contractor's investment in advanced manufacturing technology production equipment, processes, and organization of work systems that build on workers' skill and experience, and work force skill development in the development of the contract objective
  - Increased emphasis in source selection on the efficiency of production.

Additionally, Congress has put additional focus on managing manufacturing risk in Public Law by requiring MDAPs to "identify critical technologies and manufacturing processes that need to matured by Milestone A and that have not been successfully demonstrated in a relevant environment by Milestone B"[5]

The GAO found that DoD faces problems in manufacturing weapon systems — systems cost far more and take much longer to build than estimated. Billions of dollars in cost growth occur as programs transition from development to production, and unit cost increases are common after production begins. Contributing factors to these problems include the following: inattention to manufacturing during planning and design; poor supplier management; and a deficit in manufacturing knowledge among the acquisition workforce. Essentially, programs did not identify and resolve manufacturing risks early in development, but carried risks into production where they emerged as significant problems. The GAO has recommended DoD adopt the use of MRLs to help manage the manufacturing risk.[6]

DoDI 5000.88 reinforces the requirement to address manufacturing over the entire system life cycle. It requires the PQM Lead, working for the PM, to identify and manage manufacturing, producibility, and quality risks.[7] NOTE: See Section 2.3 for definitions for manufacturability and producibility.

By the end of the Technology Maturation Risk Reduction (TMRR) Phase, manufacturing and quality processes will be assessed and demonstrated to the extent needed to verify that risk has been reduced to an acceptable level.

During the Engineering and Manufacturing Development (EMD) Phase, the PQM lead will advise the PM on the maturity of critical manufacturing and quality processes to ensure they are affordable and executable. Prior to a production decision, the PQM lead will ensure that:

- Manufacturing, producibility, and quality risks are acceptable.

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[5] *National Defense Authorization Act for Fiscal Year 2017*, P.L. 114-328, 23 Dec 2016: § 807

[6] *Best Practices: DoD Can Achieve Better Outcomes by Standardizing the Way Manufacturing Risks Are Managed* (GAO-10-439), Government Accountability Office, Apr 2010

[7] DoDI 5000.88, *Engineering of Defense Systems*, Section 3.6c, Nov 2020

- Supplier qualifications are completed.
- Any applicable manufacturing processes are or will be under statistical process control.

## 1.2 Purpose and Organization of this Document

This document provides "best practices" for conducting assessments of manufacturing maturity and risk during the acquisition process using the MRL criteria. It is intended for those tasked with conducting MRL Assessments, as well as acquisition PMs, system engineers, manufacturing managers, and managers of technology development and pre-systems acquisition technology demonstration projects. This guidance is based on lessons learned, "best practices" in manufacturing, DoD policy, and real-life manufacturing experience of industry and government.

Use of MRL Assessments is recognized as a "best practice" to:

- Identify areas of risks, issues, and opportunities
- Minimize manufacturing risk in product development to transition effectively to production
- Provide earlier manufacturing input to the design and decision processes
- Allow maximum flexibility and tailorability in application by a diverse industry and contractor community developing and producing various products

The following sections of this document describe:

- Each of the MRLs in detail (Section 2)
- How manufacturing maturity and risk evolves throughout the acquisition process and is addressed in the Adaptive Acquisition Framework (Section 3)
- The process for conducting assessments using MRLs (Section 4)
- Manufacturing maturation plans and risk management (Section 5)
- Suggested contract language for implementing MRLs and relationship to AS6500A (Section 6)
- Users Guide for performing MRL Assessments (Section 7)
- Adaptation of MRL Assessments and criteria to specific situations (Section 8)
- MRL criteria and metrics by thread over the acquisition life cycle (Appendix A – MRL Criteria Matrix)
- Acronyms (Appendix B)

Additional information can be found at the DoD MRL website DoDMRL.org.

# 2. Manufacturing Readiness Levels

## 2.1 Overview of Manufacturing Readiness Levels

There are ten levels of MRL criteria that begin with pre-systems acquisition; progress through systems engineering reviews, acquisition decision points, and milestones; and culminate in production. Each of these levels is associated with the evolution of system maturity (*i.e.*, developmental state changes such as bread-board, brass-board, prototype, production configuration, Low Rate Initial Production (LRIP), Full Rate Production (FRP)).

- MRLs 1-4: Criteria address manufacturing maturity and risks beginning with pre-systems acquisition (MRLs 1-3); continue through the selection of a solution (MRL 4).
- MRLs 5-6: Manufacturing maturation of the needed technologies through early prototypes of components or subsystems/systems, culminating in a preliminary design.
- MRL 7: The criteria continue by providing metrics for an increased capability to produce systems, subsystems, or components in a production representative environment leading to a critical design review.
- MRL 8: The next level of criteria encompasses proving manufacturing process, procedure, and techniques on the designated "pilot line" (see Section 2.3).
- MRL 9: Once a decision is made to begin LRIP, the focus is on meeting both quality, throughput, and rate to enable transition to FRP.
- MRL 10: The final MRL measures aspects of lean practices and continuous improvement for systems in production.

The basic goal of all acquisition programs is to put required capability in the field in a timely manner with acceptable affordability and supportability. To be successful, the two key risk areas of critical technologies[8] being assessed, and immature manufacturing capability, including the supply chain, must be identified, mitigated, and managed effectively.

[8] *Technology Readiness Assessment Guide* (GAO-20-48G), Government Accountability Office, 11 Feb 2020, pg 47: "A technology element is considered a critical technology if it is new or novel, or used in a new or novel way, and it is needed for a system to meet its operational performance requirements within defined cost and schedule parameters."

Understanding and mitigating these risks will greatly increase the probability of successful technology insertion by the development community. This will ultimately aid the program success through improvements in cost, schedule, and performance. Manufacturing readiness metrics will help acquisition PMs mitigate these risks. Manufacturing readiness metrics are also important to technology development managers because they can be used to measure and demonstrate maturity of technology that acquisition PMs will find credible.

## 2.2 Manufacturing Readiness Levels Defined

***Although the MRLs are numbered, the numbers represent a target used to focus the team on the potential risks associated with reaching program goals***. Using numbers is simply a convenient designation. The numbers are a non-linear ordinal scale that identifies what the manufacturing maturity should be as a function of where a program is in the acquisition life cycle (as described in Section 3). The following descriptive paragraphs provide only a short summary of the criteria and metrics for each level. The full criteria and metrics are detailed in the MRL Criteria Matrix shown in Appendix A and available at DoDMRL.org.

| MRL | Description |
|---|---|
| 1 | Basic Manufacturing Implications Identified |
| 2 | Manufacturing Concepts Identified |
| 3 | Manufacturing Proof of Concept Developed |
| 4 | Capability to produce the technology prototype components in a laboratory environment |
| 5 | Capability to produce prototype components in a production relevant environment |
| 6 | Capability to produce a prototype system or subsystem in a production relevant environment |
| 7 | Capability to produce systems, subsystems, or components in a production representative environment |
| 8 | Pilot line capability demonstrated; ready to begin LRIP |
| 9 | Low rate production demonstrated; Capability in place to begin FRP |
| 10 | Full Rate Production demonstrated and lean production practices in place |

**Figure 2-1 – MRL Summaries**

### MRL 1: Basic Manufacturing Implications Identified

This is the initial level of criteria for assessing manufacturing readiness. The focus is manufacturing capability and begins in the form of studies. Criteria include identification

and investigation of global trends in the industrial and supply base, manufacturing science, material availability, supply chain, and metrology.

**MRL 2: Manufacturing Concepts Identified**

This level of criteria for assessing manufacturing readiness is characterized by identification of manufacturing concepts. Typically, this includes identification and broad-based studies that address analysis of material and process approaches, material effects and availability, potential supply chains, needed workforce skillsets, and potential future investments, etc. Potential manufacturing and quality future requirements are identified and analyzed. An understanding of manufacturing feasibility and risk is emerging.

**MRL 3: Manufacturing Proof of Concept Developed**

This level of criteria for assessing manufacturing begins with the analysis and evaluation of the producibility and manufacturability of the proposed system concepts through analytical modeling and simulations and/or laboratory experiments. System concepts comparative cost models, analyses, and budgets are identified. Manufacturing and quality requirements for proposed system concepts are identified and analyzed, including initial quality risks and issues, facility capabilities and capacity, and initial materials planning. This level of readiness is typical of technologies in Applied Research and Advanced Technology Development. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality.

**MRL 4: Capability to produce prototype components in a laboratory environment**

This level of manufacturing maturity is an exit criterion for the Materiel Solution Analysis (MSA) Phase approaching a Milestone A decision. Manufacturing and quality risks have been identified and included in the Analysis of Alternatives (AoA). These risks lead to building prototypes and documented mitigation plans. At this point, required investments such as capital, manufacturing technology development, and risk mitigation have been identified. Process variables, manufacturing, materials, and special requirement cost drivers have been identified, and cost driver uncertainty has been quantified. Initial producibility assessments of preferred material solution completed. Initial Key Performance Parameters (KPP) have been identified as well as any requirements for special tooling, special handling, manufacturing skill sets, and workforce requirements and availability of facilities.

**MRL 5: Capability to produce prototype components in a production relevant environment**

This level of manufacturing maturity is typical of the mid-point in the TMRR Phase of acquisition. The industrial base assessment should have been initiated to identify potential manufacturing sources. The manufacturing strategy developed for Milestone A's Acquisition Strategy (AS) has been refined with the technology maturation contractor and integrated into the Risk Management Plan. Identification of

enabling/critical technologies and components is complete. With release of product data required for prototype component manufacturing, evaluation of the design to determine Key Characteristics (KC) has been initiated. Prototype materials have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts, as well as producibility assessments of key technologies and components have been initiated.

**MRL 6: Capability to produce a prototype system or subsystem in a production relevant environment**

This level of manufacturing maturity is associated with readiness for a Milestone B decision to initiate an acquisition program by entering into the Engineering and Manufacturing Development (EMD) Phase of acquisition. It is normally seen as the level of manufacturing readiness that denotes acceptance of a preliminary system design. An initial manufacturing approach has been developed. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes in the system itself. However, preliminary design has been completed and producibility assessments and trade studies of key technologies and components are complete. Manufacturing processes and manufacturing technology solutions, materials, tooling and test equipment, as well as personnel skills have been demonstrated on components, subsystems, and/or systems in a production relevant environment. Cost, yield, and rate analyses have been performed to assess how prototype data compare to target objectives, and the program has developed appropriate risk reduction strategies to achieve cost requirements. Producibility trade studies and producibility considerations have shaped system development plans. Industrial capabilities assessment for Milestone B has been completed. Long-lead and key supply chain elements have been identified.

**MRL 7: Capability to produce systems, subsystems, or components in a production representative environment**

This level of manufacturing maturity is typical for the completion of system detailed design activity in the EMD Phase leading to the Critical Design Review (CDR). System detailed design activity is nearing completion. Material specifications have been approved and materials are available to meet the planned pilot line build schedule. Manufacturing processes and procedures have been demonstrated in a production representative environment. Detailed producibility trade studies are completed and producibility enhancements and risk assessments are underway. The cost model has been updated with detailed designs produced in a production relevant environment, rolled up to system level, and tracked against allocated targets. Unit cost reduction efforts have been prioritized and are underway. Yield and rate analyses have been updated with production representative data. The supply chain and supplier quality assurance have been assessed and long-lead procurement plans are in place.

Manufacturing plans and quality targets have been developed. Production tooling and test equipment design and development efforts are initiated and validation plans for Special Test Equipment/ Special Inspection Equipment (STE/SIE) are complete.

**MRL 8: Pilot line capability demonstrated; ready to begin Low-Rate Initial Production (LRIP)**

This maturity level is associated with manufacturing readiness for a Milestone C decision, and entry into LRIP. Detailed system design is sufficiently stable to enter low-rate production. All materials, manpower, tooling, test equipment, and facilities are proven on the pilot line and are available to meet the planned low-rate production schedule. STE/SIE has been validated as part of pilot line validation in accordance with validation plans. Manufacturing and quality processes and procedures have been proven on a pilot line and are under control and ready for low-rate production. Known producibility risks and issues pose no significant challenges for low-rate production. Cost model and yield and rate analyses have been updated with pilot line results. Supplier qualification testing and first article inspections have been completed. The industrial base has been assessed for Milestone C and shows industrial capability is established to support LRIP.

**MRL 9: Low-rate production demonstrated; Capability in place to begin Full Rate Production (FRP)**

At this level, the system, component, or item is in production, or has successfully achieved low-rate production. This level of readiness is normally associated with readiness for entry into FRP. All systems engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in operational test and evaluation. Materials, parts, manpower, tooling, test equipment, and facilities are available to meet planned rate production schedules. STE/SIE validation maintained and revalidated as necessary. Manufacturing process capability in a low-rate production environment is at an appropriate quality level to meet KC tolerances. Risks and issues managed with monitoring ongoing. LRIP cost targets have been met, and learning curves have been analyzed with actual data. The cost model has been updated for FRP and reflects the impact of continuous improvement.

**MRL 10: Full Rate Production demonstrated and lean production practices in place**

This is the highest level of manufacturing maturity. This level of manufacturing is normally associated with the “Production & Deployment” or “Operations & Support” phases of the acquisition life cycle. Engineering/design changes are few and generally limited to continuous improvement changes or obsolescence issues. System, components, and items are in full rate production and meet all engineering, performance, quality, and reliability requirements. Manufacturing process capability is at the appropriate quality level. All materials, tooling, inspection and test equipment,

facilities and manpower are in place and have met full rate production requirements. STE/SIE validation maintained and revalidated as necessary. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Continuous process improvements are ongoing.

## 2.3 Definition of Environments and Other Terms

As manufacturing maturity increases, demonstration of manufacturing capabilities should be accomplished in increasingly realistic manufacturing environments. Prior to Milestone A, the MRL criteria focus on manufacturing feasibility by identifying manufacturability and producibility of the proposed concepts and reducing the production risk. These proposed concepts are generally demonstrated in a laboratory environment.

> ***Laboratory Environment*** *– an environment where scientists, design engineers, manufacturing engineers, quality engineers, and production personnel develop and test processes, procedure, and equipment for making a product.*

The results from the laboratory environment should be used to assess:

- Producibility and manufacturability
- Testing of new equipment
- Testing of processes and procedures
- Initial manufacturing process quality data
- Initial manufacturing process rate data
- New workforce skill requirements

During TMRR prior to Milestone B, the MRL criteria focus on a capability to produce prototypes outside the lab in a production relevant environment. The parameters defining a production relevant environment should be based on the risks and uniqueness associated with demonstrating that manufacturing processes, procedures, and techniques meet program requirements. Production realism for this environment is well beyond what is seen in the laboratory. An emphasis should be placed on addressing higher risk areas (*e.g.*, more advanced manufacturing technologies and newer manufacturing capabilities).

> ***Production Relevant Environment*** *– An environment with some shop floor production realism present (e.g., facilities, personnel, tooling, processes, materials, etc.). There should be minimum reliance on laboratory resources during this phase. Demonstration in a production relevant environment implies that contractor(s) must demonstrate their ability to meet the cost, schedule, and performance requirements of the EMD Phase based on their production of prototypes. The demonstration must provide the program with confidence that these targets will be achieved, but does not require a production line. Furthermore, there must be an indication of how the program intends*

*to achieve the requirements in production representative and pilot environments.*

Demonstration of manufacturing capability in a production relevant environment provides a better understanding of the EMD Phase manufacturing risk of the program meeting cost, schedule, and performance requirements.

As a program enters into the EMD phase and hardware is built for qualification testing, the manufacturing processes should become more robust and mature to address production representative activities on the whole program.

***Production Representative Environment*** *– An environment that has as much production realism as possible, considering the maturity of the design. Production personnel, equipment, processes, and materials that will be present on the pilot line should be to the maximum extent possible. The work instructions and tooling should be of high quality, and the only changes anticipated on these items are associated with design changes downstream that address performance or production rate issues. There should be no reliance on a laboratory environment or personnel.*

The final stage of EMD is producing products that look and operate like they are production units from LRIP. These units need to be built on a pilot production line to adequately demonstrate the ability to migrate from EMD to LRIP. Without this realism, it would be very difficult to obtain confidence that the production processes will be able to meet cost, schedule, and performance requirements for production.

***Pilot Line*** *– An environment that incorporates all of the key production realism elements (e.g., equipment, personnel skill levels, facilities, materials, components, work instructions, processes, tooling, temperature, cleanliness, lighting etc.) required to manufacture production configuration items, subsystems or systems that meet design requirements in low-rate production. To the maximum extent practical, the pilot line should utilize full rate production processes.*

***Production Line*** *– An environment that incorporates all capabilities required to manufacture production configuration items, subsystems, or systems that meet design requirements utilizing manufacturing processes and procedures that are under control and capable of meeting required rates and quantities.*

The definitions of production relevant, production representative, pilot line, and production line environments are intended to demonstrate the natural progression of manufacturing maturity throughout the acquisition life cycle. The program office and contractor must reach agreement on the detailed production realism content for each definition above. This agreement must be based on the specific situation and its associated manufacturing risk in order to mitigate that risk in a timely and thorough manner.

Two other definitions are germane to this discussion:

***Manufacturability****—The characteristics considered in the design cycle that focus on process capabilities, machine or facility flexibility, and the overall ability to consistently produce at the required level of cost and quality. Associated activities may include some or all of the following:*

- Design for commonality and standardization—uses fewer parts
- Design for environmental and safety compliance
- Design for multi-use and dual-use applications
- Design for modularity and plug-compatible interface/integration
- Design for flexibility/adaptability or use "robust design"
- Utilize reliable processes and materials
- Utilize monolithic and determinant assembly
- Design for manufacturing and assembly
- Achieve production yield

***Producibility****—The relative ease of producing an item that meets engineering, quality, and affordability requirements. Associated activities may include some of the following:*

- Design for specific process capability and control parameters
- Perform material characterization analysis
- Perform variable reduction analysis, *e.g.*, Taguchi and design of experiments
- Develop critical materials and processes before selecting product design
- Utilize modeling and simulation for product and process design tradeoffs
- Design and development of closed-loop process control on critical items

## 2.4 MRL Threads and Sub-Threads

Successful manufacturing has many dimensions. MRL threads have been defined to organize these dimensions into nine manufacturing risk areas. The threads are as follows:

- **Technology and Industrial Base:** Requires an analysis of the capability of the National Technology Industrial Base to support the design, development, production, operation, uninterrupted maintenance support of the system and eventual disposal (*i.e.*, for environmental impacts).
- **Design:** Requires an understanding of the producibility, maturity, and stability of the evolving system design, identification, and control of KCs, and any related impact on manufacturing readiness.
- **Cost and Funding:** Requires an analysis of the adequacy of funding to achieve target manufacturing maturity levels. Examines the risks associated with reaching manufacturing cost targets.

- **Materials:** Requires an analysis of the risks associated with materials (including basic/raw materials, components, semi-finished parts, and subassemblies).
- **Process Capability and Control:** Requires an analysis of the risks that the manufacturing processes are able to reflect the design intent (repeatability and affordability) of KCs.
- **Quality:** Requires an analysis of the risks and management efforts to control quality, and foster continuous improvement.
- **Manufacturing Workforce (Engineering & Production):** Requires an assessment of the required skills, availability, and number of personnel to support the manufacturing effort.
- **Facilities:** Requires an analysis of the capabilities and capacity of key manufacturing facilities (*e.g.*, prime, subcontractor, supplier, vendor, and maintenance/repair).
- **Manufacturing Management:** Requires an analysis of the orchestration of all elements needed to translate the design into an integrated and fielded system (meeting Program goals for affordability and availability).

Many of the MRL threads have been decomposed into sub-threads. This enables a more detailed understanding of manufacturing readiness and risk, thereby ensuring continuity in maturing manufacturing from one level to the next. These include:

- Technology and Industrial Base includes **Industrial Base** issues and **Manufacturing Technology Development**
- Design includes **Producibility Program** and **Design Maturity**
- Cost and Funding includes **Production Cost Knowledge (cost modeling), Cost Analysis, and Manufacturing Investment Budget**
- Materials includes **Maturity, Availability, Supply Chain Management, and Special Handling** (*i.e.*, Government Furnished Program (GFP); shelf life; security; hazardous materials; storage environment; Environmental, Safety, and Health (ESH); etc.)
- Process Capability and Control includes **Modeling & Simulation** (product and process), **Manufacturing Process Maturity,** and **Process Yields and Rates**
- Quality includes **Quality Management, Product Quality, and Supplier Quality/Management**
- Manufacturing Management includes **Manufacturing Planning & Scheduling**, **Materials Planning**, **Manufacturing Operational Technology Cybersecurity**, and tooling/special test and inspection equipment

The MRL Criteria Matrix shown in Appendix A provides detailed criteria for each of the ten MRLs, by thread and sub-thread, throughout the acquisition life cycle. The matrix allows a user to separately trace and understand the maturation progress of each of the threads and sub-threads as readiness levels increase from MRL 1 though MRL 10.

These thread and sub-thread MRL criteria should be applied when appropriate to the situation and may be tailored to a particular technology or application.

As stated earlier, the MRL number is simply a convenience referring to the MRL criteria used by the MRL Assessment. The degree of maturity for the program element being assessed is what is important and should address the following two questions:

1. Has the program element met the appropriate manufacturing maturity; and
2. If not, what has to be accomplished to meet the metric?

This information is determined in the assessment process using the MRL Criteria Matrix, not by assigning a number to the element being assessed.

## 2.5 The MRL and TRL Relationship

PMs and Milestone Decision Authorities (MDA) should consider manufacturing-related concerns during technology development, especially for new and novel technologies that impact system-level performance characteristics. This need to consider Technology Readiness Levels (TRL) within the MRL construct has forged the basis of *Moving Manufacturing Left* in policy and practitioner circles. The TRL process has been used for many years as the maturation measurement approach for all DoD programs in tracking technology development and transition into production and fielding. MRL practitioners should understand the interplay between TRLs/MRLs when advising PMs/MDAs of manufacturing risk.

The nine hardware TRLs are:

# 2. Manufacturing Readiness Levels

| TRL | Definition | Description |
|---|---|---|
| 1 | Basic principles observed and reported | Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties. |
| 2 | Technology concept and/or applications formulated | Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies. |
| 3 | Analytical and experimental function and/or characteristic proof of concept | Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. |
| 4 | Component and/or breadboard validation in a laboratory environment | Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory. |
| 5 | Component and/or breadboard validation in a relevant environment | Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components. |
| 6 | System/subsystem model or prototype demonstration in a relevant environment | Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment. |
| 7 | System prototype demonstrated in an operational environment | Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring the demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space. |
| 8 | Actual system completed and qualified through test and demonstration | Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of the true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications. |
| 9 | Actual system proven through successful mission operations | Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluations (OT&E). Examples include using the system under operational conditions. |

**Figure 2-2 – TRLs and Descriptions**

Figure 2-3 depicts the notional relationship in the context of the acquisition pathway presented below.

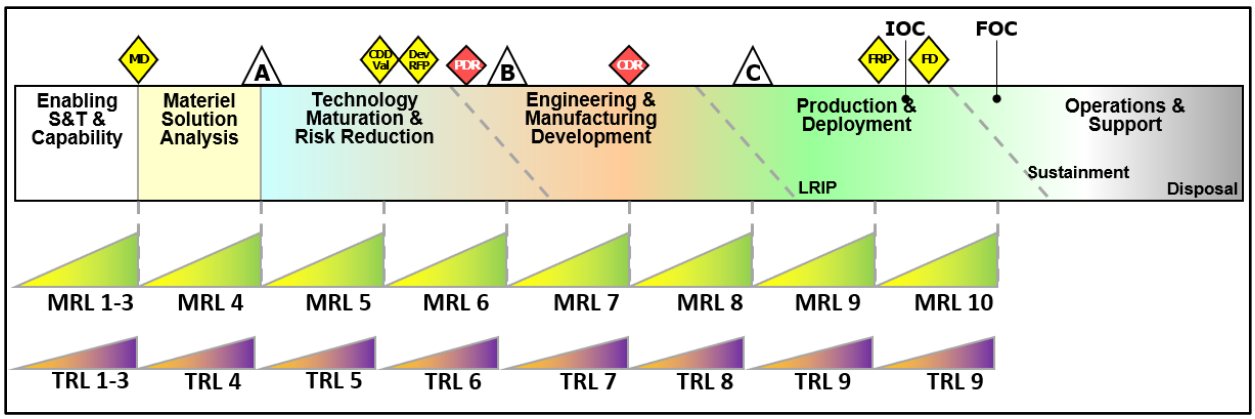



**Figure 2-3 – MRLs and TRLs in the Major Capability Acquisition Pathway**

MRLs define manufacturing maturity and risk based on the current phase of technology development. DoDI 5000.02, *Operation of the Adaptive Acquisition Framework* defines the role and frequency of evaluation of technical and manufacturing risk throughout the acquisition life cycle. As such, MRLs and TRLs are both key metrics used to assess the program's level of risk in meeting performance (*i.e.,* TRLs) and production (*i.e.,* MRLs) objectives. As MRL Assessments evaluate manufacturing risk, TRL assessments provide design maturity and aid in identifying new/unique/critical processes requiring further manufacturing development. Evaluating technical risk (*e.g.,* through Independent Technical Risk Assessments (ITRA)) provides evidence for the TRL determination within MRL Assessments.

Due to this interrelationship, the MRL criteria were designed to include an advised level of technology readiness to encourage manufacturing personnel to work closely with the technologist. NOTE: While there is a general relationship between MRLs and TRLs, there is no direct "one-to-one" requirement. While programs under the Major Capability Acquisition pathway generally have longer development life cycles, Urgent Capability or Middle Tier of Acquisitions have tighter timelines where design and manufacturing concerns have a greater impact on programmatic risk.

### 2.5.1 Best Practices for Assessing New or Novel Technologies

PMs/MDAs assess technological maturity, cost, schedule, and performance risks associated with delivering capability to the warfighter. The core of both TRLs and MRLs is demonstrating performance and manufacturability in increasingly relevant environments, respectively. Therefore, PMs balance risk between design stability and technological advancement, especially during the early acquisition phases.[9] Programs

[9] GAO-10-439: "An analysis of DoD's technical reviews that assesses how programs are progressing show that MRLs address many gaps in core manufacturing-related areas, particularly during the early acquisition phases."

with higher TRLs that haven't considered manufacturability or later-stage programs with higher MRLs but unstable designs may have higher programmatic risk overall. Best practice has shown that programs are more likely to be successful when manufacturing design and producibility concerns are considered early within technology development to allow manufacturing maturity to be paced by technology maturity. Otherwise, manufacturing processes will not be able to mature without increased risk.[10]

As stated earlier, Critical Technologies (CT) are defined as technologies that are "new and novel or used in a new and novel way and impact system performance." [11] PMs may accelerate technological development to correspond with the appropriate acquisition strategy and must evaluate programmatic risks to better understand the impact on achieving the program's overall cost, schedule, and performance objectives. Identifying gaps to achieve higher TRLs for CTs earlier in development allows the PM to effectively plan development strategies to reduce risk and is a "best practice" for achieving better cost and schedule outcomes. NOTE**:** This does not require being at a higher-level TRL; but suggests an objective "look forward" to ensure that the necessary resources, time, and funding are available for transition to the next appropriate phase.

Although technology may be inserted at any phase of the acquisition framework, many CTs are developed in S&T (or R&D) environments. Additionally, early system developers are the least likely to consider manufacturing concerns based on historical reviews of programs. So, early technology development up to MRL 4 is a prime concern for MRL practitioners as product technology may have been developed and demonstrated in S&T as an actual system prototype within an operational mission environment. Design for manufacturability and "forward-looking" assessments seek to minimize programmatic risk early-on.

At Milestone B, 10 USC 2366B requires the MDA to certify that the technology in the program has been demonstrated in a relevant environment (TRL 6) on the basis of an independent review and assessment. USD(R&E) has authority and responsibility for ITRAs, retaining Acquisition Category (ACAT) ID review and determining ITRA approval responsibility for ACAT IB/IC programs which may lie with a Service or Component. During preparation for Milestone B, the program will be assessed against MRL 6 criteria; however, PMs should review MRL 7 criteria to identify any potential gaps and develop strategies in preparation of CDR. Transition from MRL 6 to MRL 7 is a significant step requiring a high level of technical and manufacturing advancement. Inadequate considerations for design stability may result in manufacturing inferior products at scale that don't meet warfighter needs or lack of flexibility in manufacturing

[10] GAO-20-48G, pg 122.
[11] *Ibid,* pg 47.

processes for critical technologies that may result increased cost or schedule delays that impact programmatic risk.

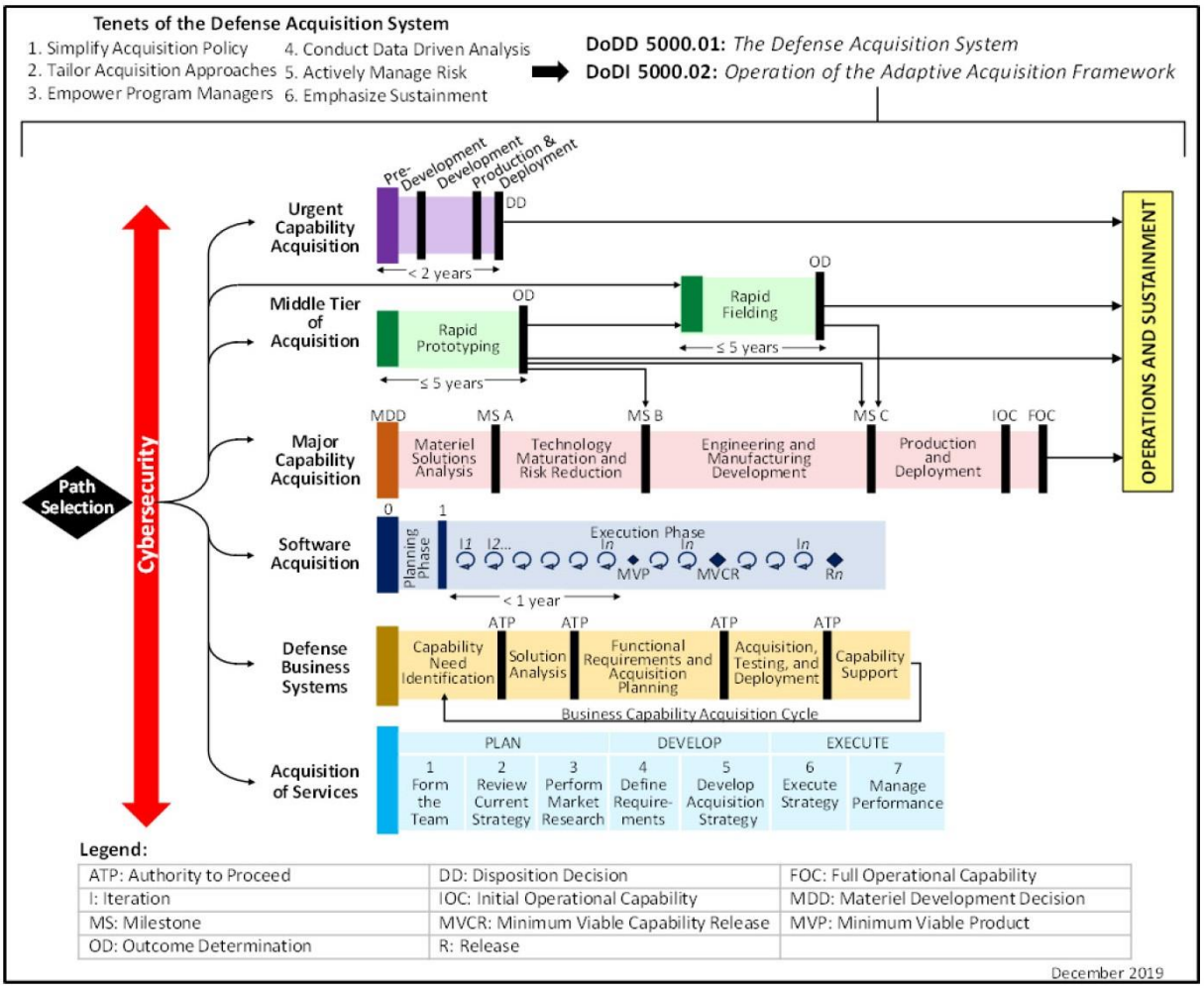
For Urgent Capability and Middle-Tier of Acquisitions pathways, higher TRLs and MRLs are required to meet rapid fielding requirements. CTs which have matured to TRL 5 (or beyond) by the Materiel Development Decision (MDD) become the “reasonable risk” candidates for consideration in the AoA during the Materiel Solution Analysis (MSA) Phase. However, if manufacturing readiness has not been considered appropriately at this level, the potential risk for re-design delays can impact cost or schedule negatively. Since the MDA is required to determine with a *high degree of confidence* that technology development during TMRR will not delay the fielding target of the program, PMs should evaluate CTs against MRL 4 criteria and analyze the technology development’s ability reach TRL 6 by Milestone B as a “best practice”.

As a manufacturing risk assessor, understanding the interplay between design for manufacturability concerns throughout the life cycle and advocating manufacturing risk is key to providing the best support to PMs/MDAs. Many MRL practitioners not only analyze and identify risk, they are critical to developing mitigation and maturation planning strategies.

# 3. MRLs in the Adaptive Acquisition Framework

## 3.1 Introduction

The Adaptive Acquisition Framework (AAF) was developed for Defense Acquisition with the objective of delivering timely, effective, suitable, survivable, sustainable, and affordable solutions to the end user. To achieve those objectives, Milestone Decision Authorities (MDA), other Decision Authorities (DA), and PMs have broad authority to plan and manage their programs consistent with sound business practice. The AAF acquisition pathways provide opportunities for MDAs/DAs and PMs to develop acquisition strategies and employ acquisition processes that match the characteristics of the capability being acquired.[12]




[12] DoDI 5000.02, Section 1, *Operation of the Adaptive Acquisition Framework*

**Figure 3-1 – Adaptive Acquisition Framework**

DoDI 5000.02, *Operation of the Adaptive Acquisition Framework*, has established multiple acquisition approaches with distinct, associated instructions:

- *Major Capability Acquisition* (DoDI 5000.85)
- *Middle Tier of Acquisition* (DoDI 5000.80)
  - Rapid Prototyping and Rapid Fielding procedures
- *Urgent Capability Acquisition* (DoDI 5000.81)
- *Business Systems* (DoDI 5000.75)
- *Defense Acquisition of Services* (DoDI 5000.74)

In general, MRL Assessments are not required for *Business Systems* or *Defense Acquisition of Services,* but are considered "best practice" for Major Capability Acquisition, Middle Tier of Acquisition and Urgent Capability Acquisitions pathways. Manufacturing risk management plays an integral part in the acquisition of all weapon systems throughout their entire life cycle. DoDI 5000.88, *Engineering of Defense Systems* requires both Systems Engineering reviews and Independent Technical Risk Assessments (ITRA). As defined in the DoD ITRA Framework, MRL Assessments can be used as a "best practice" to inform the ITRA.[13] MRL Assessments may need to be adapted based on the program acquisition pathway (similar to MRL adaptations in Section 8).

The following sections address MRL Assessments for Major Capability Acquisition, Middle Tier of Acquisition, and Urgent Capability Acquisition.

## 3.2 MRLs for Major Capability Acquisition Prior to the Materiel Development Decision

### 3.2.1 Introduction

The MRL Criteria Matrix, Deskbook and Users Guide provide detailed guidance for application of MRLs in traditional DoD major systems acquisition. These criteria show a progression of manufacturing maturity as the program progresses through the acquisition lifecycle.

The Materiel Development Decision (MDD) is the mandatory entry point into the Major Capability Acquisition process.[14] It ends with the MDD decision to initiate a program of

[13] "Department of Defense Independent Technical Risk Assessment Framework for Risk Categorization," Under Secretary of Defense for Research and Engineering, June 2018, pg 1

[14] DoDI 5000.85, Section 3.5

record [15] that is based upon the transition of mature technologies with manageable risk. Technology developed in Science and Technology (S&T) programs, procured from industry, or other sources entering the development process at Milestone A should be assessed as mature enough to transition smoothly (*i.e.*, meet cost, schedule and performance requirements) into designs.

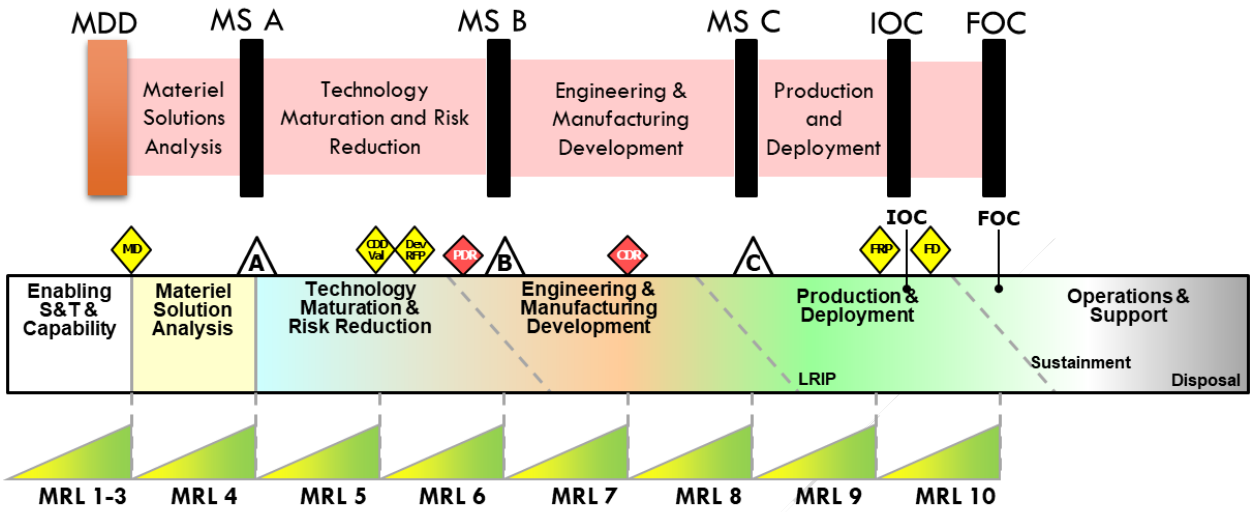



**Figure 3-2 – MRLs in Major Capability Acquisition**

Consideration of manufacturing risk and issues should begin early and intensify as product development proceeds so that manufacturing maturity is sufficient to support rapid and affordable development into a system. Some manufacturing-related "best practices" for development are:

- Include manufacturing Subject Matter Experts (SME) in all Systems Engineering technical reviews
- Perform an initial assessment in each phase to determine maturity based on the MRL criteria
- Identify the target MRLs
- Use the results of the initial assessment to set priorities and develop a Manufacturing Maturation Plan (MMP) that will achieve the target MRL or minimize risk to an acceptable level within schedule
- Fund and execute to enable achieving the target MRL, or mitigate risks to an acceptable level within budget
- Perform a final assessment of manufacturing readiness to identify all manufacturing risks prior to transitioning into the next phase

[15] Program of record: An acquisition program that has been formally initiated by the Milestone Decision Authority and has been fully funded throughout the Future Years Defense Program.

Figure 3.3 below shows the relationship between MRLs, program phases, System Engineering reviews, activities, decision points, and milestones.

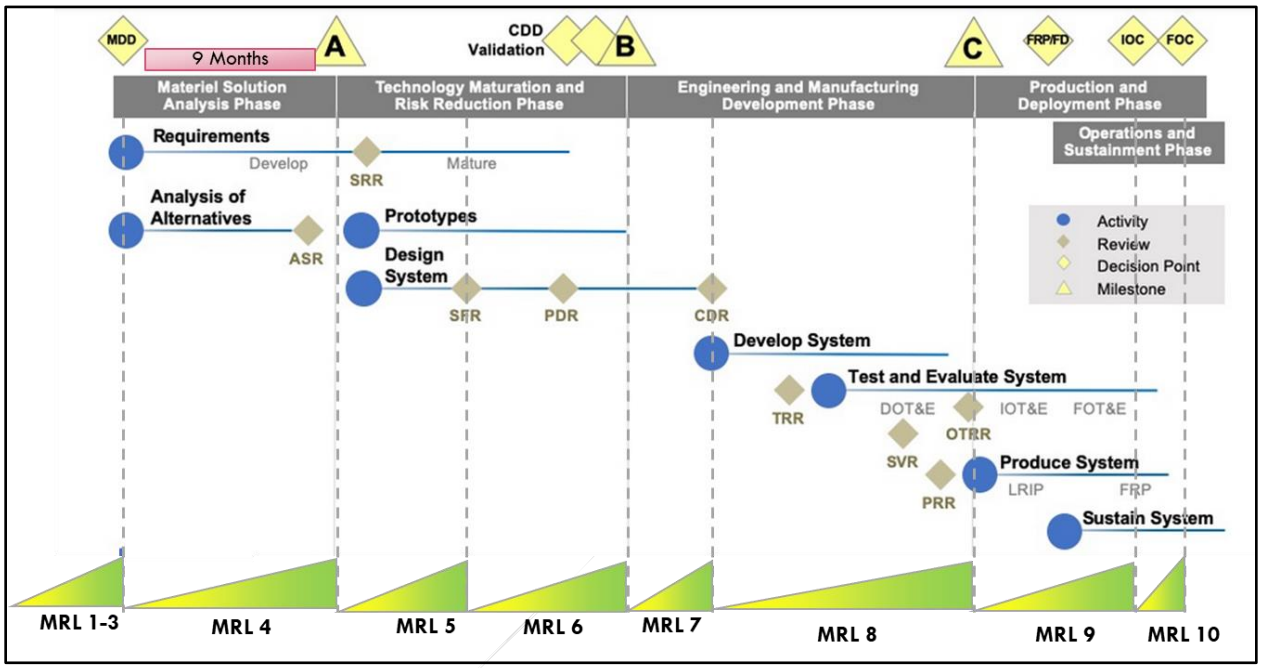



**Figure 3-3 – Major Capability Acquisition Details**

### 3.2.2 Materiel Solution Analysis (MSA) Phase

The MDD marks the start of the MSA Phase. This presents the first substantial opportunity to influence systems design by balancing technology opportunities, schedule constraints, funding availability, system performance parameters, and manufacturing feasibility. The technical approach for system development should be driven by knowledge of the manufacturing maturity and risk of the various technologies under consideration as well as their associated performance maturity.

In this phase, the viable alternative is selected by conducting an AoA with the goal of identifying the most promising option(s) that satisfy the capability need through a comparison of the operational effectiveness, suitability, and life cycle cost of alternatives. Manufacturing SMEs should participate in the AoA. MRL Assessments (MRL 4) should be conducted as a for each competing materiel solution being examined in the AoA. Special emphasis should be given to the proposed materiel solution to analyze manufacturing feasibility and determine manufacturing resources needed.

Sources of data may include plans and roadmaps for technology and mission, market research, and evaluations of technology maturity.

The Alternative Systems Review (ASR) may be conducted during MSA near the end of the AoA process. It ensures the one or more proposed materiel solution(s) are cost effective, affordable, operationally effective, and suitable, and can be developed to provide a timely solution to a need at an acceptable level of risk. As such, manufacturing-related readiness criteria should be addressed during this review and manufacturing risk associated with each of the alternatives should be identified. Risk should be based on how closely the alternatives meet the MRL 4 criteria and the degree of difficulty to meet MRL 6 criteria by the completion of TMRR.

Key considerations include:

- Manufacturing capability, capacity, and feasibility
- Identification of manufacturing technologies and processes not currently available and risks associated with development
- Cost and schedule impact analyses to support trade-offs among alternatives
- Investments needed to create new industrial capabilities
- Risks of performance vs. planned cost and schedule

The results of the assessment are provided to the required ITRA. The ITRA will highlight all technical issues that should be considered at the Milestone A Decision Review.

Other important outputs of the assessment of manufacturing readiness of the proposed materiel solution include inputs to the following:

- The ITRA
- Investments required for manufacturing technology projects
- Definition of development increments
- Systems Engineering reviews during TMRR
- Systems Engineering Plan
- Risk reduction plans
- Quality plans
- Contracting strategy for TMRR

MSA ends when the AoA is complete, an ITRA has been conducted, a draft AS has been developed, and a Milestone A decision has been made for the proposed materiel solution.

### 3.2.3 Technology Maturation and Risk Reduction (TMRR) Phase

The Milestone A decision point marks the entry into the TMRR Phase of acquisition. TMRR is a focused effort to mature, prototype, and demonstrate technologies in a

relevant environment. The purpose of this phase is to reduce technology risk and to determine the appropriate set of product technologies and manufacturing capabilities to be integrated into a full system.

While it is not expected that contractors would have a complete production line and supply chain established this early in a program, key knowledge must be obtained on critical manufacturing processes, production scale-up efforts, and potential supply chain issues. The results of the assessment of manufacturing readiness performed during the MSA Phase should be used as a baseline reference for this activity with manufacturing maturity at MRL 4. NOTE: It is also possible that some technology development activities were not assessed during the MSA Phase. In that case, it is a “best practice” to conduct a manufacturing assessment early in the TMRR Phase to establish a baseline. Technologies identified to have a maturity level less than MRL 4 at the start of this phase require special attention for maturation and risk mitigation in order to meet the target MRL 6 by Milestone B.

Three major systems engineering reviews are normally conducted during this phase, the System Requirement Review (SRR), the System Functional Review (SFR), and the Preliminary Design Review (PDR). The assessment of manufacturing readiness should be conducted prior to the Milestone B ITRA and provided as input to the ITRA. Additionally, manufacturing SMEs should participate in the ITRA process. TMRR essentially ends in a decision to release the development RFP for the system when a low-risk entry into EMD is achievable. It is expected manufacturing maturity and capabilities should also be at least MRL 6. Key risk considerations for the assessment at the end of the TMRR Phase include:

- Manufacturing processes and techniques not currently available
- Probability of meeting the delivery date (*e.g.*, for EMD prototypes)
- Design producibility risks
- Potential impact of critical and long-lead time material
- Production equipment availability
- Production unit cost goal realism
- Manufacturing capability analyses and cost and schedule impact analyses to support trade-offs
- Recommendations for production testing and demonstration efforts
- Methods for conserving critical and strategic materials and reducing reliance on foreign sources

The output of the assessment is the basis for knowledge of manufacturing maturity and risk for all technologies or products under development. This is a vital part of the decision process at Milestone B; therefore, the assessment results must indicate the key risk areas for the PDR. This technical review ensures the system under review has

a reasonable expectation of satisfying the requirements within the currently allocated budget and schedule. PDR produces a report detailing all technical risk and therefore is a key input to the Milestone B decision. The assessment of manufacturing readiness can provide input for selection criteria for the preferred prototype or competing design, if any remain, by highlighting if and where any risk areas fall short of MRL 6. Discussions of the risks these shortfalls pose to the program, and discussions of the status of efforts to mitigate those risks should be part of the PDR report.

If any risk areas are found to fall short of MRL 6, three basic courses of action are available to the program manager:

- Request a delay in the Milestone B decision to allow time to reduce the manufacturing risk
- Select an alternative lower-risk manufacturing approach
- Carry higher manufacturing risk to the Milestone B decision, with an MMP including funding requirements

Outputs of the MRL assessment process should be inputs to the following:

- The ITRA
- The PDR report
- Industrial base assessment
- The Acquisition Strategy
- The Systems Engineering Plan
- Risk Management Plan
- Investments in long-lead items
- Quality plan updates
- Manufacturing plans
- Contracting strategy for EMD
- Design reviews during EMD
- Program management reviews during EMD

### 3.2.4 Engineering and Manufacturing Development (EMD) Phase

The EMD Phase completes the development of a system, leverages design considerations, completes full system integration, develops affordable and executable manufacturing processes, and completes system fabrication, test, and evaluation. The systems engineering reviews normally conducted during this phase are the CDR, the Test Readiness Review (TRR), the System Verification Review (SVR), the Functional Configuration Audit (FCA) and the PRR as shown in Figure 3-3.

From a manufacturing perspective, the purpose of the EMD phase is to ready the acquisition program for production by completing manufacturing risk reduction activities

that are reflected in the acquisition strategy. The manufacturing planning from the previous phase should be refined in EMD and significant program emphasis should be placed on achieving manufacturing maturity prior to the Milestone C decision. MRL 8 criteria and metrics are appropriate level of maturity for LRIP. MRL 9 criteria and metrics are the appropriate level of maturity for FRP. These MRL levels should be reflected in the acquisition program baseline.

During EMD, MRL Assessments are conducted to identify remaining risks on the design and manufacturing maturity prior to a production decision. These should be conducted prior to the CDR and prior to the Milestone C decision. Sources of data may include technical reviews and audits, pre-award surveys, industrial base analyses, trade-off studies, tooling plans, make-or-buy plans, Manufacturing Plans, and bills of material. The assessments should address all manufacturing risks such as fabrication, assembly, integration and test operations; supply chain performance; the adequacy of manufacturing planning; the efficacy of manufacturing management systems; adequacy of funding for manufacturing risk reduction efforts; and other factors defined in MRL thread descriptions. Articles manufactured on a pilot line during EMD should be made using production materials, components, tooling, facilities, and personnel. Key considerations include:

- Industrial base viability
- Design completion and stability
- Quality and maturity of processes
- Manufacturing costs
- Supply chain management
- Quality management
- Probability of meeting the delivery date (*e.g.*, for qualification units)
- Facilities
- Manufacturing skills availability

The program PRR is a Systems Engineering technical review at the end of EMD to ascertain if a program is ready for production. The PRR assesses whether the prime contractor and major subcontractors have completed adequate production planning and that there are no unacceptable risks for schedule, performance, cost, or other established criteria. In verifying the system product baseline, the PRR requires that manufacturing processes are stable, mature, and have been demonstrated on a pilot line; adequate processes and quality metrics are in place; and the Manufacturing Plan is up-to-date for LRIP (*i.e.*, facilities, tooling and test equipment capacity, personnel development and certification, process documentation, inventory management, supplier management, etc.). Additionally, an ITRA will also be completed just prior to Milestone C. The assessment of manufacturing readiness should provide input to both the PRR

and the ITRA and highlight any areas that does not meet MRL 8 criteria. Manufacturing SMEs should participate in these processes.

If any key aspects of the overall program manufacturing preparation are found to fall short of MRL 8, there are three basic courses of action available to an acquisition program manager:

- Request a delay in the Milestone C decision point to reduce manufacturing risk
- Select an alternative design that would use a lower risk manufacturing approach
- Carry higher manufacturing risk to the Milestone C decision, with an MMP

Outputs of the MRL assessment process are inputs to the following:

- The ITRA
- The PRR
- Systems Engineering Plan
- The Acquisition Strategy
- Risk Management Plans
- Quality Plan updates
- Manufacturing plan updates
- Contracting strategy for production
- Program management reviews after Milestone C

### 3.2.5 Production and Deployment Phase

At Milestone C, the decision is made to proceed into the Production and Deployment Phase. The purpose of the Production and Deployment Phase is to achieve an operational capability that satisfies mission needs. A program may be structured with either one or two major decision points for this phase. The MDA for Milestone C will decide if the program will enter LRIP or FRP. Best practices call for a target of MRL 8 for LRIP and MRL 9 for FRP to minimize risks.

If LRIP is planned, this production effort should target the MRL 9 criteria and metrics to be met prior to the FRP decision to mitigate risks to an acceptable level. To achieve this, manufacturing should be performed utilizing designs, tooling, materials, components, facilities, and personnel that are representative of the production environment. The FRP decision requires that manufacturing risk is understood and that the manufacturing processes for the system be capable, in statistical control, and affordable. Prior to the FRP decision, an MRL assessment should be conducted as input to the required ITRA. This will identify any outstanding risks that may impact the ability of the program to deliver to FRP requirements.

## 3.3 MRLs for Middle Tier of Acquisition

The Middle Tier of Acquisition (MTA) pathway is used to rapidly develop fieldable prototypes within an acquisition program to demonstrate new capabilities and/or rapidly field production quantities of systems with proven technologies that require minimal development.

The MTA pathway is intended to fill a gap in the Defense acquisition for those capabilities that have a level of maturity to allow them to be rapidly prototyped within an acquisition program or rapidly fielded within 5 years of MTA program start. The MTA pathway may be used to accelerate capability maturation before transitioning to another acquisition pathway or may be used to minimally develop a capability before rapidly fielding.

### 3.3.1 MRLs for Rapid Prototyping

The rapid prototyping path provides for the use of innovative technologies to rapidly develop prototypes to demonstrate new capabilities and meet emerging military needs.

The objective of an acquisition program under this path will be to field a prototype meeting defined requirements that can be demonstrated in an operational environment and provide for a residual operational capability within 5 years of the MTA program start date.

Virtual prototyping models are acceptable if they result in a fieldable residual operational capability. MTA programs may not be planned to exceed 5 years to completion and, in execution, will not exceed 5 years after MTA program start without Defense Acquisition Executive (DAE) waiver per DoDI 5000.80.

# 3. MRLs in the Adaptive Acquisition Framework

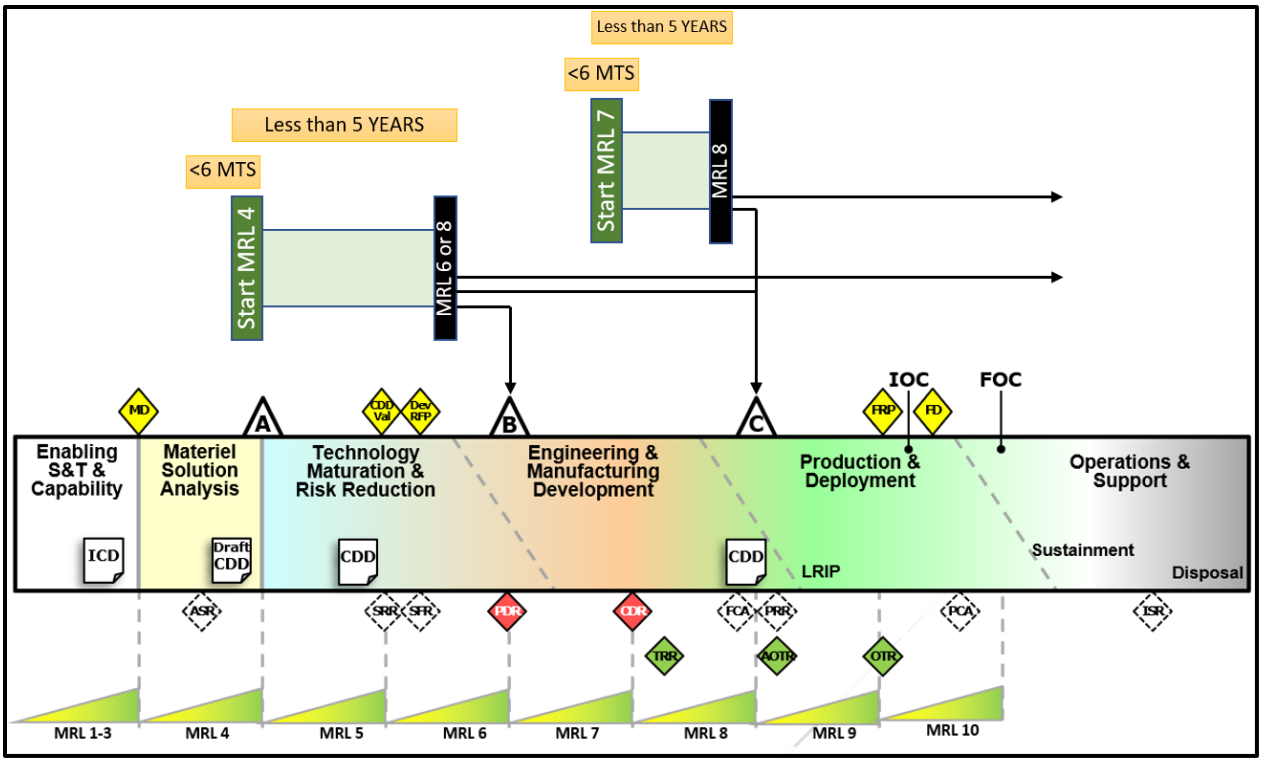



**Figure 3-4 – MRLs for Rapid Prototyping**

For Rapid Prototyping, the entry point for development is a minimum target of MRL 4 criteria to minimize risks and the prototype(s) must be ready for insertion into a program or fielding within 5 years. As the development of the prototype(s) progresses and MRL 6 criteria are met and risks are mitigated, the prototype(s) may be inserted into a program at Milestone B. If funding and time allows to continue development and the prototype(s) meets MRL 8 criteria with appropriate risk mitigation activities, then either development can be continued by insertion into a program at Milestone C; otherwise the prototype(s) can be fielded as shown in Figures 3-4 and 3-5. If manufacturing is more mature at the entry point (*e.g.*, assessed at MRL 7), then prototype(s) development will target MRL 8 criteria and either insertion into a program at Milestone C or fielding as shown.

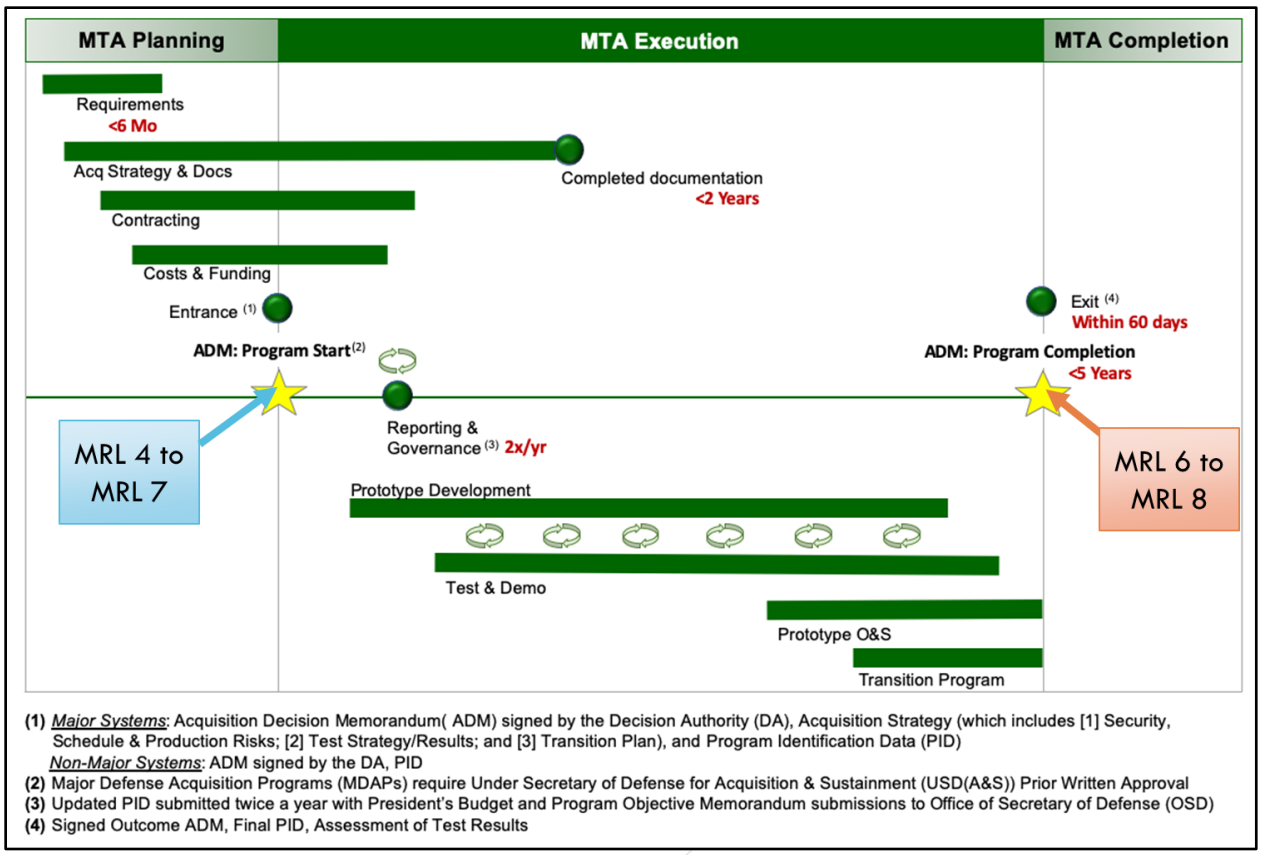



**Figure 3-5 – Rapid Prototyping Paths**

### 3.3.2 MRLs for Rapid Fielding

The rapid fielding path provides for the use of proven technologies to field production quantities of new or upgraded systems with minimal development required.

The objective of an acquisition program under this path will be to begin production within 6 months and complete fielding within 5 years of the MTA program start date.

MTA program production start date will not exceed 6 months after MTA program start date without DAE waiver per DoDI 5000.80.

# 3. MRLs in the Adaptive Acquisition Framework

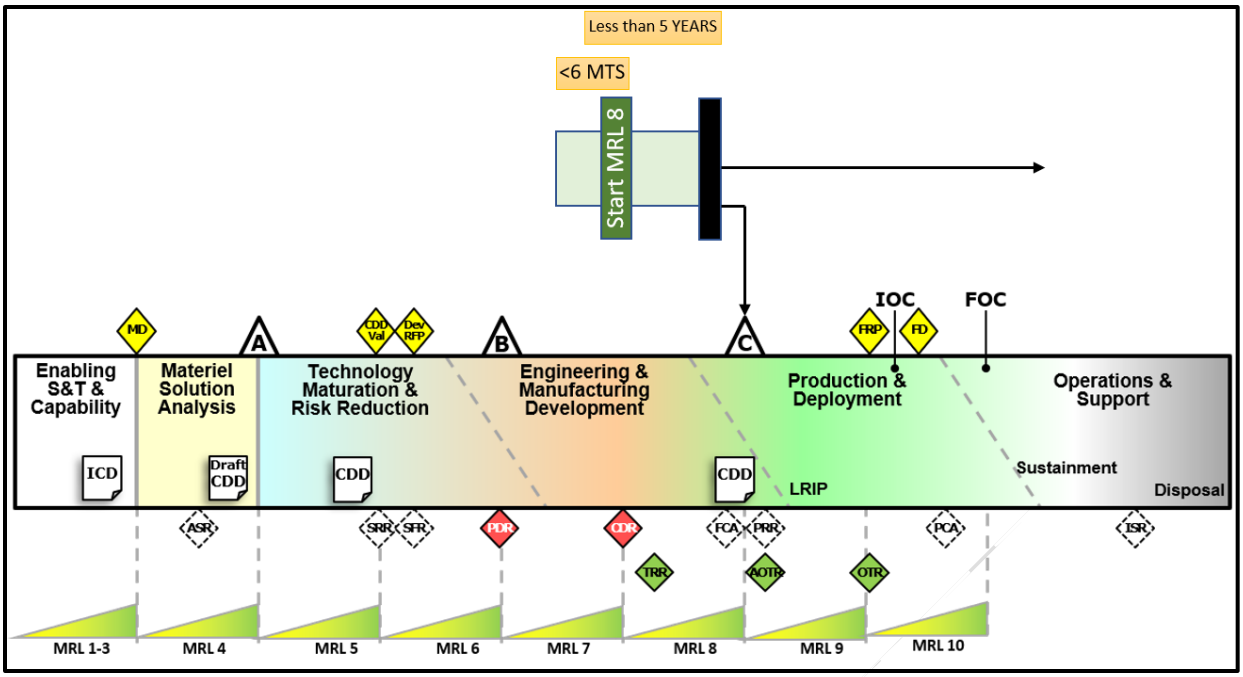



**Figure 3-6 – MRLs and Rapid Fielding**

For Rapid Fielding, the entry point for development and production is a minimum target of meeting MRL 8 criteria with appropriate risk mitigation activities in-place as necessary. Once assessed, the risk to proceed should be evaluated. Production must start within 6 months and all of the product(s) must be manufacturing within 5 years. The MTA pathway may be used to accelerate capability maturation before transitioning to another acquisition pathway or may be used to minimally develop a capability before rapidly fielding as shown in Figures 3-6 and 3-7.

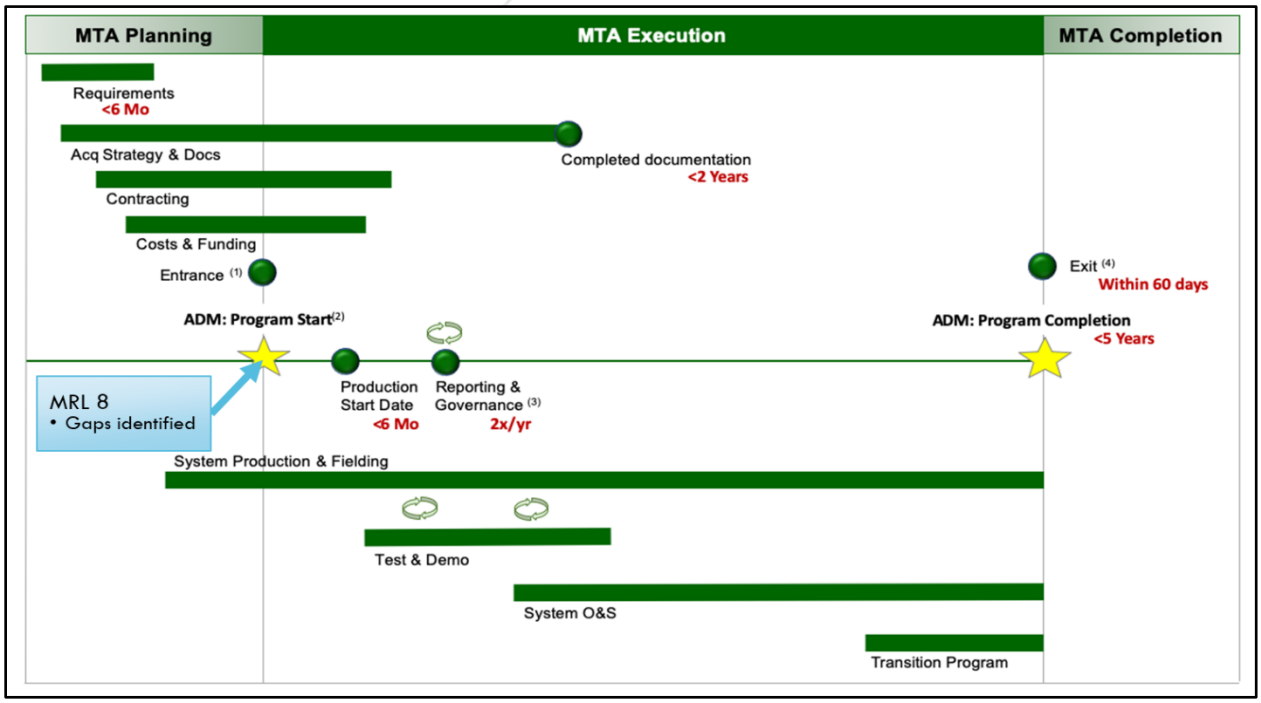



**Figure 3-7 – Rapid Fielding Pathway**

## 3.4 MRLs for Urgent Operational Needs (UON)

The PM will provide the AS and the program baseline to include requirements, schedule, activities, funding, assessment approach, and intermediate decision points and criteria as the basis for this decision within the Urgent Capability Acquisition pathway.

The MDA will determine the feasibility of fielding the capability within the required timelines to include consideration of the technical maturity of the preferred solution(s). The MDA's review of the AS and the program baseline will determine:

- Is based on technologies that are proven and available
- Does not require substantial development effort
- Whether the preferred solution can be fielded within 2 years
- Can be acquired under a fixed price contract

As shown in Figure 3-8, UONs are similar to MCAs with an entry point at Milestone B. The major difference is the less than 2-year timeframe for completion. If the MDA determines that the fielding of the capability cannot be accomplished in the required timelines, then the MDA may direct partial or interim solutions that can be fielded more rapidly or may direct that the program will be managed under a different authority.

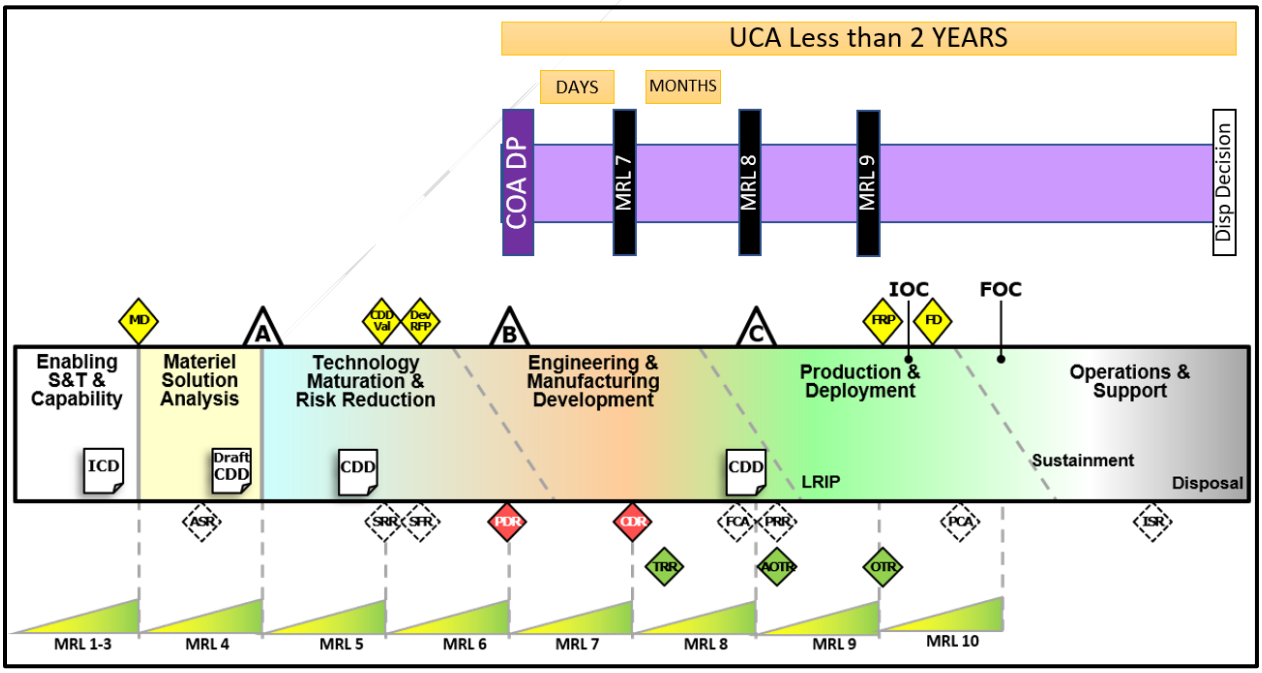



**Figure 3-8 – MRLs for Urgent Capability Acquisition Pathway**

To field the capability in the required timeline, the preferred solution should be a product that is "ready for pilot line", can be adapted from a currently manufactured product(s) (perhaps by another Service), or adapted from Commercial-off-the-Shelf (COTS)

product. In Figure 3-9 below, at the Course of Action Decision Point, the minimum manufacturing maturity should be MRL 7 as there are only days to the development Milestone. At the Development Milestone, the maturity should be assessed to MRL 8 with gaps identified. To achieve MRL 8 in the months to the Production and Deployment Milestone, the gaps must be minimal, with an objective of meeting MRL 9 during production and fielding capability within 2 years.

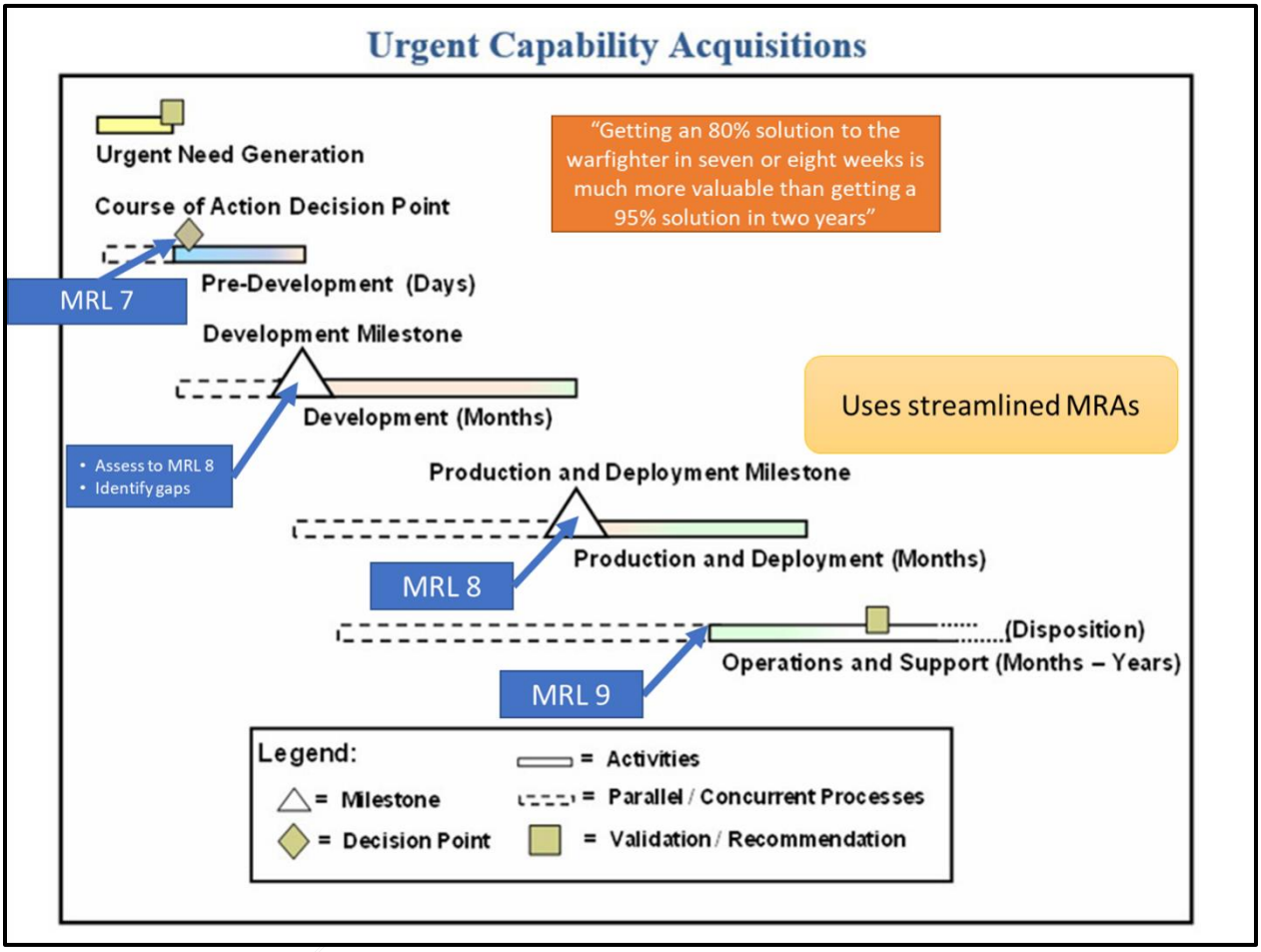



**Figure 3-9 – Urgent Capability Acquisition**

## 3.5 Summary

Manufacturing risk management plays an integral part in the acquisition of all weapon systems throughout their entire life cycle. MRL Assessments are considered "best practice" for Major Capability, Middle Tier of Acquisition, and Urgent Capability Acquisition pathways. Conduct of MRL Assessments may be tailored based on the program acquisition pathway.

For MCAs, DoDI 5000.88 require both Systems Engineering reviews and Independent Technical Risk Assessments (ITRA). As defined in the DoD ITRA Framework, MRL Assessments can be used as a "best practice" to inform the ITRA. MRL criteria should be used in source selection to assess the manufacturing maturity and risk of each offer.

If multiple prototypes are used, assessments based on MRL criteria should be performed on each configuration.

Manufacturing risk management during MTAs, highlights areas needing management attention and helps ensure successful execution and transition of the program/project into either the appropriate Milestone of a program or fielding. A common question is the return on investment for conducting MRL Assessments, however, a program cannot afford to ignore manufacturing risk because the consequences may be too severe. Conducting MRL Assessments based on MRL criteria is a “best practice” and an effective way to ensure risks are identified and managed as early as possible.

For a UON, appropriately tailored or streamlined MRL Assessments will assist a PM to effectively and efficiently determine the product is sufficiently mature to rapidly transition to a pilot line, production, and fielding. MRLs must be integrated with program objectives and time constraints within the overall environment.

MRL Assessments are a “best practice” as delivering weapon systems in a timely and cost-effective manner is not possible, if risks are not well managed.

# 4. Conducting MRL Assessments

## 4.1 Introduction

This section provides general guidance and describes "best practices" for performing MRL Assessments. It is organized around the key steps in the process as shown in Figure 4-1.

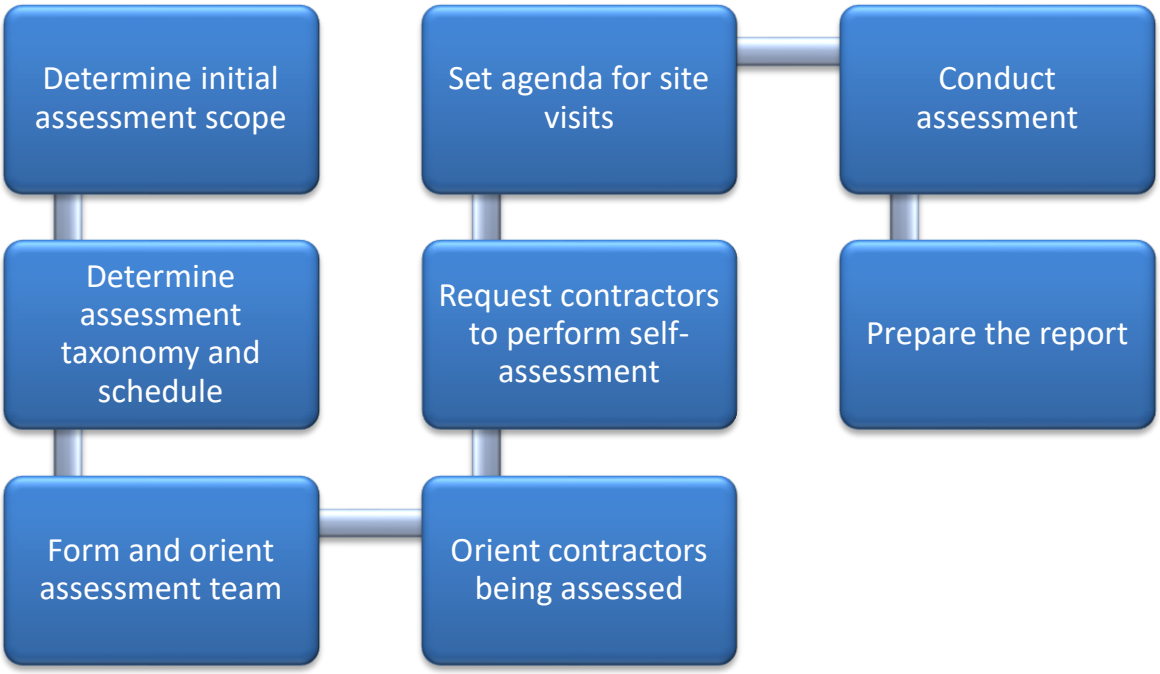



**Figure 4-1 – Sample Process Flow for Conducting MRL Assessments**

A MRL Assessment is an important tool for evaluating manufacturing maturity and risk that is most useful in the context of a broader manufacturing risk management process. These assessments should lead to actions such as setting goals for increased manufacturing maturity and reduced manufacturing risk, creating action plans and funding estimates to reach those goals, reaching decisions about the readiness of a technology, product or process to transition into a system design or onto the factory floor, and reaching decisions on a system's readiness to proceed into the next acquisition phase. Therefore, an MRL Assessment should compare the status of the key program elements to a nominal MRL appropriate for the stage of the program, describe the risk associated with elements that fall short of the goal, and lay the foundation for manufacturing risk mitigation planning and investment.

## 4.2 Determine Initial Assessment Scope

The program/project office should establish the initial schedule and scope for the assessment in conjunction with the prime contractor or equivalent thereof.

- At Milestone A, the program/project office may not be established this early in the acquisition process. Additionally, prime contractors may not have been selected. In that case, the lead DoD Component should identify who will carry out the responsibilities associated with the MRL Assessment.
- At Milestone B, there will be prime contractors associated with every system-level preliminary design still in competition. However, there may be circumstances where the preliminary design is not the starting point for the detailed design effort in EMD because a new technology or product has become available or there has been a change in the requirement. Therefore, MRL Assessments are also applicable to the prime contractors associated with these situations if the risk warrants it.
- At CDR, there will be a prime contractor associated with the detailed design.
- At Milestone C, the prime contractor will be associated with the system-level PRR.
- At FRP, there will be a prime contractor associated with production.

Program/project personnel are likely to need training and additional information. The MRL criteria, threads, tutorials, tools and other information can be found on the DoD MRL site.

The scope of the assessment and the associated MRL target will vary as a function of the stage of the life cycle[16] and specific program requirements. For example, one would not expect the same manufacturing maturity requirements for a low-rate production item (*e.g.*, a satellite) as compared to a high-rate production program (*e.g.*, ammunition, radios). However, in both cases there should be an adequate demonstration of manufacturing maturity, albeit different specific requirements, to ensure the program can achieve the cost, schedule, and performance requirements at the next level. Some examples that demonstrate how the scope may change are as follows:

- During the Materiel Solutions Analysis (MSA) Phase, an assessment of manufacturing feasibility should be conducted for a particular prototype conceptual design in the context of an AoA. Early consideration of producibility and affordability of a particular concept allows for adjustments to design margins before expensive testing or commitment to the achieved performance makes

[16] Section 3 of this Deskbook provided guidelines for expectations at key decision points in the acquisition management system.

those changes irreversible. It also helps identify manufacturing technologies/capabilities that need to be developed in the next phase. The goal would be to meet the MRL 4 criteria for a Milestone A review.

- In the early stages of TMRR, an examination of the maturity and producibility of a proposed design allows for trades on cost, performance, and schedule to be accomplished when it is significantly easier to make changes and where changes potentially have a greater impact on key performance metrics. The nominal MRL target would be in the range of MRL 4 to MRL 5. By the conclusion of TMRR, the goal should be to meet MRL 6 criteria for maturity and risk.
- In a source selection for EMD, assessments can aid in determining the maturity of the design relative to the offeror's ability to achieve projected cost or schedule targets. An assessment to MRL 6 criteria should define manufacturing progress and risk for the next phase and ensure prototype hardware was produced in a relevant environment. The use of criteria associated with MRL 7 will assist in determining maturity and risks during EMD as a program moves toward CDR.
- At CDR, in order to meet MRL 7 maturity and manage risk, it is necessary to examine integration processes such as assembly, installation, and test. Whether a subsystem and/or component is built either in-house by a prime contractor or by an outside supplier, assembly and test processes should be examined as part of an integrated process. At the system level, required assembly processes, intermediate test processes, installation, and final acceptance testing, at all work breakdown structure levels must be considered to effectively gauge manufacturing maturity and risk, and the ability to meet projected cost and schedule targets.
- The criteria associated with MRL 8 reflect a maturity level consistent with requirements for the approaching a LRIP decision. With an assessment conducted on an actual pilot line, emphasis should be placed on understanding what the production capability and capacity is of the eventual production line to meet program objectives for cost, schedule, and performance. Emphasis should also be placed on anticipating any problems with FRP processes. The criteria associated with MRL 8 reflect a level of maturity of a program as it moves toward Milestone C full rate production.

## 4.3 Determine Assessment Taxonomy and Schedule

The assessment taxonomy encompasses what will be assessed, where the assessments will take place, and who will lead the assessment.

The government program/project office, in conjunction with the prime contractor, should make an early determination of potential issues by breaking out system, subsystem, item, or component level for analysis and then determining the applicability of components for evaluation. Consideration should also be given to associated test and assembly processes. The following questions have been developed to assist in the determination of elements to be assessed. All critical technologies, immature manufacturing processes, and other significant areas of the work breakdown structure

(WBS) or bill of materials (BOM) should be subject to the following filtering questions. Any "yes" responses imply that an MRL Assessment may be needed for that element to categorize the degree of technical and manufacturing risk.

- **Materials:** Are there materials which have not been demonstrated in similar products or manufacturing processes?
- **Cost:** Is this item a driver that significantly impacts lifecycle cost (development, unit, or operations and support costs)? Is the technology or product new with high cost uncertainty?
- **Design:** Is the item design novel or does it contain nonstandard dimensions or tolerances or arrangements?
- **Manufacturing Process:** Will the item require the use of manufacturing technology, processes, inspection, or capabilities that are unproven in the current environment?
- **Quality:** Does the item have historical/anticipated yield or quality issues?
- **Schedule:** Does this item have lead time issues or does it significantly impact schedule?
- **Facilities:** Does this item require a new manufacturing facility or scale up of existing facilities (*i.e.*, new capability or capacity)?
- **Supply Chain Management:** Does the item have anticipated or historical sub-tier supplier problems (*e.g.*, cost, quality, delivery)?
- **Industrial Base:** Does the item have an industrial base footprint with critical shortfalls or is this a critical item manufactured by a sole or foreign source?

It is rarely feasible to visit every supplier of every material, component, and assembly to examine the status of their key manufacturing processes. Some elements should be assessed on-site and others may utilize alternative approaches. The type and depth of the assessment is determined by the risk level of the element. On-site evaluations are typically reserved for the locations where one or more of the following apply:

- The highest percentage of manufacturing cost is incurred
- Final assembly and test are conducted
- The most sensitive manufacturing tasks are accomplished
- The materials, components or subsystems that are the least technologically mature are produced or availability issues exist
- Known significant problems or risks (*e.g.*, low yields, high costs, immature manufacturing processes, etc.) exist

Normally, the government program/project office will lead the assessments at the prime contractor(s) and the prime contractor(s) will lead the assessments for its suppliers. Prior to Milestone A, site visits might not be possible since there rarely is any hardware to support the conceptual designs. Under special circumstances, currently running production lines may be visited if it is anticipated that similar process and tooling will be utilized.

The schedule is typically driven by a variety of considerations including timing of acquisition milestone reviews or program baseline reviews; availability of qualified team members; and contractor scheduling concerns; etc. For a small technology demonstration project, an assessment might take a single day at one contractor's facility and require a team of two or three persons. Conversely, a major acquisition program may require multiple site visits over a period of months and involve a larger team, not all of whom will go to every site.

## 4.4 Form and Orient Assessment Team

Assessments of manufacturing readiness are typically performed by teams and the government program/project office is responsible for forming them. It is a "best practice" for the government program/project office to lead the team at prime contractors and the prime contractor to lead the team for the sub-tiers. When the prime contractor leads the assessment, it will determine who it wants to include on the team; however, the program/project office should add its own representatives. Team members should be experienced and knowledgeable in the areas of manufacturing engineering, industrial base, quality, supply chain, design, systems engineering, and production to identify potential manufacturing constraints, risks, and the capability of the technology and industrial base to execute the manufacturing efforts. This experience and knowledge is also important for tailoring the reviews to the specific circumstances of the program. Technology, product, or process SMEs may be required to identify issues not expected to be uncovered by general manufacturing, industrial base, quality, and production experts.

Team selection can begin once the scope and a rough schedule of activity is developed. These teams will vary in size depending on the scope of the assessment. Sub teams may be put together to focus on various components, subsystems, or technologies. The team composition will normally lean heavily toward program/project office and service manufacturing SMEs. Representatives from DoD staff organizations may participate as well, if the assessment is being performed on an acquisition program approaching a milestone decision.

Strong consideration should be given to including a level of independence for several reasons:

- It adds credibility to the assessment

- It enables alternative views from others who may have a different perspective
- It provides an opportunity to obtain opinions from SMEs not normally available to the program
- It promotes a cross-flow of information well beyond the program office

Such a level of independence may be obtained by a variety of means, at the discretion of the service and the program office. Some ideas for achieving independence are as follows:

- Appoint a co-chair independent of the program
- Include SMEs independent of the program
- Use an independent technical authority to review the results of the assessment

Team members from outside the program/project being assessed should familiarize themselves with the program/project. They will need to understand the purpose of the assessment, the objectives, and the status of the program, critical technologies, critical manufacturing processes, configuration of hardware, and roles and locations of key contractors and suppliers. This can usually be accomplished by reviewing existing briefing materials, contracts, and progress reports and through interaction with program/project personnel.

The program/project office should consider contacting the appropriate Defense Contract Management Agency (DCMA) office to gather information on the contractor's current and past performance. DCMA personnel interact with most prime contractors and their key suppliers frequently and may have very useful information about quality problems and other risk areas. Consider including DCMA personnel in on-site evaluation teams if they are available.

It is also important for the program/project office to set expectations for team members early in the process. The following are some of the key areas to be covered:

- Initial schedule
- Format and timing of reporting their results to the team
- Standards of behavior at the contractor's facility
- Security clearances or nondisclosure agreements
- Personal preparation
- The need for a detailed understanding of their assigned area and the role of shop floor observations and off-line discussions with contractor personnel
- Responsibilities after the on-site review

## 4.5 Orient Contractors Being Assessed

The leader of the assessment (either the government program/project office or the prime contractor) should orient the contractor(s) before the assessment occurs. This orientation may involve including contractor personnel in planning meetings as well as providing the contractor with an orientation package that includes:

- The MRL criteria and threads
- Directions to additional materials on DoDMRL.org
- Self-assessment questions
- An indication of technologies or processes of special interest that should be included in the self-assessment

For on-site assessments, the orientation package should also include:

- The questions the assessment team will use
- A draft agenda for the assessment visit
- Evidence to be provided at the onsite visit (*e.g.*, process maps, proposed Manufacturing Plans, process capability data, yield data, technology development plans, risk reduction plans, value stream analyses, etc.)
- High-interest areas where shop floor visits and/or discussions with contractor experts will be desired
- Expectations of resources, time, etc. required for the assessment

Make arrangements with the contractor for an assessment team meeting room to be available where private discussions can be held and team members can record their observations. Also, make arrangements with the contractor for assessment team members to bring computers into the facility to facilitate the capture of their observations in electronic format.

## 4.6 Request Contractors Perform Self-Assessment

The leader of the assessment should ask the contractor(s) to conduct a self-assessment to address the following basic questions:

- What is the current MRL for each of the key technologies or products being developed and each key manufacturing process being used?
- If currently funded activities continue as planned, what MRL will be achieved for each key technology, product or process by the end of this acquisition phase or program? What activities and schedules are required to achieve this MRL?
- In the case of an advanced technology demonstration, what MRL would be sufficient for you to commit to in a product baseline design?

In the case of on-site assessments, the contractor should be prepared to brief the results to the assessment team when it is on-site. For companies that provide key components or subassemblies and for which a site visit is not feasible, the contractor's written self-assessment should be analyzed by the assessment team.

## 4.7 Set Agenda for Site Visits

The leader of the assessment should set the agenda for site visits. Site visits are intended to provide a more detailed understanding than can be gained from briefings and documents. Assessments of manufacturing readiness should be structured in such a way as to take maximum advantage of discussions with contractor experts and first-hand observations of the status of shop floor activities. A balance must be struck between the time spent in briefing rooms and the time spent making observations in the contractor's facility and having discussions with individuals and small groups of the contractor's personnel. A typical agenda for a review may contain the following elements:

1. Contractor welcome, review of agenda, assessment schedule and orientation to the facility
2. Introduction of assessment team and contractor personnel
3. Briefing to contractor describing objectives and expectations for the on-site visit
4. Contractor overview and discussion of the results of their self-assessment
5. Shop-floor visits to key areas by individuals or small groups
6. One-on-one or small group discussions between assessment team members and contractor subject matter experts focused on key areas
7. Private meeting of assessment team to record and discuss observations
8. Out-briefing by assessment team to contractor

## 4.8 Conduct the MRL Assessment

### 4.8.1 Review the Self-Assessment

The assessment team should initiate focused dialog at the component, test, and/or assembly process based on complexity, location, personnel availability, etc. In larger assessments, specific technologies, assemblies, subsystems, or processes should be assigned to individuals or sub teams.

The MRL criteria are used for determining manufacturing maturity. The leader of the assessment should review the self-assessment and examine targeted components, subsystem and system-level test and assembly processes with respect to the threads. These threads have different applicability at various times during a product development life cycle. The threads can apply at each component, subsystem, system, and eventually at the program level. They should be used to guide examination of various

data sources such as process maps, work instructions, and factory tours to assign an MRL to a technology, component, subsystem, or system.

A series of knowledge-based questions derived from the MRL criteria and threads are typically used to guide the assessment process and determine the MRL of specific elements that are embodied in hardware (*e.g.*, materials, components, assemblies, subsystems). The questions are adaptable and have been incorporated into tools that store the MRL data for the self-assessment. They can be found at the DoD MRL website.

### 4.8.2 Conduct Assessment

When conducting an MRL Assessment, there should be a well-defined hierarchy among the elements assessed. The hierarchy should start at the system level and flow down to the lowest component that forms the smallest unit for examination. The assessment team should determine the MRL threads applicable to each element in the hierarchy and identify the needed systems-level test and assembly processes that require an MRL assignment. This includes test and assembly steps that would be included in a subsystem or component fabrication. For example, a Printed Wiring Board (PWB) has several assembly and testing steps during the fabrication of the board. That PWB would be included in a subsystem buildup in an avionics box (*e.g.*, radar) that may require a next higher-level assembly and test process.

The threads also serve as a guide to alert the assessment team of the need to examine other areas. For example, the self-assessment may be for a missile guidance system (as initially determined by the taxonomy in Section 4.3) that was reported to be MRL 3 but targeted to be MRL 4. Additional detail may be needed to discern why it was assessed at MRL 3 and identify the critical steps needed to mature it. Therefore, further component-level assessments may be necessary as shown in Figure 4-2.

| Subsystem | MRL Criteria | Observations | Most Critical |
|---|---|---|---|
| **Guidance** | 3 | • Lacking detailed process information<br>• Key suppliers identified; need key performance parameters<br>• Need detailed process plans | • Detector from Supplier A<br>• Design and production issues<br>• No alternate source |
| **Data Processor** | 3 | • New processor architecture<br>• Immature design tools<br>• New attachment processes needed | • Board supplier cannot test at its site<br>• Low yields on initial run |
| **Propulsion** | 6 | • Same as other systems in use<br>• New component scheme | • Revalidate manufacturing process<br>• Supplier ability to handle increased rate |
| **Air Vehicle** | 7 | • Same supplier as System X<br>• Need to test new mating and assembly processes at the prime | • No critical items |

| | | | |
|---|---|---|---|
| **Test Plan** | 6 | • Several instances of redesign work and new test processes | • New test strategy and plan<br>• What will new design incorporate<br>• Manufacturing experience vital |

**Figure 4-2 – Example of Added Detail Derived from Site Visits**

During the assessment process, a component or subsystem may be found to be more complex than originally thought, so an even more detailed analysis, or "deep dive," may be warranted. If the assessment team determines further examination of critical components is necessary, the MRL threads should be applied at that level. Sub-components are examined along with process steps, and an MRL is determined for this final sub-tier element. Team members should seek existing, objective documentation that supports assessment results in key areas (*e.g.*, plans, yield data, reports, briefings, work instructions).

In determining the manufacturing readiness of a component or subsystem, use the MRL criteria to structure the review and establish targets for each thread/sub-thread. If the target criteria are not met, the team should analyze and characterize the risks utilizing the approach in the "DoD Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs" available at the USD(R&E) Engineering Resources for Program Offices website. The team assesses the likelihood and severity of the risks from each thread/sub-thread not met by the component or subsystem.

Finally, the assessment team should include the actions necessary to mitigate the risks and achieve the target level in time to transition a technology or product; or support a milestone decision with manageable risk. Risk mitigation strategies should be developed into a MMP.

### 4.8.3 Complete the Assessment

DCMA personnel should be asked to provide their perspective and insight on the contractor's presentations and status. If the contractor was unable to provide adequate information to support an assessment in a key area, assign an action item for the contractor to provide the information by a specific date.

Near the end of the assessment, the team should meet at the contractor's facility to discuss and capture its observations and impressions. The team should also provide an out brief to the contractor highlighting strengths and risks, MRL achievements compared to targets, and action items. Finally, the hospitality and cooperation of the contractors should be recognized.

MRL Assessments are not a simple "go/no-go" gauge. Therefore, assigning a single MRL to a technology, product or an entire weapon system often has little value. Even in a relatively simple case, where an assessment is being accomplished on a single

technology or product with perhaps a half-dozen hardware components, it is likely the MRL will vary widely from component to component and perhaps even manufacturing process by manufacturing process for a specific component. Some components may be off-the-shelf, standard hardware, or made with well-established materials and processes from reliable suppliers, thus perhaps having an MRL in the range of 8 to 10. Other components may incorporate new design elements that move well beyond the proven capabilities of a key manufacturing process and perhaps are at MRL 4.

Using a “weakest link” basis, a technology, product or system would have to receive an overall MRL that reflects the element that had the lowest level of readiness, in this case, MRL 4. In many instances, this approach could be misleading and give the impression of an overall level of risk greater than the actual situation. For assessments of more complex subsystems and systems, this simplification becomes even less useful since it is unlikely that every element is going to beat MRL 6, for example, by Milestone B.

Therefore, the assessment report (as described in section 4.9), should contain a bottom-up assessment of the relative manufacturing readiness at the system, sub-system and component level. Findings for lower-level components can be fit into a format for analysis and decision-making at higher levels of the program as shown in Table 4-1. Each MRL (at any level) should be identified to provide insight into specific risks.

## 4.9 Prepare the Assessment Report

The results should be documented by team members in a format agreed to in advance. Except in the simplest cases, it may not be feasible for the team to agree on an assessment while on-site at the contractor’s facility. Usually, some analysis is required by the assessment team after site visits are complete to clearly define the manufacturing readiness and risk status of the key technologies or products and manufacturing processes and to put the identified risks into a program context. These final results are then typically documented in a written report or out-brief containing the following:

1. A description of the technology, component, sub-system or system which identifies the elements that were assessed; the key objectives of the development effort; and a discussion of the current state of the art
2. A discussion of the companies which are responsible for the elements that were assessed
3. A list of team members
4. Dates and locations of site visits
5. A description of the manufacturing processes for the elements that were assessed
6. The manufacturing readiness for each element that was assessed

7. Areas where manufacturing readiness falls short of the MRL criteria
    - Identify key factors
    - Describe driving issues
8. Plans to achieve the target MRL
9. Assessments of the type and significance of risk to cost, schedule or performance
10. Assessments of the effectiveness of current risk mitigation plans
    - Address right issues?
    - Timely?
    - Adequately funded?
    - Probability of success?
    - Options for increased effectiveness?

The government program/project office is the primary audience for the report since it forms the basis for managing manufacturing risk. In general, the report establishes a manufacturing maturity baseline that should be used to either create a plan to increase manufacturing readiness/maturity sufficiently to support transition to the next phase of acquisition or to demonstrate that the technology or product is ready for transition. The report may also provide information to an MDA determination of whether the level of manufacturing risk supports Milestone approval.

When actual MRLs are compared to target values based on the stage of the life cycle, the report provides a basis for an analysis and assessment of the risks associated with each manufacturing thread. Cost, schedule or performance manufacturing risks that are not resolved must be defined and require manufacturing maturity plans. These plans should include a description of the approach to resolve the risk, cost estimates, resources available, and schedule impacts. The manufacturing maturation plan is normally delivered along with the assessment report as described in Section 5 of this Deskbook.

# 5. Manufacturing Maturation Plans (MMP) and Risk Management

## 5.1 Introduction

The purpose of an assessment of manufacturing readiness utilizing the MRL criteria is to analyze current conditions and to identify manufacturing risks in order to assist the program/project manager in creating a plan or options to reduce or remove those risks. Identifying risk is a key part of developing mitigation efforts; it is a key enabler of program success. Risk management includes risk planning, risk assessment, risk handling and mitigation strategies, and risk monitoring approaches. Thorough assessments of maturity, development of manufacturing maturation plans, and the use of technology transition plans are fundamental tools for mitigation. See the following for further information on risk management:

- DoD Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs

A key product resulting from an assessment of manufacturing readiness is the MMP, which addresses the manufacturing risk and provides a mitigation plan for each risk area throughout the duration of the program/project, including supplier and sub-tier supplier risk management shortfalls. Every assessment of manufacturing readiness should have an associated MMP for those areas where the MRL has not achieved its target level.

A low MRL assigned to a component is not necessarily bad at an early stage of acquisition. By identifying the risk area(s), necessary investment can be channeled to attain the target MRL by the time of transition to the next phase of the program/project. As a result of risk identification, the program/project can formulate and execute MMPs before the risks become severe. A manufacturing maturity shortfall in an element can be easy or difficult to fix; therefore, the following information is needed to decide whether a technology, product or weapon system is ready to move to the next phase of its life cycle.

- Identification of any elements (technologies, components, assemblies, subsystems, processes, etc.) that have not reached the target MRL
- Understanding of the potential impact if the element fails to mature to the target level as well as how difficult, time consuming, and expensive it will be to bring the element up to an acceptable level of maturity or develop an adequate work around

# 5. Manufacturing Maturation Plans (MMP) and Risk Management

The remainder of this section describes activities to address risk. The recommended format of an MMP which serves as the manufacturing risk mitigation plan is shown in Section 5.2. Best practices for manufacturing risk mitigation are listed in Section 5.3. Additionally, Section 6.4 contains suggested SOW language that includes contract deliverables and related Data Item Descriptions (DID) for the both the MRL Assessment and the MMP.

## 5.2 Development of a Manufacturing Maturation Plan

In conjunction with the contractor, the program/project office should prepare an MMP that covers all manufacturing risk areas. The MMP as a follow-on to MRL Assessment report. The following outline for an MMP includes the most essential items in planning for the maturity of a specific element of assessment found to be below its target MRL:

1. Title
2. Statement of the problem
   - Describe the element of assessment and its maturity status
   - Describe how this element of assessment would be used in the system
   - Show areas where manufacturing readiness falls short of target MRL including key factors and driving issues
   - Assess type and significance of risk to cost, schedule or performance
3. Solution options
   - Benefits of using the preferred approach
   - Fall-back options and the consequences of each option
4. Maturation plan with schedule and funding breakout
5. Key activities for the preferred approach
6. Preparations for using an alternative approach
7. The latest time that an alternative approach can be chosen
8. Status of funding to execute the Manufacturing Plan
9. Specific actions to be taken (what will be done and by whom)
10. Prototypes or test articles to be built and a description of how the test environment relates to the manufacturing environment
11. Threshold performance to be met
12. MRL criteria to be achieved and when it will be achieved

## 5.3 Risk Management Best Practices

The following "best practices" recommended for both acquisition programs and technology development projects and demonstrations are categorized into five areas:

1. Recognize the importance of manufacturing and mitigating manufacturing risk to the success of a program/project
   - Accept manufacturing risk management as a basic responsibility, on par with the management of any other risk
   - Recognize that mitigating manufacturing risk can be the key ingredient of success in transitioning a technology, product or process to a program
   - Recognize manufacturing maturity and risk as key factors in defining and achieving program/project cost, schedule and performance goals
2. Manage manufacturing risk
   - Incorporate the management of manufacturing maturity, risk, and cost into the basic fabric of managing the program/project
   - Assess, plan, budget, and manage to reach manufacturing maturity and cost targets.
   - Conduct assessments of manufacturing maturity and risk to increase the probability of program success and integrate the results into a broader effort to manage programmatic risk
3. Monitor the status and progress of manufacturing risk mitigation activities
   - Know the MRL of every technology or product being considered for application in the program/project
   - Assess and understand manufacturing readiness and risk early in each phase of an acquisition program to establish a baseline
   - Include contractual Statement of Work (SOW) taskings (see Section 6) for the prime contractor and suppliers to support MRL Assessments including "best practices" that improve producibility, quality, and affordability
   - Do not rely totally on contractor manufacturing assessments
   - Incorporate manufacturing maturity examination and progress monitoring in management reviews, system engineering technical reviews, and progress reporting
4. Utilize SMEs from outside the program to help mitigate manufacturing risk
   - Use manufacturing expertise available on product center and within the Service/Agency manufacturing technology programs to supplement staff
   - Identify and access trained and experienced manufacturing subject matter experts outside of the Service/Agency

- Use DCMA as a source of information about strengths and weaknesses in a contractor's manufacturing operations

5. Develop staff skills in identifying and mitigating manufacturing risk
   - Review the information and tools available on the DoD MRL site
   - Support manufacturing training for program/project staff

# 6. Applying MRLs in Contract Language

## 6.1 Introduction

Section 6 is provided to guide planning and implementation and is intended to highlight the use of manufacturing and quality industry standards for contractual actions for both the government and industry. Inclusion of these management standards in development and acquisition strategies is a "best practice" for government agencies as well as commercial enterprises; and should be tailored for each specific situation to meet program needs.

> NOTE: *The following section is intended as a "best practice" for development of Requests for Proposal (RFPs) and contract requirements and does not supersede DoD policy, law, Federal Acquisition Regulation (FAR), or Defense Federal Acquisition Regulation Supplement (DFARS). These "best practices" and suggested approaches/examples are provided for consideration in contract development, are not prescriptive, and should be tailored to meet program requirements.*

Proper implementation of applicable manufacturing and quality industry standards will assist in successful management of risks and achievement of the required maturity. For example, Section 4.3 of SAE standard AS6500A, *Manufacturing Management Program* requires manufacturing risk identification and management activities. These manufacturing risk activities are required to be identified with mitigation plans established and tracked to completion. Identified risks are required to be integrated into program risk management processes throughout the entire program life cycle. Other conformances to the standard are manufacturing feasibility assessments, MRL Assessments and Production Readiness Reviews (PRR).

The following sections outline strategies and suggestions for addressing manufacturing and quality risks and maturity and should be included as part of acquisition planning and activities. Strategies for all RFPs or Solicitations should include assessments using the MRL criteria and metrics to determine manufacturing risks, maturity, and quality. This input can be used as a discriminator between offerors, but at a minimum should impact the requirements of the contract. Responses to RFPs or Solicitations should include maturity of manufacturing, recognized risks, and level of quality for the effort proposed. Ideally, this would be from a self-assessment, or independent assessment utilizing the MRL criteria.

Assessments of manufacturing maturity and risk should also be included in the Statement of Work (SOW), with associated DIDs, as a formal part of the contract. From a Government standpoint, including the appropriate language in Section L (Instructions

to Offerors) and Section M (Evaluation Criteria) of the RFP ensures these criteria are used during the source selection process.

## 6.2 Acquisition Planning

During acquisition planning, requirements for manufacturing and quality are determined for the applicable milestone or phase (*i.e.*, pre-Milestone A, Milestone A, Milestone B, Milestone C, Full Rate Production (FRP) or Operations & Sustainment). The organization (program and contractor) should identify the required manufacturing maturity and document manufacturing risks. At a minimum, the organization should be required to conduct assessments prior to major milestone and technical reviews (*e.g.*, PDR, CDR, PRR) to assess progress toward achievement of the required maturity by use of assessments using MRL criteria and metrics. The assessment results should be presented at those reviews, including assessments of key or essential suppliers, to provide decision makers with factual knowledge of manufacturing and quality maturity and risks. For those items that are not at the required maturity, Manufacturing Maturation Plans should be developed, and provided at the reviews.

***Example: Pre-Milestone A (i.e., MSA Phase)***

*The program should conduct and document a manufacturing feasibility assessment for each competing design alternative under consideration to identify critical technologies and manufacturing processes that need matured by Milestone A. The assessment should use the Manufacturing Readiness Level criteria as a guide in determining the elements to be evaluated. Assessment of feasibility includes the identification of all required production processes, immature manufacturing technologies, and the risks associated with the development of those processes and technologies.*

***Example Post-Milestone A (i.e., TMRR Phase)***

*The program and/or the contractor should conduct and document an assessment of manufacturing maturity using the MRL criteria as a gap analysis to identify and determine critical technologies and manufacturing processes that need to be successfully demonstrated by Milestone B.*

***Example Program initiated at Milestone C***

*The organization should be required to conduct Production Readiness Reviews (PRRs) that use input from an assessment of manufacturing maturity and risk using the MRL criteria prior to the production decision, with the results provided for that decision.*

The System Engineering Plan should include target levels of manufacturing maturity, both entry and exit levels, appropriate to the development phase. Similarly, from an industry standpoint, contracts to their supply chain should include flow-down clause requirements for assessments of manufacturing risk, maturity, and quality in those contracts.

Note: Major Defense Acquisition Programs (MDAP) are required, by statute, to categorize the degree of technical and manufacturing risk under Public Law 114-328.

## 6.3 RFP Language

The RFP should require the offeror's proposal to document the results of an assessment of manufacturing maturity and risk according to the MRL criteria appropriate for the current phase. In addition, adherence to manufacturing and quality "best practices" (*i.e.*, national and/or international standards) could be a determinant in solicitations and proposals. The offeror could describe use of assessments and/or "best practices" as an integral part of the manufacturing enterprise.

The guidance in this section focuses primarily on acquisition/product programs. For Science and Technology (S&T) projects, the responsible party should modify the language, as appropriate, since the use of national and/or international standards may not be applicable in the early development process.

### 6.3.1 Section L (Instructions, Conditions, and Notices to Offerors or Respondents)

Section L of the RFP should specify the content and required format the offeror must submit to substantiate their use of assessments and/or "best practices". This will reduce the likelihood of misunderstandings between the offeror and government when discussing the program's manufacturing and quality risks and plans.

***Example: Manufacturing Management System***

*The offeror shall describe how their Manufacturing Management System meets the requirements of SAE AS6500 (or as tailored).*

***Example: Manufacturing Readiness Level Demonstration***

*The offeror's proposal shall identify those elements being assessed for manufacturing maturity and risk and their target MRL using the criteria and process identified in the DoD Manufacturing Readiness Level Deskbook available at* DoDMRL.org*. The offeror shall describe the approach used to assess the MRL criteria. The offeror shall address in Manufacturing Maturation Plans (MMPs) how risks identified in the MRA, against the MRL Criteria, will be managed to ensure that the required manufacturing maturity will be achieved.*

NOTE: For DoD programs, DFARS Subpart 215.304, *Evaluation Factors and Significant Subfactors* requires that the manufacturing readiness of offerors be considered during source selection for ACAT I programs.

***Example: Manufacturing Plan***

*The offeror shall describe the major assembly sequence chart and anticipated manufacturing process flow; the manufacturing build schedule, including drawing release; tooling design, build, and proofing; key supplier deliveries; and fabrication,*

*assembly, and delivery schedules; facility requirements and layouts; plans to provide the needed manpower, facilities, and equipment for expected delivery rates.*

***Example: Quality Management System***

*The offeror shall describe how their quality system conforms to national or international quality standards and assures product quality; achieves stable, capable processes; prevents defects; and employs effective methods for conducting root cause analyses and implementation of corrective actions.*

***Example: Supplier Management System***

*The offeror shall describe how their supplier management system evaluates manufacturing and quality maturity and risks, and integrates with their manufacturing and quality management systems.*

### 6.3.2 Section M (Evaluation Factors for Award)

Section M of the RFP should specify the evaluation criteria for the offeror's submission detailed under Section L on their use of assessments and/or "best practices". This will reduce the likelihood of misunderstandings between the offeror and government when discussing the program's manufacturing and quality risks and plans.

***Example: Manufacturing Management System***

*The offeror's proposal will be evaluated on their Manufacturing Management System and how it meets the requirements of AS6500.*

***Example: Manufacturing Readiness Level Demonstration***

*The offeror's proposal will be evaluated on the maturity of their stated manufacturing and quality capabilities, the adequacy of supporting documentation that justifies the stated capabilities, and the risks identified and the offeror's process and plans to mitigate or manage those risks, and achieve the required level of manufacturing maturity (as described in the Manufacturing Readiness Level Deskbook).*

***Example: Manufacturing Plan***

*The offeror's proposal will be evaluated on the included content of the Manufacturing Plan which should address major assembly sequences; anticipated manufacturing process flow; manufacturing build schedule; key suppliers; manpower, facility, equipment, tooling requirements, and investments with scoring based on completeness of the plans*.

***Example: Quality Management Systems***

*The offeror's proposal will be evaluated on their quality management system. The offeror should also specify any QMS certifications (e.g., ISO 9000, AS9100, etc.). The scoring will be based on the offeror's description of policies and practices that will assure product quality; achieve stable, capable processes; prevent defects; and result in effective root cause analyses and corrective actions.*

***Example: Supplier Management***

*The offeror's proposal will be evaluated and scored on the efficacy and completeness of their supplier management system. Scoring should be based on how key suppliers are selected and managed based on evaluation of their manufacturing and quality maturity and risks; how supplier activities are integrated in the design process and manufacturing and quality management systems; and how supplier risk management and mitigation is integrated into the overall program.*

## 6.4 SOW Language for Contracts

It is expected that the SOW will contain appropriate statements to support "best practices" in identification, management and maturation of manufacturing and quality.

The guidance in this section focuses primarily on acquisition/product programs. For S&T projects, the responsible party should modify the language, as appropriate, since the use of national and/or international standards may not be applicable in the early development process.

The following are examples of manufacturing and quality "best practice" statements that should be included, as appropriate, in the SOW:

- The contractor shall conduct assessments to identify manufacturing and quality risks according to the guidance in the MRL Deskbook.
- The contractor shall conduct MRL Assessments and monitor activities to achieve the required manufacturing maturity in accordance with their MMPs.
- The contractor shall plan for and conduct on-site assessments based on the MRL Deskbook guidelines. (NOTE: Not all suppliers may need to be assessed.)
- The contractor shall specify the locations and frequencies of all MRL Assessments, along with the required resources and include these events in the Integrated Master Schedule.
- The contractor shall include appropriate manufacturing and quality risk mitigation and maturation plans in the Program Risk Management System and the Integrated Master Schedule and report status and updates at all program and technical reviews.
- The contractor shall provide status and updates of MMPs at all program and technical reviews.
- The contractor shall support the government assessment of manufacturing readiness at the prime contractor and the prime contractor will lead the assessments at the suppliers with government participation unless clearly specified otherwise in the proposal.

- The contractor shall identify its approach for flowing down these requirements.

In addition, the SOW should specify conformance to industry standards, such as:

- The contractor shall utilize and maintain a quality management system that meets ISO 9000, AS9100, or equivalent.
- The contractor shall utilize and maintain a manufacturing management system that conforms to SAE AS6500A.
    - The government and the contractor shall agree and specify the appropriate requirements from AS6500A to be met.
    - The contractor shall provide an analysis of conformance of their organization's policies, processes, procedures, systems to the AS6500A requirements in a cross-reference matrix that will reference the documentation, artifacts, objective evidence, and rationale that demonstrates their conformance to the standard.

For additional guidance on contractually implementing AS6500A, refer to MIL-HDBK-896A, *Manufacturing Management Program Guide*. (NOTE**:** MIL-HDBK-896A can also be used as guidance by industry entities for their suppliers.)

***Example:***
*The contractor shall establish and maintain a Manufacturing Management Program that meets the requirements of AS6500A and flow this requirement down to key and critical suppliers. The contractor and key and critical suppliers shall document this program as part of their Manufacturing Plan. The contractor shall include its plans for MRL Assessments in the Manufacturing Plan.*

Suggested Data Item Description (DID): DI-MGMT-81889B, Manufacturing Plan

***Example:***
*The contractor shall conduct MRL Assessments using the Manufacturing Readiness Level (MRL) definitions, criteria, and process defined in the latest version of the DoD MRL Deskbook available at DoDMRL.org as a guide. MRAs shall be conducted at the locations and frequencies specified in (SOW Section/Appendix X). The government will lead MRAs at the contractor's facilities; and the contractor will lead MRAs at their suppliers and will include government representatives. The selection of suppliers to be reviewed will be made using the MRL Deskbook, Section 4.3 as a guide. The contractor shall develop and implement Manufacturing Maturation Plans (MMPs) for risks identified in the MRAs, against the target MRL Criteria, to ensure the required manufacturing maturity will be achieved. The contractor shall monitor and provide status at all program reviews for in-house and supplier MRAs and shall re-assess areas for which design, process, source of supply, or facility location changes have occurred that could impact manufacturing maturity and risk. The contractor*

*shall provide substantiating objective evidence (artifacts) to support all target MRL criteria assessed in MRAs.*

Suggested DID: DI-SESS-81974, Assessment of Manufacturing Risk and Readiness

## 6.5 Deliverables

Implementation of MRL Assessments utilizing the MRL criteria may require some deliverable documentation from the contractor and, if so, should be included in the SOW. Generally, requirements for deliverable Data Item Descriptions (DIDs) should be minimized.

For example, DI-MGMT-81889B, Manufacturing Plan, is a deliverable that is consistent with AS6500A requirements and can be applied in the RFP and contract for all phases of system acquisition. Updates to the Manufacturing Plan will be as specified as part of the DID tailoring activity. This DID must be tailored to meet program requirements. This DID may or may not be required based on other available evidence of conformance to AS6500A, (*e.g.*, integration of a Manufacturing Plan into the contractor's command media).

Another example, DI-SESS-81974, Assessment of Manufacturing Risk and Readiness. If MMPs are being generated as a result of maturity shortfalls, the government should determine if these plans need to be deliverable items. Preferably, the MMPs should be documented as part of the program's normal Risk Management process, which should include documented risk mitigation plans, which may or may not be deliverable. If desired as a deliverable, the SOW should include the Data Item Description (DID) DI-SESS-81974, Assessment of Manufacturing Risk and Readiness, as a formal Contract Data Requirements List (CDRL) item.

A third example, DI-QCIC-81794A, Quality Assurance Program Plan is a deliverable that is consistent with AS9100D requirements. This report: provides complete coverage of all of the information, instructions and documentation necessary to produce a quality part, component, equipment, subsystem or system of high acceptance; ensure conformance with contractual requirements; and specify measurable quality objectives and the metrics by which they are to be measured.

Note: Sections applicable to acquisition programs should be identified by the government by tailoring these DIDs in the DD Form 1423, Contract Data Requirements List (CDRL).

## 6.6 Additional Quality Considerations

Contractual requirements must meet the Federal Acquisition Regulations (FAR) and Defense Acquisition Federal Acquisition Regulations Supplement (DFARS).

- Contract Quality Requirements - shall meet all requirements of FAR Part 46, Subpart 46.2
- Government Contract Quality Assurance - shall meet all requirements of DFARS Subpart 246.4

The FAR and DFARS are additional resources for performing MRL Assessments.

## 6.7 MRLs Relationship to AS6500A and Quality Standards

### 6.7.1 Requirements for Activities Related to MRL Threads in AS6500A

The MRL Criteria Matrix is a collection of criteria against which manufacturing maturity is measured. The criteria themselves do not contractually direct that certain activities be accomplished. AS6500A is a tasking document that can require many of those activities be accomplished.

Using Key Characteristics (KC) as an example, the criteria for MRL 6, Sub-thread B.2, Design Maturity, states that, “Preliminary KCs for the design have been identified…” The MRL criteria does not require all contractors to identify all KCs. Rather, it is an expectation for what should take place, in this case, with respect to KCs prior to PDR. On the other hand, full conformance with AS6500A specifically requires organizations to identify KCs in the Technical Data Package. If the requirements of AS6500A are implemented, then the criteria of MRL 6, Sub-thread B-2 should be satisfied.

The activities required by AS6500A and the criteria in the MRL matrix are highly complementary (refer to Figure 6-1). While not every MRL criterion is covered, AS6500A requires activities that correspond with many of the topics addressed in the MRL threads. Ideally, if AS6500A is implemented effectively, then there is a high probability that the activities being assessed by the MRL criteria will have been accomplished and the product/process will successfully achieve the target MRL.

Requirements for AS9100D and AS6500A standards have common affiliations to the MRL criterion (see Figure below). Neither standard satisfies all MRL criteria but are recommended as additional resources for performing MRL Assessments.

| MRL Thread | AS6500A Requirement | AS9100D Requirement |
|---|---|---|
| Industrial Base and Manufacturing Technology | 4.4.2 Materials Management | 8.4 Control of Externally Provided Processes, Products, and Services |
| | 4.4.3 Manufacturing Technology Development | 6.1.2.b The organization shall plan<br>7.1.3 Infrastructure |
| Design | 4.2.1 Producibility Analysis | 8.1.a Operational Planning and Control |
| | 4.2.1c Design Trade Studies | 8.3 Design and Development of Products and Services |

| MRL Thread | AS6500A Requirement | AS9100D Requirement |
|---|---|---|
| | 4.2.2 Key and Critical Characteristics | 8.3.5e Design and Development Outputs<br>8.4.3.h Information for External Providers<br>Note: Additional info on this topic can be found in AS9103A |
| | 4.2.3 Process FMEAs | 8.1.b.2 Operational Planning and Control |
| Cost & Funding | 4.4.4 Cost | Use of AS9100D should result in improved quality, cost, and delivery performance. |
| Materials | 4.4.2 Supply Chain and Material Management | 8.4 Control of Externally Provided Processes, Products, and Services |
| | 4.5.8 Supplier Management | 8.4 Control of Externally Provided Processes, Products, and Services |
| Process Capability & control | 4.4.5 Manufacturing Modeling & Simulation | N/A |
| | 4.5.3 Continuous Improvement | 10.3 Continual Improvement |
| | 4.5.4 Variability Reduction | 8.5.1.a.2 Note 2 Production and Service Provision<br>8.5.1.3 Production Process Verification |
| | 4.5.5 Process Capabilities | 8.1.b.2 Operational Planning and Control<br>8.5.1.3 Production Process Verification |
| Quality Management | 4.3 Manufacturing Risk Identification | 6.1 Actions to Address Risks and Opportunities<br>8.1.1 Operational Risk Management |
| | 4.5.2 Manufacturing Surveillance | 7.1.5 Monitoring and Measuring Resources<br>7.4 Communication<br>8.5.1 Control of Production and Service Provision |
| | 4.5.3 Continuous Improvement | 10.3 Continual Improvement |
| | 4.5.7 FAIs/FATs | 8.5.1.3 Production Process Verification<br>Note: Additional information on this topic can be found in AS9102B |
| | 4.5.8 Supplier Management | 8.4 Control of Externally Provided Processes, Products, and Services |
| | 4.5.9 Supplier Quality | 8.4 Control of Externally Provided Processes, Products, and Services |

| MRL Thread | AS6500A Requirement | AS9100D Requirement |
|---|---|---|
| Manufacturing Workforce | 4.4.7 Manufacturing Workforce | 7.1 Resources |
| Facilities | 4.4.8 Tooling/Test Equipment/Facilities | 7.1.5.2 Measurement traceability<br>8.5.1.1 Control of Equipment, Tools, and Software Programs<br>8.5.1.2.c. Validation of Control of Special Processes |
| Manufacturing Management | 4.4 Manufacturing Planning | 8.1 Operational Planning and Control |
| | 4.4.6 Manufacturing System Verification | 8.5.1.3 Production Process Verification |
| | 4.5.1 Production Scheduling and Control | 8.1 Operational Planning and Control |
| | 4.5.2 Manufacturing Surveillance | 7.1.5 Monitoring and Measuring Resources<br>7.4 Communication<br>8.5.1 Control of Production and Service Provision |

**Figure 6-1 – Mapping of MRL Threads to AS6500A & AS9100D Requirements**

### 6.7.2 Quality Standards and MRL Criteria

A number of Aerospace and Industry Standards are available for implementing Quality Management Systems (MRL criteria in the Quality thread). SAE AS9100D “Quality Management Systems” includes requirements for aviation, space and defense organizations. AS9100D can also be used for other industry sectors and their sub-tier suppliers. Other Quality Industry Standards include ISO 9001 and IATF 16949. These standards are applicable to all phases of the acquisition and product life cycle and applicable for contractual requirements for any program having manufacturing scope.

The International Aerospace Quality Group (IAQG) standards were developed by the IAQG to provide supporting information for organizations and industry sectors applying the 9100 standard. The IAQG is responsible for three quality management systems standards; AS9100D “Aviation, Space, and Defense Organizations”, AS9110 “Aviation Maintenance Organizations”, and AS9120 “Aviation, Space and Defense Distributors”. In addition, the IAQG has developed numerous standards for quality management and quality management systems to provide additional guidance for specific clauses of AS9100D, AS9110, and AS9120 standards (refer to Figure 6.2).

| IAQG Quality Management Systems Standards |
|---|
| • 9100, Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations<br>• 9110, Quality Management Systems – Requirements for Aviation Maintenance Organizations<br>• 9120, Quality Management Systems – Requirements for Aviation, Space and Defense Distributors |
| IAQG Standards (additional standards for guidance) |
| • 9101, Quality Management Systems – Audit Requirements for Aviation, Space, and Defense Organizations<br>• 9102, Aerospace First Article Inspection Requirement<br>• 9103, Variation Management of Key Characteristics |

**Figure 6-2 – IAQG Standards**

NOTE**:** AS9100D Annex B contains a listing of ISO standards available for industry and organizations requiring additional guidance that are independent of AS9100D requirements.

NOTE: AS9100D Annex C contains a listing of available IAQG standards.

# 7. Users Guide for Performing MRL Assessments

## 7.1 The MRL Users Guide

The MS Excel™ based MRL Users Guide was developed to supplement this Deskbook and provide the user with most of the information needed to perform an assessment utilizing the MRL criteria at any stage of the acquisition or product development life cycle.

### 7.1.1 MRL Users Guide Worksheets

The MRL Users Guide consists of six named worksheets:

**Introduction –** The first worksheet contains instructions on how to operate the Users Guide.

**Users Guide –** The second worksheet is the digital Users Guide. Each cell is linked to a pop-up dialog box that will display detailed information about the MRL or product life cycle simply by clicking on a given cell or icon for which information is desired. The cells down Column A provide information about the specific threads that are traced in that row of the matrix. The cells and icons in Rows 2 through 6 display information about the phases of the Product Life Cycle, Acquisition Reviews, Acquisition Milestone descriptions, MRL definitions and background information for that stage of the product life cycle.

**Definitions –** The third worksheet is a list of definitions for terms typically used in the acquisition and manufacturing readiness assessment process.

**Acronyms –** The fourth worksheet is a list of acronyms commonly used in manufacturing and in the development and acquisition process.

**MRL Printable Matrix –** The fifth worksheet contains an MRL Matrix for those who wish to view or print the entire matrix on a single sheet.

**Questionnaire –** The sixth worksheet contains a complete list of questions in a table format, derived from the MRL criteria, to be used in MRL Assessments. This questionnaire is intended to be tailored to the system, subsystem, or component being assessed and be limited to questions focused on the target MRL or one level lower. The user may make a copy of the questionnaire which can then be sorted and tailored to select appropriate questions for the item and target MRL.

### 7.1.2 Description of the Pop-up Boxes

Selecting a specific cell in the MRL Users Guide worksheet will display a pop-up dialog box with the following: The Sub-thread (*i.e.*, A1, B2, etc.) and the Maturity level (MRL 1 through MRL 10) will appear at the top. The MRL Criteria Matrix criterion is in the next

block for reference to let the user know which cell is being viewed. The Help Text section of the dialog box contains the following information:

- **Purpose:** This describes the intent for doing the assessment for this particular sub-thread at this point in the life cycle and the reason for doing the assessment of this particular thread at this point, *i.e.*, what requirements/documents/ procedures drive the assessment?
- **Sources of Information:** This is where data can be collected for a particular assessment at that stage of the product life cycle.
- **Examples of Objective Evidence:** Specific evidence to address the criteria.
- **Questions:** These are directly derived from the text of the MRL Criteria Matrix from the latest revised version of the MRL Questionnaire.
- **Additional Considerations:** Sometimes from past experience, Services or industry have optional questions they may want to ask for specific threads or sub-threads at specific times in the life cycle. If so, these will be included.
- **Lessons Learned:** These are particular lessons derived from past experience of personnel doing risk assessments in this particular sub-thread at this specific point in the product life cycle. These may change as people gain more experience doing MRL Assessments and readiness.

# 8. Effectively Adapting and Utilizing MRL Criteria

## 8.1 Introduction

The development of MRLs has been a joint industry and government activity for nearly two decades. The participants have been experts in both manufacturing and acquisition from numerous DoD prime contractor and key suppliers, academia, and government. The MRL Assessments utilizing the MRL criteria have been used on numerous programs with excellent results in identifying and managing manufacturing risk.

In reviewing the successful programs, there are some basic attributes that stand out.

- First and foremost is having trained SMEs involved in the assessment of manufacturing readiness based on the MRL criteria. Their expertise is essential in not only assessing readiness, but also in adapting the assessment using the MRL criteria to the given situation.
- The second is that assessments using the MRL criteria will support most applications with only minor adaptations. Terms such as “production relevant,” “production representative,” “pilot line,” and “rate tooling” may have different implications for Science & Technology (S&T), ship, or space programs as opposed to ground vehicle, aircraft, or electronic programs; therefore, notional definitions have been defined within this document in order to clarify the intent of specific terminology.

This chapter provides the user with insight in adapting the assessment using the MRL criteria to specific situations. While adaptations for assessments can be made for a specific technology, product, or application, traceability to the MRL criteria must be maintained to provide a sound foundation for manufacturing risk management. If one of the criteria requires information about an acquisition or follow-on program, it may be determined after careful consideration that it is not feasible to assess or apply those criteria. However, another similar criterion (even within the same sub-thread) may be feasible to assess and apply. Even though it might not be feasible or practical for an S&T effort to assess using all of the MRL criteria, discretion must be used when choosing not to assess certain criteria since each represents its own unique risk area. Any criterion which is not thoroughly assessed at the appropriate time is a “known-unknown” risk. Any criterion which is eliminated from the manufacturing readiness assessment could leave risks buried until later phases of the S&T effort or until after the technology or product has transitioned to an acquisition program. Most MRL threads and sub-threads have multiple criteria to address, and while not all criteria may be feasible to assess, the entire thread or sub-thread cannot not be ignored. Rather than being quick to decide not to assess criteria which appear to be out-of-scope, not

feasible, or too difficult to assess, assess to what is appropriate for the given phase and unique reality of the S&T effort. The goal is not to simply perform an assessment, but rather to identify risk as early as possible so appropriate action can be taken to maximize the likelihood of successful transition.

## 8.2 MRL Criteria in the S&T Environment

### 8.2.1 Introduction

Adapting MRL Assessments using the MRL criteria effectively in the S&T environment is probably the most challenging of all the various situations. The MRL criteria were designed to measure the manufacturing readiness of a product and/or process as it matures towards production. However, in early S&T there is often very little linkage between the researches being performed and a product or specific production program. Therefore, the assessment using the MRL criteria might have to be adapted to achieve the goals of an S&T environment (*i.e.*, to obtain fundamental knowledge). The primary objective for using the MRL criteria is to improve the decision makers' ability to understand and mitigate manufacturing risk in development efforts transitioning from S&T to acquisition. Our ability to transition technology or product smoothly and efficiently from concept, into the lab, onto the factory floor, and into the field is essential to be cost effective and to reduce cycle times in an acquisition program.

### 8.2.2 Basic Research

The earliest effort in the S&T process is Basic Research. The purpose of Basic Research is the systematic study of the fundamental science and phenomenology based upon observable facts without regard to a specific process or product. An assessment using the MRL criteria in Basic Research should focus on the extension of observations for the potential use or purpose of the scientific discovery. As the application of this new knowledge to a notional product matures, information becomes available which highlights potential downstream manufacturing risks and provides insight into new manufacturing processes, the industrial base, and cost goals that need to be developed to achieve innovative new products. These identified risks should be considerations in the Applied Research phase. MRL 1–3 criteria typically indicate the desired manufacturing knowledge for Basic Research.

### 8.2.3 Applied Research

The next phase of the S&T process, Applied Research, is a systematic study to gain knowledge to determine the means by which a recognized and specific user's need may be met. Applied Research translates Basic Research into solutions for broadly defined user needs. Applied Research is taking the knowledge of process/science and demonstrating application of the fundamental principles learned in Basic Research. It is generally performed in a laboratory environment where small samples are developed to

allow measurement and observation of process and technique. The resulting item should have materials and processes that can be assessed. Upon completion of Applied Research, application of these processes and techniques is ready for demonstration on a prototype. Meeting the MRL 4 criteria typically indicates the desired manufacturing knowledge for Applied Research, provides an assessment of the manufacturing feasibility of the S&T project, and should be useful in determining the next steps.

### 8.2.4 Advanced Technology Development (ATD)

ATD is a systematic application of knowledge or understanding directed toward the development of useful materials, devices, systems, or methods, including the design, development, and improvement of prototypes and new manufacturing processes to meet specific requirements. The results of ATD are proof of technological feasibility and assessment of subsystem and component operability and producibility rather than the development of hardware for service use. ATD includes the functions of design engineering, prototyping, and engineering testing. This phase of S&T requires a much greater degree of collaboration between the S&T and Acquisition communities than Basic or Applied Research. Assessments using the MRL criteria are valuable tools in maturing manufacturing capability for a new technology or product; which should be a major concern to the transition customer (*i.e.*, Acquisition community). Therefore, adapting the assessment using the MRL criteria to ATD should be a joint effort between the S&T and transition customer. Furthermore, given the current phase of the program, the appropriate target MRL criteria should be understood and agreed upon by both parties. The goal is to understand, minimize, and manage the risk associated with manufacturing maturity as the ATD transitions into an acquisition program. MRL 5 – 6 criteria typically indicate the desired manufacturing knowledge for ATD.

### 8.2.5 Examples of Adaption

S&T efforts funded by the S&T community are not usually funded beyond the S&T work. This puts the S&T community in a dilemma, especially if the goal is to achieve MRL 5 or 6 maturity at the time of transition. Some of the MRL criteria contain acquisition language which may not be feasible or practical for an S&T funded effort to consider (*e.g.*, MRL criteria referring to cost models and budget estimates for Milestones B or C). It is understood that fully accomplishing all of the MRL 5 or 6 criteria for most S&T efforts is likely not feasible or practical. However, many MRL criteria (such as those dealing with quality, design, materials, facilities and workforce) are very valuable in reducing manufacturing risk for technology transition and are more feasible to assess in S&T. Therefore, it is recommended the assessment using the MRL criteria be adapted to take advantage of valuable risk reduction while not spending valuable resources on manufacturing maturation efforts which are not feasible.

For example, in MRL 4-6 criteria, Thread C – Cost and Funding, there are references to budget and cost estimates to reach Milestone B and Milestone C. If an S&T program is only funded through ATD (or earlier), then these criteria may not be feasible to consider for the specific S&T effort. In general, references to future activities relevant to a follow-on program not funded by the S&T effort are not feasible to be considered during the S&T effort. The criteria which were not feasible to consider and the associated justifications, must be documented and provided to the transition customer for the sake of transparency.

Likewise, MRL 5 criteria, Thread E – Process Capability and Control; and Thread I – Manufacturing Management, speak to target yields and make/buy evaluations for pilot line, LRIP, and FRP. These criteria may also not be feasible or practical to consider if the S&T effort is not funded to do so. Again, the criteria which were not feasible to consider, and the associated justifications, must be documented and provided to the transition customer for the sake of transparency.

In addition, Sub-thread E.1 – Modeling & Simulation (Product & Process), should be evaluated to determine what level of modeling and simulation is appropriate for the application being assessed. In some cases, extensive modeling and simulation is required while in other cases a simple spreadsheet calculation is sufficient. In this case, a simple spreadsheet calculation is adequate to meet these criteria.

MRL 6 criteria require solutions and processes to be demonstrated in a production relevant environment. Prior to conducting a manufacturing assessment, the production relevant environment for the application should be agreed upon by all stakeholders and trained SMEs. The definition of production relevant environment (Section 2.4) should serve as a helpful guide. In some cases, a laboratory environment is acceptable as a production relevant environment; especially if some production line realism is present and can demonstrate manufacturing readiness or identify potential risks to manufacturing processes.

### 8.2.6 Summary

Adaptation of assessments using the MRL criteria to S&T programs is challenging, but there are several key attributes that can help. First and foremost, trained SMEs should participate in MRL Assessments. It is critical the stakeholders work together to understand what is needed to meet the MRL criteria in their application. Tying MRL criteria to program objectives, providing analysis of the criteria with respect to program developments, and identifying potential risks that need to be managed moving forward are all areas where trained SMEs can provide assistance. MRL Assessments must stay focused on the manufacturing risks of transitioning a technology or product from the lab to production and should consider impact on product success. Managing manufacturing

risks improves the ability to transition technologies or products smoothly and efficiently and is essential for cost effective and reduced cycle times in an acquisition program.

## 8.3 MRL Criteria for Sustainment/Maintenance, Repair & Overhaul (MRO) and Depot Activities

### 8.3.1 Using MRL Criteria to Enhance Product Support Management

The DoD Product Support Manager (PSM) Guidebook, another “best practice”, stresses proper early planning for Life-Cycle Logistics which corresponds to early planning for manufacturing activities. The relationship of MRL Assessments using MRL criteria to Product Support Decision Points or activities begins in the Pre-Material Solution Analysis phase. The DoD PSM Guidebook stresses the use of Sustainment Maturity Levels (SML) to identify decisions/activities for Product Support. SMLs have a direct correlation to MRL criteria as depicted in figure 8.1.

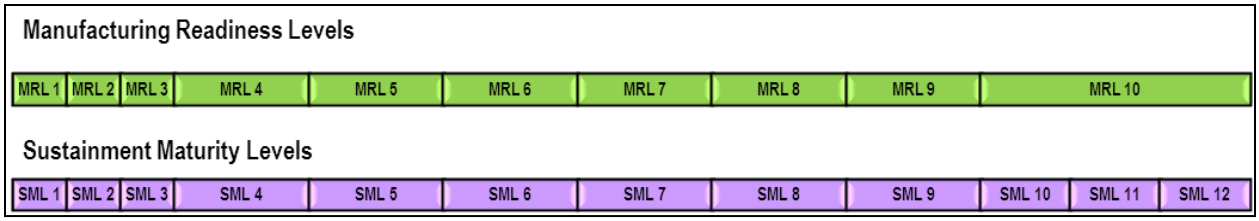



**Figure 8-1 – Relationship of MRLs to SMLs**

MRL Assessments using the MRL criteria can support the SML activities in the progression of a program where sustainment is properly addressed as a normal day-to-day activity. It is essential to understand the manufacturing maturity corresponding to the sustainment maturity and use that data to determine the risk to depot or program objectives; then implement the appropriate risk management efforts, especially for Depot Activation. Existing depot manufacturing procedures and processes need to have the same rigor of evaluation of manufacturing maturity to determine the risk to your project/program objectives.

### 8.3.2 Using MRL Criteria to Enhance Logistics Assessments

The DoD PSM Guidebook states that a thorough Logistics Assessment will assist leaders in making informed decisions at milestones and/or at key program decision points. Many of the criteria in the DoD PSM Guidebook are directly supported by the MRL criteria. Assessing manufacturing using the MRL criteria provides better understanding of the manufacturing capability of suppliers, allowing decisions based on objective data. Minor adaptations to the language for the assessment process using MRL criteria may be required.

### 8.3.3 Using MRL Criteria to Enhance Depot Activities

Assessing depot manufacturing capability using the MRL criteria provides better understanding of the organic depot and depot supplier capabilities. Often, depot support decisions have to be adjusted based on “fact of life” changes. For example, support of a product was originally contracted to a business; but due to unforeseen circumstances that business is no longer available. The support activities would likely be absorbed by a military depot. This would initiate the Depot Activation process which includes major elements of the SML and MRL processes. If this product requires processes, capabilities, or components that are not within the current depot capability, then these need to be “matured.” Assessments of manufacturing (using MRL criteria) need to be performed to identify and “mature” the necessary manufacturing activities to support the product.

Figure 8.2 depicts a situation where the depot was directed to stand-up (unplanned) a capability for a product (which is Post-Milestone C/Initial Operational Capability (IOC)). If no engineering technical data is available, the assessment of manufacturing readiness could have a target of MRL 5 (which does not support an SML 8). If limited data is available, the assessment of manufacturing readiness could have a target of MRL 6 (not supporting an SML 8). If a majority of data is available, the assessment of manufacturing readiness could have a target of MRL 7. Unless all data and processes are in place to support a product, it will take time, funding, and resources to achieve MRL 8 and support an SML 8.

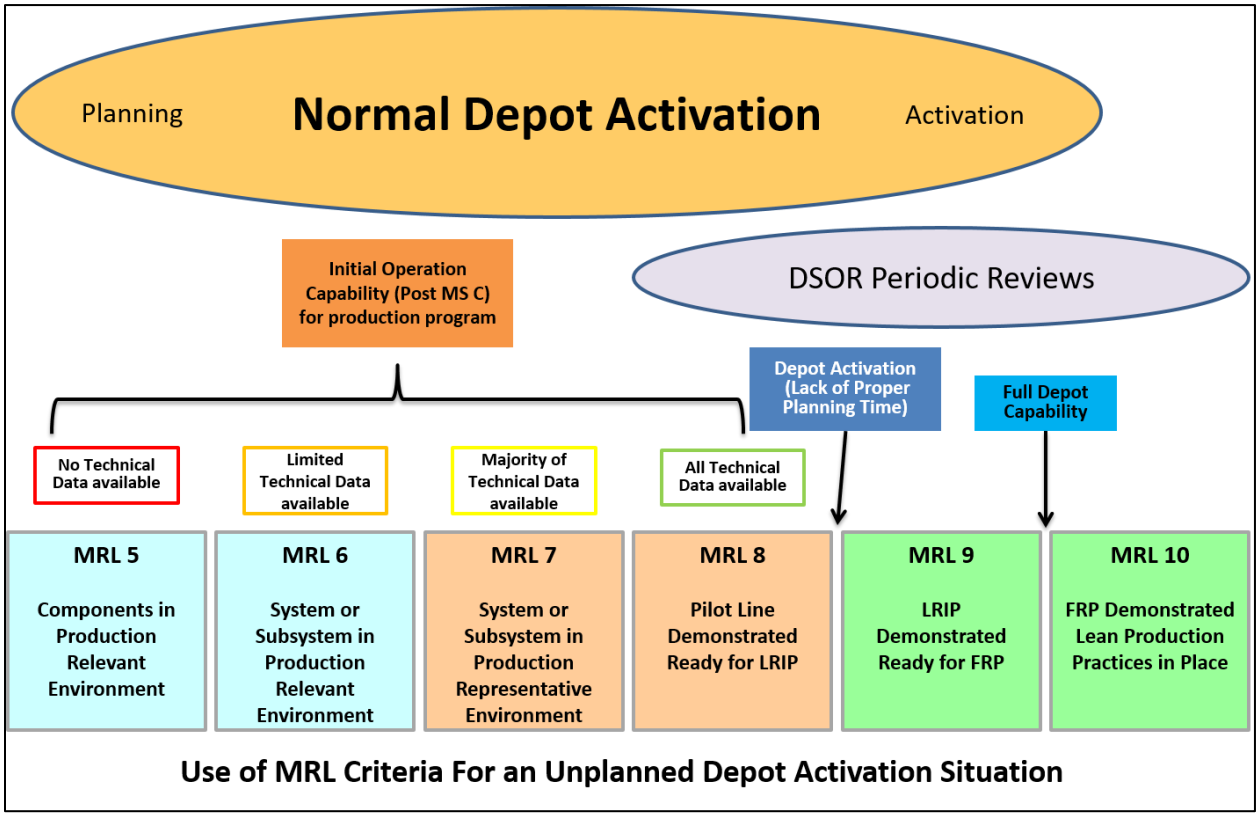



**Figure 8-2 – Example of Unplanned Depot Activation Circumstance**

### 8.3.4 Summary

In summary, assessments using MRL criteria can support sustainment, MRO, and Depot Activation activities. A SME trained in assessment of manufacturing readiness and logistics planning is essential for product support management, logistics assessments, and depot activities. It is critical the stakeholders work together to understand what is needed to meet the MRL criteria in their application and link them to program or depot objectives risks that need to be managed. MRL Assessments are essential for cost effective and reduced cycle times for sustainment and depot activities.

## 8.4 MRLs for Single or Limited System Acquisition

Manufacturing readiness assessments using the MRL criteria can be adapted for the acquisition of a single system or limited production systems. A single or limited production system is defined as a system in which the first unit becomes the first operational unit, *e.g.*, a large-scale radar, a class of ships, or a single or small family of satellites.

### 8.4.1 Single or Limited Systems – Except Ships

Assessments of this type of system are accomplished by modifying the relationship of MRLs to decision points or milestones. Prior to CDR, as these systems proceed normally through the acquisition process, MRL Assessments using the MRL criteria are performed through Milestone B as described in Section 3.2 (or if there is no Milestone B decision planned then through PDR).

Per DoDI 5000.85, 3.12.d.:

> Some programs such as spacecraft and ships will not produce prototypes during EMD for use solely as test articles because of the high cost of each article. In that case, the first article produced will be tested and evaluated, and then fielded as an operational asset. The acquisition approach for these programs can be tailored by measures such as combining development and initial production investment commitments and a combined Milestone B and C. Additional decision points with appropriate criteria may be established for subsequent production commitments.

Whether traditional or tailored, a CDR that assesses design maturity, design build-to or code-to documentation, and remaining risks and establishes the initial product baseline, is required. Manufacturing maturity at CDR must be sufficient to support a First Build decision point with acceptable risk. First Build approval and First System Build normally occur shortly after successful CDR completion (see Figure 8.3). Although the build occurs during EMD, this is also the first (and possibly only) production system. As such, to achieve an acceptable level of risk, the system level manufacturing maturity must meet MRL 8 criteria at the CDR decision point, and the sub-system and component levels maturity must meet MRL 8 or 9 criteria. As a waypoint in mid-development between PDR and CDR, an MRL 7 assessment may be performed to meet program objectives.

In addition, for space systems, where hardware replacement or repair is not possible and quality and reliability are of paramount importance, the initial units (*i.e.*, EMD units for satellites) are required to meet all mission operational requirements. This dictates complete documentation and traceability of all flight units (the “as-built” documentation), which is key in support of on-orbit anomaly analysis. Quality and reliability must be emphasized when conducting manufacturing readiness assessments of space vehicles.

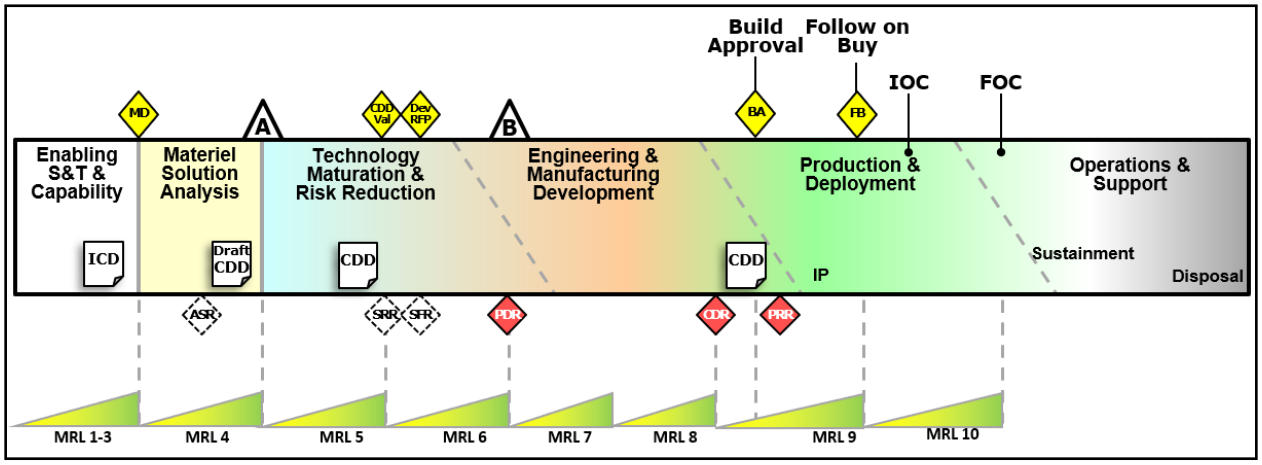



**Figure 8-3 – Single or Limited System Acquisitions – except Ships Relationship of MRLs to Decision Points**

Certain criteria and language in the MRL threads and sub-threads may require adhering to a more stringent definition to meet the requirements for single or limited system acquisitions. For example, in the Materials Maturity sub-thread (D.1), MRL 7, "Material Maturity sufficient for pilot line build," sufficient means fully characterized. For MRL 8, "Materials proven and validated during EMD as adequate to support LRIP," as LRIP is the initial production EMD system, adequate means fully proven and validated. The strict adherence to a high-level definition reduces risk for successful production of single or limited systems where manufacturing risk control is a primary concern.

Another example, in the Manufacturing Process Maturity sub-thread (E.2), demonstrating and verifying manufacturing processes can be difficult, as can collection and calculation of process capability when producing a single system. Existing proven and capable manufacturing procedures and processes should be utilized for production process verification as much as possible and equipment utilized must meet capability requirements.

### 8.4.2 Single or Limited Systems – Ships

For ship acquisitions, a complex systems of systems, the major systems and subsystems should be fully characterized, if not in production (*i.e.*, MRL 8 or 9) before ship CDR. At the overall ship development level, as Milestone B typically takes place three to six months after CDR, the overall ship design should be at MRL 7 by Milestone B.

Multiple shipyards may be working independently to prepare functional designs in accordance with their particular shipyard's production methodology and processes, moving their designs towards MRL 8.

In order to improve governance and insight, ensure alignment between capability requirements and acquisition, improve senior leadership decision making, and gain better understanding of risks and costs, the Department of the Navy has implemented a "2-pass, 6-gate" process. Gates 1, 2, and 3 are "requirement gates", starting prior to Materiel Development Decision which lead to approval of the ICD, the AoA guidance, section of an AoA "optimal" alternative, approval of a CDD, development of a CONOPS, and approval of a System Design Specification (SDS) Development Plan. At System Design (SD) 1 Final Design Review (equivalent to PDR) the system maturity should be at MRL 6. Gates 4, 5, and 6, the "acquisition" gates, start after Gate 3, end after Milestone B (initial EMD phase). This process results in approval of the SDS, releasing of the RFP, assessing readiness for production, and approval of the Initial Baseline Review. Post Gate 4 (and potentially Gate 5) with the SD2 completion (equivalent to CDR) at Milestone B, the system maturity should be at MRL 7.

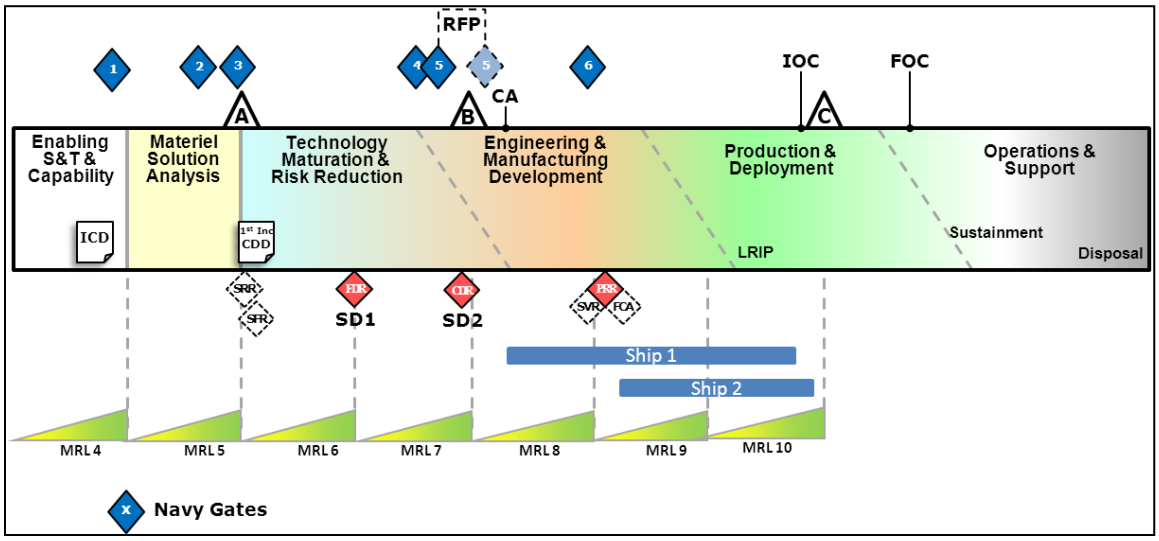



**Figure 8-4 – Single or Limited System Acquisitions – Ships Relationship of MRLs to Decision Points**

Once MS B has taken place, the ship's detailed design and construction begins. With Contract Award (CA), the winning shipyard continues with the design and construction in preparation for PRR at MRL 8. A year or more may elapse between CA and PRR, with PRR required before the LRIP/lead ship construction start decision (laying the keel) and follow-on ships.

For ships at CDR all major ship sub-systems (propulsion, weapon systems, combat systems, etc.) required for the platform to function as a ship should be at MRL 8. Also, any sub-system in this systems-of-systems that is not possible to replace or retrofit must be at MRL 8. To reach this level of maturity, modeling and simulations, including potentially building full scale subsystems (not part of the ship systems) may be used.

### 8.4.3 Summary

In summary, MRL Assessments based on MRL criteria can encompass single or limited system acquisitions with adaptions to the assessment process and maturity required at decision points or milestones.

## 8.5 MRL Criteria for Industry

Industry can leverage and adapt the DoD MRL criteria to their company processes. The criteria translate easily across both military and commercial application.

A simple step to adapt the tool begins with embedding business vernacular into the criteria that improve the understanding and acceptance of the assessment process. For example, using company vocabulary instead of the DoD terms (*e.g.*, business or engineering Gates instead of Milestones) as depicted in Figure 8.5.

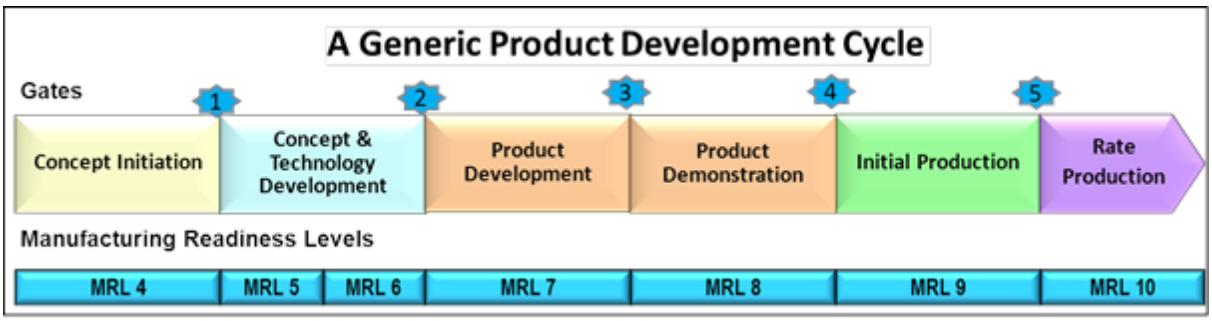



**Figure 8-5 – Gated Product Development**

To aid in building the manufacturing maturation plan, a company may create a roadmap to follow into the future, emphasizing value added processes instead of identifying what actions were not completed.

A company can embed the complete MRL criteria and assessment process into one spreadsheet or management dashboard. As results are presented and team buy-in increases, improvements are seen by increased productivity. Standardized report out presentation or standardized dashboard formats across the business aids in better upper level management buy-in. When a business assumes ownership of the MRL criteria, it can be concise and controllable, allowing for quick resolution of interpretation problems. Ownership also allows lessons learned to be added to the MRL criteria. For example, including an Environmental, Safety, and Health (ESH) thread, insures that ESH issues are addressed early in the maturation process.

Manufacturing assessments using MRL criteria should be adapted as an integral required element of a company's new product introduction process. Similar to implementation of ISO 9000/9001 and AS6500, implementation of manufacturing assessments using the MRL criteria to manage risk will improve company operations,

leading to improved quality, reduced cycle times, reduced costs, and positive overall impact.

# APPENDIX A – Detailed MRL Criteria

**Table A-1. Manufacturing Readiness Levels for the Technology and Industrial Base Thread**

| Acquisition Phase | | Pre-Materiel Development Decision (Pre-MDD) | | | Materiel Solution Analysis (MSA) | Technology Maturation and Risk Reduction (TMRR) | | Engineering & Manufacturing Development (EMD) | | Low-Rate Initial Production (LRIP) | Full-Rate Production (FRP) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Reviews | | | | MDD | ASR A | SRR/SFR | PDR B | CDR | PRR/SVR C | PCA FRP | |
| Thread | Sub-Thread | MRL 1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 | MRL 7 | MRL 8 | MRL 9 | MRL 10 |
| A - Technology and Industrial Base | A.0 Technology Maturity | Should be assessed at TRL 1. | Should be assessed at TRL 2. | Should be assessed at TRL 3. | Should be assessed at TRL 4. | Should be assessed at TRL 5. | Should be assessed at TRL 6. | Should be assessed at TRL 7. | Should be assessed at TRL 8. | Should be assessed at TRL 9. | Should be assessed at TRL 9. |
| | A.1 Industrial Base | Global trends in emerging industrial base capabilities identified. | Potential industrial base capability gaps identified. | Industrial base capabilities for potential sources identified for system concepts. | Industrial base including capacities and capabilities surveyed for preferred materiel solution, key technologies, components, and/or key processes. Industrial base considerations included in AoA with capability risks and issues documented in the AS. | Industrial base analysis initiated to identify potential manufacturing sources. Sole/single/FOCI sources identified and planning initiated to minimize risks. | Industrial base (IB) analysis including capacity and capability for MS B completed. Industrial capability in place to support manufacturing of development articles. Plans to avoid or justification of sole/single/FOCI IB sources complete. | Industrial base capacity and capability to support production analyzed. Justified Sole/single/FOCI industrial base sources assessed and monitored. | Industrial base capacity and capability analysis for MS C completed. Industrial capability is in place to support LRIP. | Industrial base capacity and capability analysis for FRP has been completed and capability is in place to support start of FRP. | Industrial base analysis capacity and capability supports FRP and includes support for modifications, upgrades, surge and other potential manufacturing requirements. |
| | A.2 Manufacturing Technology Development | Global trends in manufacturing science and technology identified (i.e., concepts, capabilities). | Potential manufacturing science and technology gaps identified. | Manufacturing technology requirements identified to address potential capability gaps for system concepts. | Manufacturing technology development initiatives defined for preferred materiel solution. Manufacturing technology development requirements considered in the AoA. | Required manufacturing technology development efforts initiated. | Manufacturing technology efforts continuing. Required manufacturing technology development solutions demonstrated in a production relevant environment. | Manufacturing technology efforts continuing. Required manufacturing technology development solutions demonstrated in a production representative environment. | Primary manufacturing technology efforts concluding. Improvement efforts continuing. Required manufacturing technology solutions validated on a pilot line. | Manufacturing technology process improvements efforts initiated for FRP. | Manufacturing technology continuous process improvements ongoing. |

**Table A-2. Manufacturing Readiness Levels for the Design Thread**

| Acquisition Phase | | Pre-Materiel Development Decision (Pre-MDD) | | | Materiel Solution Analysis (MSA) | Technology Maturation and Risk Reduction (TMRR) | | Engineering & Manufacturing Development (EMD) | | Low-Rate Initial Production (LRIP) | Full-Rate Production (FRP) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Reviews | | | | MDD | ASR A | SRR/SFR | PDR B | CDR | PRR/SVR C | PCA FRP | |
| Thread | Sub-Thread | MRL 1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 | MRL 7 | MRL 8 | MRL 9 | MRL 10 |
| B - Design | B.1 Producibility Program | Hypotheses developed for cause-effect relationships between technology variables and producibility. | Studies performed to test hypotheses regarding cause-effect relationships between technology variables and producibility. Elements identified which have a potential impact to producibility (i.e., materials, processes, capabilities, limitations). | System concept elements evaluated for manufacturability and producibility using experiments and modelsing, and simulation. | Initial producibility assessments of preferred materiel solution complete. Results considered in AoA and documented in AS key components/technologies. | Producibility and manufacturability assessments of key technologies and components initiated. Ongoing design trades consider manufacturing processes and industrial base capability constraints. Manufacturing processes assessed for capability to be tested and verified in production. Manufacturing processes assessed for influence on O&S. | Producibility assessments and producibility trade studies (performance vs. producibility) of key technologies/components completed. Results used to shape AS, SEP, manufacturing and producibility plans, and planning for EMD or technology insertion programs. Preliminary design choices assessed against manufacturing processes and industrial base capability constraints. Producibility enhancement efforts (i.e., DFM, DFA, etc.) initiated. | Detailed producibility trade studies using knowledge of key design characteristics and related manufacturing process capability completed. Producibility enhancement efforts (i.e., DFM, DFA, etc.) ongoing for optimized integrated system. Manufacturing processes re-assessed as needed for capability to be tested and verified. Manufacturing processes re-assessed as needed for potential influence on O&S. | Producibility improvements implemented on system. Known producibility risks and issues managed for LRIP. | Prior producibility improvements analyzed for effectiveness during LRIP. Producibility risks and issues discovered in LRIP managed for FRP. | Design producibility improvements demonstrated in FRP. Process producibility improvements ongoing. All modifications, upgrades, DMSMS and other changes assessed for producibility. |
| | B.2 Design Maturity | Current capability deficiencies and gaps identified. | Analyses performed to evaluate the feasibility of potential solutions to address capability gaps. | High-level performance, lifecycle, and technical requirements defined and evaluated for system concepts. Trade-offs in design options assessed based on experiments and initial MOEs. | Form, fit, and function constraints identified for preferred materiel solution. SEP and T&E Strategy recognize the need for the establishment and validation of manufacturing capability and management of manufacturing risk for the product life cycle. Initial KPPs identified for preferred materiel solution. System technical requirements and measures to support required capabilities identified. | Lower level performance requirements sufficient to proceed to preliminary design. All enabling/critical technologies and components identified and the product lifecycle considered. Evaluation of the design for KCs initiated. Product data required for prototype component manufacturing released. | System allocated baseline established. Product requirements and features are well enough defined to support PDR. Product data essential for subsystem/ system prototyping has been released, and all enabling/critical components have been prototyped. Preliminary KCs for the design identified and mitigation plans initiated. | Product design and features are well enough defined to support CDR, even though design change traffic may be significant. All product data essential for component manufacturing released. Potential KC risks and issues identified with mitigation plans in place. | Detailed design of product features and interfaces completed. All product data essential for system manufacturing released. Design change traffic does not significantly impact LRIP. KCs are attainable based upon pilot line demonstrations. | Major product design features and configuration are stable. System design has been validated through operational testing of LRIP items. PCA or equivalent complete as necessary. Design change traffic is limited. All KCs are controlled in LRIP to appropriate quality levels. | Product design is stable. Design changes are few and generally limited to those required for continuous improvement or in reaction to obsolescence. All KCs are controlled in FRP to appropriate quality levels. |

**Table A-3. Manufacturing Readiness Levels for the Cost and Funding Thread**

| Acquisition Phase | | Pre-Materiel Development Decision (Pre-MDD) | | | Materiel Solution Analysis (MSA) | Technology Maturation and Risk Reduction (TMRR) | | Engineering & Manufacturing Development (EMD) | | Low-Rate Initial Production (LRIP) | Full-Rate Production (FRP) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Reviews | | | | MDD | ASR A | SRR/SFR | PDR B | CDR | PRR/SVR C | PCA FRP | |
| Thread | Sub-Thread | MRL 1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 | MRL 7 | MRL 8 | MRL 9 | MRL 10 |
| C - Cost & Funding | C.1 Production Cost Knowledge (Cost modeling) | Hypotheses developed regarding technology impact on affordability. | Cost model approach defined. | Manufacturing cost estimates for system concepts developed. Initial cost models developed which include high-level process steps and materials. | Cost estimates refined based on anticipated production volumes associated with preferred materiel solution. Cost model updated with identified cost drivers (i.e., process variables, manufacturing, materials, and special requirements). Cost model supports AoA and ASR. | Prototype components produced in a production relevant environment, or simulations drive end-to-end cost models. Cost model includes materials, labor, equipment, tooling/STE/SIE, setup, yield/scrap/rework, WIP, and capability/capacity constraints. | Cost model updated with design requirements, material specifications, tolerances, IMS, results of system/subsystem simulations and production relevant prototype demonstrations. | Cost model updated with the results of systems/sub-systems produced in a production representative environment, production plant layout and design, and obsolescence solutions. | Cost model updated with results of pilot line build. | FRP cost model updated with result of LRIP build. | Cost model validated against actual FRP cost. |
| | C.2 Cost Analysis | Initial manufacturing and quality costs identified. | Potential manufacturing and quality cost drivers and system affordability gaps identified. | Analysis conducted to refine manufacturing and quality cost drivers, risks, and development strategy (i.e. lab to pilot to factory). Potential cost reduction and system affordability gap closure strategies identified. | Producibility and lifecycle cost risks and issues assessed for preferred materiel solution. Initial cost analysis supports the AoA and ASR. | Costs analyzed using prototype component actuals to ensure target costs are achievable. Decisions regarding design choices, make/buy, capacity, process capability, sources, quality, KCs, yield/rate, and variability influenced by cost models. | Costs analyzed using prototype system/sub-system actuals to ensure target costs are achievable. Cost targets allocated to subsystems. Cost reduction and avoidance strategies developed. Manufacturing cost drivers for "Should-Cost" model provided. | Manufacturing costs rolled up to system/sub-system level and tracked against targets. Detailed trade studies and engineering change requests supported by cost estimates. Cost reduction and avoidance strategies underway. Manufacturing cost drivers for "Should-Cost" model updated. | Costs analyzed using pilot line actuals to ensure target costs are achievable. Manufacturing cost analysis supports proposed changes to requirements or configuration. Cost reduction initiatives ongoing. Manufacturing cost drivers for "Should-Cost" model updated. | LRIP cost goals met and learning curves analyzed with actual data. Cost reduction initiatives ongoing. Touch labor efficiency analyzed to meet production rates and elements of inefficiency are identified with plans in place for reduction. | FRP cost goals met. Cost reduction initiatives ongoing. |
| | C.3 Manufacturing Investment Budget | Potential manufacturing investment strategy developed. | Program/projects have reasonable budget estimates for reaching MRL 3 through experiment. Manufacturing investment budget ROM estimates identified to support industrial base and manufacturing capability gap closure strategies. | Program/projects have reasonable budget estimates for reaching MRL 4 by MS A. Preliminary manufacturing investment budget estimates for manufacturing gap closure recommendations developed. | Manufacturing technology budget initiatives developed and incorporated to reduce costs. Program has reasonable budget estimate for reaching MRL 6 by MS B. Estimate includes capital investment for production relevant equipment. All outstanding MRL 4 risks and issues understood with approved mitigation plans in place. | Program has updated budget estimate for reaching MRL 6 by MS B. All outstanding MRL 5 risks and issues understood with approved mitigation plans in place. | Program has reasonable budget estimate for reaching MRL 8 by MS C. Estimate includes capital investment for production-representative equipment by CDR and pilot line equipment by MS C. All outstanding MRL 6 risks and issues understood with approved mitigation plans in place. | Program has updated budget estimate for reaching MRL 8 by MS C. All outstanding MRL 7 risks and issues understood with approved mitigation plans in place. | Program has reasonable budget estimate for reaching MRL 9 by the FRP decision point. Estimate includes investment for LRIP and FRP. All outstanding MRL 8 risks and issues understood with approved mitigation plans in place. | Program has reasonable budget estimate for FRP. All outstanding MRL 9 risks and issues understood with approved mitigation plans in place. | Production budgets sufficient for production at required rates and schedule to support funded program. |

| Acquisition Phase | | Pre-Materiel Development Decision (Pre-MDD) | | | Materiel Solution Analysis (MSA) | Technology Maturation and Risk Reduction (TMRR) | | Engineering & Manufacturing Development (EMD) | | Low-Rate Initial Production (LRIP) | Full-Rate Production (FRP) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Reviews | | | | MDD | ASR A | SRR/SFR | PDR B | CDR | PRR/SVR C | PCA FRP | |
| Thread | Sub-Thread | MRL 1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 | MRL 7 | MRL 8 | MRL 9 | MRL 10 |
| D - Materials (Raw Materials, Components, Sub-assemblies and Sub-systems) | D.1 Maturity | New material properties and characteristics surveyed and identified for research (e.g., manufacturability, quality). | Potential effects of new material properties on design application manufacturability and quality predicted based on research. | Effects of new material properties on design concept manufacturability and quality validated using experiments and models. | New materials and components for preferred materiel solution demonstrated in a laboratory environment. | Materials manufactured or produced in a prototype environment (may be in a similar application/program). Maturation efforts in place to address new material production risks for technology demonstration. | Material maturity verified through technology demonstration articles. Preliminary material specifications in place. Material properties adequately characterized. | Material maturity sufficient for pilot line build. Material specifications approved. | Materials proven and validated during EMD as adequate to support LRIP. Material specifications stable. | Materials controlled to specifications in LRIP. Materials proven and validated as adequate to support FRP. | Materials controlled to specifications in FRP. |
| | D.2 Availability | Global trends for material availability, obsolescence, and DMSMS surveyed and identified for research. | Material availability, obsolescence, and DMSMS gaps identified. | Material availability, obsolescence, and DMSMS gap closure strategy defined. | Projected lead times identified for all difficult to obtain, difficult to process, or hazardous materials. Quantities and lead times estimated. Material availability risks and issues for preferred materiel solution considered in AoA. Mitigation plans incorporated in SEP for the preferred materiel solution. | Availability risks and issues addressed for prototype build. Significant material risks identified for all materials. Planning initiated to address scale-up issues. | Availability risks and issues addressed to meet EMD build. Long-lead items identified. Potential obsolescence issues identified. Components assessed for future DMSMS risk. | Availability risks and issues addressed to meet LRIP builds. Long lead procurements identified and mitigated. Obsolescence plan in place. DMSMS mitigation strategies for components in place. | Availability risks and issues managed for LRIP. Long lead procurement initiated for LRIP. Availability issues addressed to meet FRP builds. | Long lead procurement initiated for FRP. Availability risks and issues managed for FRP. | All material availability risks and issues managed. |
| | D.3 Supply Chain Management | Global trends for supply chain capability and capacity surveyed. | Potential supply chain capability and capacity gaps identified. | Supply chain capability and capacity gap closure strategies defined. | Survey of potential supply chain sources for preferred materiel solution completed. Supply chain capability and capacity analyses considered in the AoA. | Potential supply chain sources identified and evaluated as able to support prototype build. | Lifecycle Supply Chain requirements updated. Critical suppliers list updated. Supply chain plans in place (e.g. teaming agreements, etc.) supporting an EMD contract award. | Effective supply chain management processes defined, documented, and in place. Plan developed for predictive indicators. Assessment of critical first tier supply chain completed (i.e., capability, capacity, etc.). | Assessment of critical second and lower tier supply chain completed. Robust requirements flow down processes in place and verified. Supplier compliance with program requirements and changes validated. Plan for predictive indicators for use in production updated. Supply chain adequate to support LRIP. | Long term agreements in place where practical. Prime's supplier management metrics (including thresholds and goals) in place and used to manage risks. Predictive indicators to manage suppliers in place. Supply chain is stable and adequate to support FRP. | Supply chain proven and supports FRP requirements. |
| | D.4 Special Handling (i.e. GFP, shelf life, security, hazardous materials, storage environment, ESH, etc.) | Hazardous materials identified and safety procedures in place. | Raw materials and components assessed for special handling and potential regulatory requirements. | ESH compliance risk identified. List of hazardous materials identified and alternatives evaluated. Special handling procedures applied in the lab. Special handling [illegible] assessed. | ESH compliance risk mitigated in lab environment. List of hazardous materials updated and alternatives assessed. Special handling procedures applied and disposal procedures evaluated. Special handling requirements identified, analyzed, and documented in the SEP. | ESH requirements and special handling procedures applied in production relevant environment. Special handling requirement gaps identified. New special handling processes demonstrated in lab environment. | ESH requirements addressed and documented. Special handling procedures demonstrated in production relevant environment. Plans to address special handling requirement gaps, risks, and issues complete. Manufacturing assessed for material storage and waste handling risks. | ESH compliance demonstrated in production representative environment. Special handling procedures applied in production representative environment. Special handling procedures developed and annotated on work instructions for pilot line. Hazardous material storage and disposal plan in place for the pilot line. | ESH compliance demonstrated in pilot line production. Special handling procedures applied in pilot line environment and demonstrated in EMD or technology insertion programs. Special handling risks and issues managed for LRIP. All work instructions contain special handling provisions as required. Hazardous material storage and disposal plan evaluated and in place for LRIP. | ESH compliance demonstrated in LRIP. Special handling, and hazardous material storage and disposal procedures demonstrated in LRIP environment. Special handling, and hazardous material storage and disposal risks and issues managed for FRP. | ESH compliance demonstrated in FRP. Special handling and hazardous material storage and disposal procedures effectively implemented in FRP. |

**Table A-5. Manufacturing Readiness Levels for the Process Capability and Control Thread**

| Acquisition Phase | | Pre-Materiel Development Decision (Pre-MDD) | | | Materiel Solution Analysis (MSA) | Technology Maturation and Risk Reduction (TMRR) | | Engineering & Manufacturing Development (EMD) | | Low-Rate Initial Production (LRIP) | Full-Rate Production (FRP) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Reviews | | | | MDD | ASR A | SRR/SFR | PDR B | CDR | PRR/SVR C | PCA FRP | |
| Thread | Sub-Thread | MRL 1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 | MRL 7 | MRL 8 | MRL 9 | MRL 10 |
| E - Process Capability & Control | E.1 Modeling & Simulation (Product & Process) | Modeling and simulation approaches/tools identified to support manufacturing and quality activities. | Modeling and simulation development initiated. | Manufacturing and quality gaps for system concepts identified using modeling and simulation. | Modeling and simulation tools utilized to define manufacturing and quality requirements for preferred materiel solution. Modeling and simulation results considered in the AoA." | Initial modeling & simulations (product or process) developed at the component level and used to determine constraints. | Initial modeling & simulations developed at the sub-system or system level, and used to determine system constraints. | Modeling & simulations used to determine system constraints and to identify improvement opportunities. | Modeling & simulations verified by pilot line build. Results used to improve process and demonstrate that LRIP requirements can be met. | Modeling & simulations verified by LRIP build, assist in management of LRIP, and demonstrate that FRP requirements can be met. | Modeling & simulations verified by FRP build. Production simulation models used as tools to assist in management of FRP. |
| | E.2 Manufacturing Process Maturity | Hypotheses developed regarding cause-effect relationships between process variables and process stability and repeatability. | Studies performed to test hypotheses regarding cause-effect relationships. Initial process approaches identified. | Cause-effect relationships between process control variables and process stability and repeatability validated through laboratory experiments. Critical process control variables identified. | Maturity of critical processes for preferred materiel solution assessed. Process capability requirements and improvement plans developed and documented in the SEP. | Process Maturity assessed on similar processes in production. Process capability requirements identified for pilot line, LRIP and FRP. | Manufacturing processes demonstrated in production relevant environment. Collection or estimation of process capability data from prototype build and refinement of process capability requirements initiated. | Manufacturing processes demonstrated in a production representative environment. Collection and/or estimation of process capability data and refinement of process capability requirements ongoing. | Manufacturing processes for LRIP verified on a pilot line. Process Capability data from pilot line meets target. Process capability requirements for LRIP and FRP refined based upon pilot line data. | Manufacturing processes are stable, adequately controlled, capable, and have achieved program LRIP objectives. Variability experiments conducted to show FRP impact and potential for continuous improvement. | Manufacturing processes are stable, adequately controlled, capable, and have achieved program FRP objectives. |
| | E.3 Process Yields and Rates | Hypotheses developed regarding future state manufacturing yields and rates. | Studies performed to test hypotheses regarding yields and rates. | Initial estimates of yields and rates for system concepts identified through laboratory. Yield and rate gaps for system concepts identified. | Yield and rate assessments on preferred materiel solution completed and considered in the AoA. Yield and rate gap closure strategies identified for the preferred materiel solution and documented in the SEP. | Target yields and rates established for pilot line, LRIP, and FRP. Yield and rate issues identified. Improvement plans developed/initiated. | Yields and rates from production relevant environment evaluated against targets and the results feed improvement plan. | Yields and rates from production representative environment evaluated against pilot line targets and the results feed improvement plans. | Pilot line targets achieved. Yields and rates required to begin LRIP refined using pilot line results. Improvement plans ongoing and updated. | LRIP yield and rate targets achieved. Yields and rates required to begin FRP refined using LRIP results. Yield improvements on-going. | FRP yield and rate targets achieved. Yield improvements on-going. |

**Table A-6. Manufacturing Readiness Levels for the Quality Management Thread**

| Acquisition Phase | | Pre-Materiel Development Decision (Pre-MDD) | | | Materiel Solution Analysis (MSA) | Technology Maturation and Risk Reduction (TMRR) | | Engineering & Manufacturing Development (EMD) | | Low-Rate Initial Production (LRIP) | Full-Rate Production (FRP) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Reviews | | | | MDD | ASR | A SRR/SFR | PDR | B CDR | PRR/SVR | C PCA | FRP |
| Thread | Sub-Thread | MRL 1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 | MRL 7 | MRL 8 | MRL 9 | MRL 10 |
| F - Quality | F.1 Quality Management | Quality management considerations surveyed and included in early planning activities | Quality management needs assessed, analyzed, and validated. | Quality management requirements for system concepts identified. | Quality strategy for the preferred materiel solution developed, considered in the AoA, and documented in the SEP and the AS. | Quality strategy updated to reflect KC identification activities. | Initial Quality Plan and QMS are in place. Quality risks, issues, and metrics have been identified and improvement plans initiated. | Quality targets established. QMS elements (i.e., control of nonconforming material, corrective action, etc.) meet requirements of appropriate industry standards. Program-specific Quality Program Plan developed. | Program-specific Quality Program Plan established. Program Quality Manager assigned. Quality targets assessed against pilot line, results feed continuous quality improvements. | Quality targets verified on LRIP line. Continuous quality improvement on-going. Management review of Quality measures conducted on regular basis and appropriate actions taken. | Quality targets verified on FRP line. Continuous quality improvement on-going. Statistical controls applied where appropriate. |
| | F.2 Product Quality | Quality metrology state of the art surveyed. Hypotheses developed regarding cause-effect relationships between technology variables and quality. | Studies performed to test hypotheses regarding cause-effect relationships between technology variables and quality. Elements identified which have a potential impact on quality (i.e., materials, processes, capabilities, limitations). | System concept elements evaluated for quality using experiments, modeling and simulation. Initial product quality requirements, risks, and issues identified. Inspection technologies identified. | Product quality requirements and the inspection and acceptance testing strategy for the preferred materiel solution considered in AoA and documented in the AS. Product quality risk and issue mitigation plans documented in the SEP. | Roles and responsibilities identified for acceptance test procedures, in-process and final inspections, and statistical process controls for prototype units. | KC management approach defined. Initial requirements identified for acceptance test procedures and in-process and final inspection requirements for EMD units. Appropriate inspection and acceptance test procedures identified for prototype units. | Quality data from the production representative environment collected and analyzed and results used to shape improvement plans. Control plans completed for management of KCs. Test and Inspection plans being developed for EMD units. | KCs managed. Measurement procedures and controls in place (e.g. SPC, FRACAS, audits, customer satisfaction, etc.). Pilot line data meets capability requirements for all KCs. Test and Inspection plans complete and validated for production units. | Data from LRIP demonstrates production processes, for all KCs and other manufacturing processes critical to quality, are capable and under control for FRP. | KCs controlled at rate. Results achieve targeted statistical level on all KCs. Results reflect continuous improvement. |
| | F.3 Supplier Quality/ Management | Supplier quality and quality management systems state of the art surveyed. | Initial supplier quality and quality management systems evaluated. | Supplier quality and quality management system requirements for system concepts identified. | Potential supplier quality capabilities, risks, and issues identified for the preferred materiel solution, including subtier suppliers. Supplier quality management system requirements defined, and documented in the AS. | Supply base quality capabilities and risks identified, including subtier supplier quality management. | Supply base quality improvement initiatives identified addressing supplier QMS shortfalls, including subtier supplier quality management. | Key supplier QMSs meet appropriate industry standards. Supplier quality data from production representative units collected and analyzed. Strategy for audits of critical supplier processes outlined. | Supplier program-specific QMSs adequate. Supplier products qualification testing and first article inspection completed. Acceptance testing of supplier products adequate to begin LRIP. Plan for subcontractor process audits in place and implemented by prime contractor. | Supplier quality management of KCs and other critical manufacturing processes demonstrates capability and control for FRP. Acceptance testing of supplier products reflects control of quality adequate to begin FRP. Subcontractor quality audits performed as necessary to ensure subcontractor specification compliance. | Supplier quality data reflects adequate management of KCs and control of critical manufacturing processes, including quality management down to subtier suppliers. Results achieve high statistical level (e.g., 6-sigma) on all critical dimensions. Subcontractor quality audits performed as necessary to ensure subcontractor specification compliance. |

**Table A-7. Manufacturing Readiness Levels for the Manufacturing Personnel and Facilities Threads**

# APPENDIX A – Detailed MRL Criteria

| Acquisition Phase | | Pre-Materiel Development Decision (Pre-MDD) | | | Materiel Solution Analysis (MSA) | Technology Maturation and Risk Reduction (TMRR) | | Engineering & Manufacturing Development (EMD) | | Low-Rate Initial Production (LRIP) | Full-Rate Production (FRP) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Reviews | | | | MDD | ASR | SRR/SFR | PDR | CDR | PRR/SVR | PCA | FRP |
| Thread | Sub-Thread | MRL 1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 | MRL 7 | MRL 8 | MRL 9 | MRL 10 |
| G - Manufacturing Workforce (Engineering & Production) | G.1 Manufacturing Workforce (Engineering & Production) | Workforce skill sets to support emerging trends in manufacturing and technology surveyed. | Workforce skill sets to support emerging trends in manufacturing and technology evaluated. | Workforce skill set requirements for system concepts identified. Workforce skill set capability gaps identified. | Workforce skill set requirements for preferred materiel solution identified and considered in the AoA. Workforce training and development requirements to close skill set gaps defined. Availability of workforce for the TMRR phase determined. | Skill sets identified and plans developed to meet prototype and production needs. Special skills certification and training requirements established. | Manufacturing workforce skills available for the production relevant environment. Resources (quantities and skill sets) identified and initial plans developed to achieve requirements for pilot line and production. | Manufacturing workforce resource requirements identified and plans developed to achieve pilot line requirements. Plans to achieve LRIP workforce requirements updated. Pilot line workforce trained in production representative environment. | Manufacturing workforce resource requirements identified and plans developed to achieve LRIP requirements. LRIP personnel trained on pilot line where possible. Plans to achieve FRP workforce requirements initiated based on pilot line. | LRIP personnel requirements met. Plan to achieve FRP workforce requirements implemented. | FRP personnel requirements met. Production workforce skill sets maintained in spite of workforce attrition. |
| H - Facilities | H.1 Tooling/STE/SIE | State of the art tooling, test and inspection equipment surveyed. | Potential tooling, STE, and SIE requirements identified. | Tooling, STE, and SIE requirements and gaps for system concepts identified. | Tooling/STE/SIE requirements for the preferred materiel solution considered as part of AoA. | Tooling and STE/SIE requirements identified with supporting rationale and schedule. | Prototype tooling and STE/SIE concepts demonstrated in production relevant environment. Requirements development efforts for production tooling and STE/SIE complete. | Design and development efforts for production tooling and STE/SIE initiated with STE/SIE validation plans complete. Manufacturing equipment maintenance strategy developed. | Tooling, test and inspection equipment proven on pilot line and additional requirements identified for LRIP. STE/SIE validated as part of pilot line validation IAW validation plan. Manufacturing equipment maintenance demonstrated on pilot line. | All tooling, test and inspection equipment proven in LRIP and additional requirements identified for FRP. Manufacturing equipment maintenance schedule demonstrated. STE/SIE validation maintained as necessary. | Proven tooling, test and inspection equipment in place to support maximum FRP. Planned equipment maintenance schedule achieved. STE/SIE validation maintained as necessary. |
| | H.2 Facilities | Current facility capabilities and capacity surveyed. | Potential facility capabilities and capacity requirements identified. | Facility capabilities and capacity requirements and gaps for system concepts identified. | Capability and availability of manufacturing facilities for prototype development and production of the preferred materiel solution evaluated, included in the AoA, and documented in the AS and SEP. Human factors & ergonomics and safety requirements for manufacturing (personnel, processes & equipment) identified. | Manufacturing facilities identified and plans developed to produce prototypes. Human factors & ergonomics and safety requirements for manufacturing (personnel, processes & equipment) assessed. | Manufacturing facilities identified and plans developed to produce pilot line build. Human factors & ergonomics and safety requirements for manufacturing (personnel, processes & equipment) verified in a production relevant environment. | Manufacturing facilities identified and plans developed to produce LRIP build. Human factors & ergonomics and safety practices for manufacturing (personnel, processes & equipment) validated in a production representative environment. | Pilot line facilities demonstrated. Manufacturing facilities adequate to begin LRIP. Plans in place to support transition to FRP. Workplace safety is adequate. Human factors & ergonomics and safety practices for manufacturing (personnel, processes & equipment) demonstrated on a pilot line. | Manufacturing facilities in place and demonstrated in LRIP. Capacity plans adequate to support FRP. Human factors & ergonomics and safety practices for manufacturing (personnel, processes & equipment) demonstrated in LRIP . | Production facilities in place and capacity demonstrated to meet maximum FRP requirements. Human factors & ergonomics and safety requirements for manufacturing (personnel, processes & equipment) demonstrated in FRP. |

**Table A-8. Manufacturing Readiness Levels for the Manufacturing Management Thread**

| Acquisition Phase | | Pre-Materiel Development Decision (Pre-MDD) | | | Materiel Solution Analysis (MSA) | Technology Maturation and Risk Reduction (TMRR) | | Engineering & Manufacturing Development (EMD) | | Low-Rate Initial Production (LRIP) | Full-Rate Production (FRP) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical Reviews | | | | MDD | ASR A | SRR/SFR | PDR B | CDR | PRR/SVR C | PCA FRP | |
| Thread | Sub-Thread | MRL 1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 | MRL 7 | MRL 8 | MRL 9 | MRL 10 |
| I - Manufacturing Management | I.1 Manufacturing Planning & Scheduling | Manufacturing management considerations surveyed and included in early planning activities. | Manufacturing management needs assessed, analyzed and validated. | Manufacturing management requirements for system concepts identified. | Manufacturing strategy for the preferred materiel solution developed, considered in the AoA, and documented in the AS. Prototype schedule risk mitigation efforts documented in the SEP. | Manufacturing strategy refined based upon preferred concept. Prototype schedule risk mitigation efforts initiated. | Initial manufacturing approach developed. All system design related manufacturing events included in IMP/IMS. Manufacturing risk, and issue mitigation approach for pilot line and/or technology insertion programs defined. | Initial Manufacturing Plan developed and included in IMP/IMS. Manufacturing risks and issues integrated into mitigation plans. Initial work instructions developed. Effective production control system in place to support pilot line. | Manufacturing Plan updated for LRIP. All manufacturing risks and issues identified and assessed with approved mitigation plans in place. Work instructions finalized. Effective production control system in place to support LRIP. | Manufacturing plan updated for FRP. All manufacturing risks and issues managed. Effective production control system in place to support FRP. | All manufacturing risks and issues managed. |
| | I.2 Materials Planning | Materials planning state of the art surveyed. | Initial availability, lead time, handling and storage requirements for potential materials and components evaluated. | Materials and components list for system concepts developed. Initial materials planning requirements (i.e., availability, lead times, handling, and storage) identified. | Materials and components list with estimates for availability, lead times, handling and storage requirements developed and considered in the AoA. | Make/buy evaluations initiated and include production considerations for pilot line, LRIP, and FRP needs. Lead times and other materials risks and issues identified. | Most material make/buy decisions complete, material risks and issues identified, and mitigation plans developed. BOM initiated. | Make/Buy decisions and BOM complete for pilot line build. Material planning systems in place for pilot line build. | Make/Buy decisions and BOM complete to support LRIP. Material planning systems proven on pilot line for LRIP build. | Make/Buy decisions and BOM complete to support FRP. Material planning systems proven in LRIP and sufficient for FRP. | Material planning systems validated on FRP build. |
| | I.3 Manufacturing OT Cybersecurity | | | OT cybersecurity requirements for system concepts identified. OT cybersecurity vulnerabilities of potential manufacturing facilities identified. | Manufacturing operations cybersecurity capabilities and cyber-vulnerabilities evaluated. OT cybersecurity approach and requirements for the preferred materiel solution considered as part of AoA. OT cybersecurity risks in the anticipated industrial base have been assessed. Identify impacts of cybersecurity measures on manufacturing processes for preferred materiel solutions. Potential supply chain OT cybersecurity and vulnerability risks identified. | Required OT cybersecurity development efforts initiated. OT cyber Incident Reporting procedures developed. (e.g., System Security Plan). Potential OT cybersecurity measures are assessed for impacts to producibility and manufacturability. Supply chain OT cybersecurity and vulnerability risks assessed and risk management plans developed. Workforce trained as appropriate in cybersecurity. Cybersecurity requirements for OT systems identified (i.e., in-house factory systems, production equipment, STE/SIE, and tooling). | Required OT cybersecurity solutions demonstrated in a production relevant environment. OT cyber Incident Reporting procedures in place, including reporting, tracking, and corrective actions. Supply chain OT cybersecurity and vulnerability risk mitigation plans initiated. Workforce trained as appropriate in up-to-date cybersecurity procedures for production relevant environment. Planning for OT systems (i.e., in-house factory systems, production equipment, STE/SIE, and tooling) include cybersecurity and physical/digital access requirements. | Required OT cybersecurity solutions demonstrated in a production representative environment. OT cybersecurity Incident Reporting procedures in-place, including reporting, tracking, and corrective actions. Supply chain OT cybersecurity and vulnerability risk mitigation plans implemented. Workforce trained as appropriate in up-to-date cybersecurity procedures for production representative environment. Design of OT systems for facilities and equipment (i.e., in-house factory systems, production equipment, STE/SIE, and tooling) include cybersecurity and physical/digital controls and access requirements. | OT cybersecurity incidents are identified and assessed. OT cyber incidents throughout the supply chain are identified and assessed. Workforce trained as appropriate in up-to-date cybersecurity procedures for a pilot line environment. Planning and documentation for LRIP facilities and equipment OT systems including cybersecurity and physical/ digital controls and access requirements complete. OT cybersecurity procedures and controls validated on a pilot line. | OT cybersecurity incidents are identified and assessed. OT cyber incidents throughout the supply chain are identified and assessed. Workforce trained as appropriate in up-to-date cybersecurity procedures for production. Planning and documentation for FRP facilities and equipment OT systems including cybersecurity and physical/digital controls and access requirements complete. OT cybersecurity improvement efforts initiated for FRP. OT cybersecurity procedures implemented in LRIP and support FRP. | OT cybersecurity procedures reviewed and updated. OT cybersecurity capabilities and solutions tested to support modifications, upgrades, surge and other potential manufacturing requirements. Minimal cybersecurity incident occurrence. Prompt incident identification and corrective actions minimizing impacts. Workforce trained as appropriate in up-to-date cybersecurity procedures for production. OT cybersecurity continuous improvement efforts ongoing. |

# APPENDIX B – Acronyms

| | |
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| AAF | Adaptive Acquisition Framework |
| ACAT | Acquisition Category |
| ACTD | Advanced Concept Technology Demonstration |
| AoA | Analysis of Alternatives |
| AS | Acquisition Strategy |
| ASR | Alternative System Review |
| ATD | Advanced Technology Development |
| BOM | Bill of Materials |
| CA | Contract Award |
| CDD | Capability Development Document |
| CDR | Critical Design Review |
| CDRL | Contract Data Requirements List |
| CONOPS | Concept of Operations |
| COTS | Commercial-Off-the-Shelf |
| CPD | Capability Production Document |
| CT | Critical Technology |
| DA | Decision Authorities |
| DAB | Defense Acquisition Board |
| DAE | Defense Acquisition Executive |
| DAG | Defense Acquisition Guidebook |
| DCMA | Defense Contract Management Agency |
| DFA | Design for Assembly |
| DFARS | Defense Federal Acquisition Regulation Supplement |
| DFM | Design for Manufacturing |
| DID | Data Item Description |
| DoDI | Department of Defense Instruction |

# APPENDIX B

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| DMSMS | Diminishing Manufacturing Sources and Material Shortages |
| ESH | Environmental, Safety, and Health |
| EMD | Engineering and Manufacturing Development |
| FAR | Federal Acquisition Regulation |
| FCA | Functional Configuration Audit |
| FOC | Full Operational Capability |
| FRACAS | Failure, Reporting, Analysis, and Corrective Action System |
| FRP | Full Rate Production |
| GAO | Government Accountability Office |
| GFP | Government Furnished Property |
| IAQG | International Quality Group |
| IAW | In accordance with |
| ICA | Industrial Capabilities Assessment |
| ICD | Initial Capabilities Document |
| IMP | Integrated Master Plan |
| IMS | Integrated Master Schedule |
| IOC | Initial Operational Capability |
| ITR | Initial Technical Review |
| ITRA | Independent Technical Risk Assessment |
| JDMTP | Joint Defense Manufacturing Technology Panel |
| KC | Key Characteristic |
| KPP | Key Performance Parameter |
| LRIP | Low Rate Initial Production |
| MDA | Milestone Decision Authority |
| MDAP | Major Defense Acquisition Program |
| MDD | Materiel Development Decision |
| MMP | Manufacturing Maturation Plan |

| | |
|---|---|
| MRL | Manufacturing Readiness Level |
| MRO | Maintenance, Repair & Overhaul |
| MS A | Milestone A (DoD decision point) |
| MS B | Milestone B (DoD decision point) |
| MS C | Milestone C (DoD decision point) |
| MSA | Materiel Solution Analysis |
| MTA | Middle Tier of Acquisition |
| NASA | National Aeronautics and Space Agency |
| NTIB | National Technology Industrial Base |
| O&S | Operations and Support (DoD acquisition phase) |
| PCA | Physical Configuration Audit |
| PDR | Preliminary Design Review |
| Pre-MDD | Pre-Materiel Development Decision (DoD acquisition phase) |
| PQM | Production, Quality, and Manufacturing |
| PRR | Production Readiness Review |
| PSM | Product Support Manager Guidebook |
| PWB | Printed Wiring Board |
| QMS | Quality Management System |
| R&D | Research & Development |
| RFP | Request for Proposals |
| S&T | Science & Technology |
| SD | System Design |
| SDS | System Design Specification |
| SEP | Systems Engineering Plan |
| SFR | System Functional Review |
| SIE | Special Inspection Equipment |
| SME | Subject Matter Expert |

# APPENDIX B

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| SML | Sustainment Maturity Level |
| SOO | Statement of Objectives |
| SOW | Statement of Work |
| SPC | Statistical Process Control |
| SRR | System Requirement Review |
| STE | Special Test Equipment |
| SVR | System Verification Review |
| T&E | Test and Evaluation |
| TBD | To Be Determined |
| TMRR | Technology Maturation Risk Reduction |
| TRA | Technology Readiness Assessment |
| TRL | Technology Readiness Level |
| TRR | Test Readiness Review |
| UON | Urgent Operational Need |
| WBS | Work Breakdown Structure |
| WIP | Work in Process |

# Appendix C – Operational Technology Cybersecurity

Malicious actors have increasingly targeted the manufacturing industrial base with software attacks that could disrupt manufacturing operations and degrade the quality of the products being produced without being detected. Therefore, manufacturing readiness must include the protection of shop floor computer networks and equipment.

To assess this critical area, the MRL Working Group developed cybersecurity criteria to be included in multiple threads throughout the MRL matrix. The scope of the cybersecurity protections being assessed as a part of MRLs is limited to Operational Technologies (OT).

National Institute of Standards and Technology (NIST) standard NIST SP 800-37, 'Risk Management Framework for Information Systems and Organizations' defines **Operational Technology** as:

> *"Programmable systems or devices that interact with the physical environment (or manage devices that interact with the physical environment). These systems/devices detect or cause a direct change through the monitoring and/or control of devices, processes, and events. Examples include industrial control systems, building management systems, fire control systems, and physical access control mechanisms."*

Other examples of OT systems include NC machines, automated inspection equipment, and sensors. The term 'Operational Technology' (OT) is used to distinguish manufacturing technologies from Information Technologies (IT), Platform Information Technology (PIT)/mission data, or other enterprise/business Management Information Systems (MIS). OT sometimes slips through the cracks and may not always be controlled as tightly by the IT department or evaluated as thoroughly as part of IT reviews and audits. Therefore, OT should be addressed during MRL Assessments.

MRL Assessments using the cybersecurity criteria are not intended to be detailed cybersecurity audits. Instead, the purpose is to ask simple, fundamental questions to assess whether or not OT cybersecurity has been considered by the organization and determine whether or not basic, common-sense controls have been implemented. The end goal is to identify risks or potential major gaps in OT protection.

Manufacturing Subject Matter Experts (SME) who are conducting MRL Assessments are not expected to be cybersecurity experts. The new criteria are

written at a top level and address basic controls and considerations that do not require specialized cyber knowledge to evaluate. However, if the discussions begin to get too technical, or it appears something is not quite right based on unclear or incomplete answers, the Manufacturing SME should get help from a cybersecurity expert.

When asking questions about the OT cybersecurity criteria, team members should keep in mind that this is a new area for many companies. Organizations are still adapting to meet current and emerging DoD cybersecurity requirements and guidance. There will likely be a great deal of variability in how the OT cybersecurity controls are implemented, so evaluators will need to be flexible.

Prior to conducting Manufacturing Readiness Level assessments, the following business environment related to OT cybersecurity should be understood:

1) If the effort is under a Federal Acquisition Regulation (FAR) based contract, the MRL assessment team should be aware of what types of information the manufacturing facility handles:
    a. When classified information is involved, then FAR Clause 52.204-2 Security Requirements apply, and implementation status at the manufacturing facility is documented in the contractor's "Security Plan"—contact the Defense Counterintelligence and Security Agency.
    b. When Controlled Technical Information (CTI) (includes but not limited to export controlled), then Defense Federal Acquisition Regulation Supplement (DFARS) Clause 252.204-7012 *Safeguarding Covered Defense Information and Cyber Incident Reporting* applies
2) Type of organization that operates the manufacturing facility:
    a. Federal System - that is, a system used or operated by an executive agency (*e.g.*, DoD), by a contractor of an executive agency, or by another organization on behalf of an executive agency - must comply with the requirements in FISMA (Federal Information Security Modernization Act), including the requirements in FIPS 200 and security controls in NIST SP 800-53 (See 44 USC 3554, Federal agency responsibilities). This includes DoD (*e.g.* Army, Navy, Air Force etc.) owned and operated systems and



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contractor systems operated on behalf of DoD. Examples of Federal/DoD Information Systems include:

- Systems Operated on Behalf of the DoD
- Systems Operated on Behalf of a Federal Agency
- Information systems embedded in DoD Systems/DoD Equipment
- Information systems embedded in Federal Systems/Federal Equipment
- Cloud Services provided by a federal Agency/DoD

b. Non-Federal Systems – When systems that do not meet criteria of a Federal information system, NIST SP 800-171 contains recommended security requirements for protecting the confidentiality of CUI (Controlled Unclassified Information, which is unclassified information that must be safeguarded from unauthorized disclosure and is governed by DoD Instruction 5200.48, "Controlled Unclassified Information," ) when the information is resident in Nonfederal information systems This includes contractor owned - contractor operated systems. The following are examples of Non-Federal/Contractor Information Systems:

- Internal cloud services provided by a Non-Federal Organization/Contractor and operated on behalf of the contractor
- Internal IT processing (operated on behalf of the contractor) to develop a product or service for a Federal Agency/DoD (not including IT processing services that a Federal Agency would normally provide for itself)

Cybersecurity requirements for Non-Federal Systems are captured in NIST SP 800-171, Protecting Controlled Unclassified Information in Non-Federal Systems and Organizations and conveyed in contractual vehicles or other agreements established between agencies and Non-Federal organizations (*e.g.*, FAR 52.204-21, Basic Safeguarding of Covered Contractor Information Systems; DFARS 252.204-7012, Safeguarding Covered Defense Information and Cyber Incident Reporting; or as otherwise identified in the contract for certain specified CUI safeguarding requirements, such as HIPAA).



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**Contractor Owned and Operated manufacturing facilities**: When DFARS 252.204-7012 is in the contract, security requirements should be implemented in accordance with NIST SP 800-171 *Protecting Controlled Unclassified Information in Nonfederal Systems and Organizations*). Other DFARS clauses (such as 252.204-7019 and 252.204-7020) require that a NIST SP 800-171 DoD Assessment be completed to assess a contractor's implementation of the NIST SP 800-171 security requirements and assessment results will be posted in the Supplier Performance Risk System (SPRS). The SPRS can be accessed to see the assessment results for each contractor (non-federal) information system/system security plan that has been assessed.

The following are some general cybersecurity concepts to consider from NIST SP 800-82, *Guide to Industrial Control Systems (ICS) Security*. Additional considerations can be found in the MRL Users Guide under the appropriate MRL thread.

- Identify security policies, procedures, training and educational materials that apply specifically to the manufacturing environment.
- Address cybersecurity throughout manufacturing readiness level maturation starting with manufacturing concept development to full-rate production manufacturing capability.
- Implement a network topology for IT/OT networks in a manufacturing environment that have multiple layers, with the most critical communications occurring in the most secure and reliable layer.
- Provide logical separation between corporate and IT/OT networks.
- Employ a DMZ network architecture (*i.e.*, prevent direct traffic between the corporate and IT/OT networks of the manufacturing environment).
- Ensure that critical components, such as those of a process control system (PCS) are on redundant networks.
- Consider protecting manufacturing process related data including recipes, configuration control information, test parameters and results, etc. (may be a counterintelligence challenge).
- Where possible, use operator authentication to manufacturing OT equipment.
- Ensure the protection of non-conformance issues associated with critical manufacturing processes. For example, handle all non-conformance information with Marking and Dissemination Statements for controlled technical information that have been directed in the contract or use of



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company proprietary markings; each are categories of Controlled Unclassified Information

Small Business manufacturing companies should make use of guidance and training offered by the Small Business Administration Office, such as the Procurement Technical Assistance Centers (PTAC), NIST Manufacturing Extension Partnership (MEP), Cybersecurity Evaluation Tool (CSET), prior to using an external or independent organization check/audit/test and after they have conducted an internal self-test.

**Note regarding CMMC (Cybersecurity Maturity Model Certification):** CMMC is a certification process that leverages the security requirements in NIST SP 800-171; it is not the source of the requirements required to protect CUI. The requirements to protect CUI (including Controlled Technical Information) when it is processed on, stored or, or transits a Non-Federal system are found in NIST SP 800-171.

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