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Human Readiness Level Scale in the System Development Process

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AAF	Adaptive Acquisition Framework
AAMI	Association for the Advancement of Medical Instrumentation
ANSI	American National Standards Institute
APA	American Psychological Association
BA	Budget Activity
BCPE	Board of Certification in Professional Ergonomics
DAU	Defense Acquisition University
DBS	Defense Business Systems
DOD	Department of Defense
DOE	Department of Energy
GPS	Global Positioning System
GUI	Graphical User Interface
HF	Human Factors
HFACS	Human Factors Analysis and Classification System
HFACS-MA	Human Factors Analysis and Classification System for Maritime Accidents
HFES	Human Factors and Ergonomics Society
HMD	Helmet-Mounted Display
HOF	Human and Organizational Factors
HRL	Human Readiness Level
HSI	Human Systems Integration
IMPRINT	Improved Performance and Research Integration Tool
ISO	International Organization for Standardization
KPP	Key Performance Parameter
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
NUREG	Nuclear Regulation
O&M	Operations and Maintenance
PPE	Personal Protective Equipment
RDT&E	Research, Development, Test, and Evaluation
SAE	Society of Automotive Engineers
SHERPA	Systematic Human Error Reduction and Prediction Approach
STD	Standard
TRL	Technology Readiness Level

DEFINITIONS

Disuse: neglect or underutilization of technology features intended to effectively support mission accomplishment.

Environment: the external context in which the technology under design will function. Environment is one domain within human systems integration (in some organizations, it is combined with the safety and occupational health domain). Activities within this domain address interactions between the technology and humans within the anticipated operational environment. The scope varies significantly according to the system definition and may include physical, cyber, geopolitical, social, market, and organizational considerations. The scope nearly always includes human use environments characterized in terms of the visual, auditory, tactile, motion, and climatic environments in which tasks will occur (e.g., luminance, glare, ambient noise, vibration, weather, and environmental hazards).

Ergonomics: the International Ergonomics Association and the Human Factors and Ergonomics Society define ergonomics as the scientific discipline concerned with understanding interactions among humans and other elements of a system and the profession that applies theory, principles, data, and methods to design in order to optimize human wellbeing and overall system performance. Key goals of ergonomics are to decrease the risks of musculoskeletal injuries, illness, and work discomfort while improving the quality of work life and worker performance. The term is frequently used synonymously with human factors engineering.

Graphical User Interface: the use of direct manipulation and icons or other graphical symbols on a display to interact with a computer (Stramler, 1993).

Habitability: habitability is one domain within human systems integration. Activities in this domain focus on living and working conditions necessary to sustain the morale, safety, health, quality of life, quality of work, and comfort of the target population. Habitability considerations can include the physical environment (space, lighting, and ventilation), the cultural environment (beliefs, customs, and behaviors), the social environment (relationships, interactions, and support networks), personal services (religious and medical), and living conditions (breathing and personal hygiene).

High-Fidelity Simulation: a functioning and realistic approximation of the intended final system with respect to form, fit, and function as well as the operational environment in which it functions. Simulations may involve hardware, software, or both.

Human Capabilities and Limitations: traits and states that define what humans can and cannot do or do well. Key areas of consideration for human capabilities and limitations include sensation/perception (vision, audition, touch, taste, olfaction, vestibulation, proprioception, and interoception), information processing (cognitive functions such as reading, interpretation, attention, memory, and decision making), and action (anthropometrics, biomechanics, physiological capacity, motor skills, and reaction times). Capabilities and limitations are typically described in terms of statistically defined ranges of performance for basic tasks across people and conditions.

Human-Centered Evaluation: systematic data collection and analysis of human interactions within a developing system to assess relevant and applicable elements of human performance and to determine the extent to which specified criteria have been met. Methods may include instrumented measurement, observations, interviews, and surveys to collect objective data and subjective user feedback.

Human-Centered Guidelines: established principles, standards, and guidance to inform human systems designs and promote efficient human-technology interactions. Example guidelines include designing for simplicity and consistency, minimizing memory requirements, enhancing system transparency to users, incorporating redundancy, using feedback to improve learning, and designing for fail-safe operations.

Human Factors Engineering: human factors engineering is one domain within human systems integration. Human factors is based on a body of knowledge about human abilities, limitations, and other characteristics that are relevant to system design. Human factors engineering is the application of human factors knowledge to the design of tools, machines, systems, tasks, jobs, and environments for safe, comfortable, and effective human use. Human factors engineering is a multidisciplinary field that encompasses aspects of ergonomics; anthropometry; biomechanics; human-computer interaction; user experience; cognitive engineering; industrial engineering; and organizational, cognitive, and experimental psychology.

Human-Machine Function Allocation: strategies for distributing system functions and tasks across people and technology in order to maximize human-system effectiveness and optimize operator workload. Function allocations may be static, or they may vary dynamically over time.

Human Performance: all relevant and applicable aspects of both individual and team behavior that impact overall system performance and mission accomplishment. Common human performance metrics include accuracy, response and completion times, error types and frequency, workload, situation awareness, user satisfaction, usability, fatigue, strain, risk of injury, reach, fit, layout, comfort, accessibility, learning rate, training demands, and manpower and personnel impacts.

Human Performance Issue: a human characteristics or state that may result in a performance risk or adverse condition in a system or operation. For example, if effective use of a proposed system involves monitoring and interpretation of visual displays, then characteristics of human visual acuity, the perceptibility of alternative display technologies, and the ability to process display information for a given design represent potential human performance issues. If users cannot adequately see the displays or interpret and use the information in the displays, they may not be able to effectively perform required tasks.

Human Performance Modeling: tools for analyzing human systems designs via analytic and computer-based models. Examples include the ACT-R cognitive modeling tool, the Jack modeling software and simulation tool for ergonomics, and the Improved Performance and Research Integration Tool (IMPRINT) tool for simulation and modeling of human workload.

Human-System Interface: any region or point at which humans interact with other system components such as hardware, software, procedures, environment, and other humans (Stramler, 1993).

Human Systems Design: the design of the technology and system with respect to all of its interactions with human users of all types. Human systems design includes design of the physical system, software interface, perceptual features, interaction methods, functionality, automation interaction, processes and procedures, task flows, and training. It includes a consideration of the broader organizational system, culture, and environment of which the system is a part. It also includes the design of technologies and concepts for fostering human performance augmentation (e.g., human-centered concepts and applications).

Human Systems Experts: qualified professionals with specific training or experience in human factors engineering, human systems integration, or related field who ensure that human systems considerations are adequately identified and addressed throughout system design and development. Human systems experts typically have advanced degrees or certificates in human factors, human systems integration, industrial engineering, safety, psychology, physiology, or a related field. Practitioners may also obtain professional certification through the Board of Certification in Professional Ergonomics (BCPE). Human systems experts may be practitioners specializing in a particular human systems integration domain (e.g., human factors engineer, safety engineer, training system developer, or manpower planner).

Human Systems Integration: the Department of Defense Joint Human Systems Integration Working Group defines human systems integration as a disciplined, unified, and interactive approach to integrate human considerations into system design in order to optimize total system performance and minimize lifecycle costs. The human domains of a system typically include manpower, personnel, training, human factors engineering, environment, safety and occupational health, force protection and survivability, and habitability. These domains are highly interrelated and often overlap. Different organizations may tailor the domain definitions to their missions.

Human Systems Mapping: linking human needs, capabilities, limitations, and characteristics directly to expected operational and system demands to understand human performance implications, identify requirements to support human performance, and mitigate likely scenarios for human error.

Manpower, Personnel, and Training: manpower, personnel, and training are three related human systems integration domains that are frequently considered concurrently. A change in strategy for one domain frequently impacts one or both of the other domains. Manpower considers the number of qualified people required to operate, maintain, and support a system. Personnel considers the knowledge, skills, abilities, and limitations of system users. Training considers the instruction, education, and on-the-job training needed to provide personnel with the specific knowledge, skills, and abilities required to successfully perform system tasks.

Mission-Relevant Simulation: tools that represent key aspects of the system and mission environment, including relevant tasks and conditions. Computerized tools for simulation are often used, including realistic displays of system information and environmental conditions on

large-screen displays or virtual reality devices. Simulations may occur within the laboratory in part-task or full-mission simulators, or they may involve exercises in actual environments.

Misuse: improper interaction with technology features in ways other than intended, resulting in reduced mission effectiveness, mission failure, personnel injury or casualty, or other undesired effect.

Operational Envelope: the set of tasks and conditions within which the system can be safely operated.

Operational Environment: the conditions and influences that affect operation of a system, including organizational structures, climate, requirements, rules, procedures, and the socio-political environment. The operational environment is a combination of conditions and circumstances that impact mission accomplishment.

Operational/System Demands: requirements imposed on human users in order to accomplish task goals in both normal and non-normal conditions.

Operational Use Conditions: the operational environment, physical environment, and expected conditions of use (e.g., number of users, mobility, pace of operations, stress, fatigue, and time of use) for a system.

Part-Task Testing: demonstration and testing of segments of a complex mission. The mission is divided into smaller, simpler portions so that elements of the mission can be tested. However, they may not be tested concurrently or in the sequence in which they would occur during the entire operational mission.

Proof of Concept: initial rough and incomplete demonstration of the feasibility of a concept or idea to show that it is functional and capable of being developed. Key elements of the technology are not yet integrated or representative.

Prototype: representation of all or part of a proposed system that transforms a concept into physical form, offering aspects of the features, the functionality, or performance expected in the final configuration. Key elements are integrated and can be used to support analysis, design, and evaluation; but the prototype may be limited in some way (e.g., ad hoc hardware, mock materials, or only portions of hardware or software).

Qualified System: a system that has been verified, validated, and approved as suitable for its intended mission in accordance with an established qualification process.

Representative Users: individuals who have the range of characteristics identified as relevant for the intended system users in the target population. Representative users may or may not be the final end users of the fielded system.

Safety and Occupational Health: safety and occupational health is one domain within human systems integration (depending on the organization, it may be separated into two domains). Activities within this domain focus on addressing hazards to minimize the risk of death, injury, acute or chronic illness, or disability to humans.

States: temporary conditions experienced for a short period of time, depending on circumstances (e.g., anxiety before taking a test required to pass a training course).

Survivability: force protection and survivability is one domain within human systems integration that facilitates system operation and personnel safety during exposure to hostile situations or environments. Activities in this domain focus on mitigating hostile actions and enabling personnel to avoid or withstand hostile environments, while accomplishing their mission. The survivability hierarchy for threats is to avoid detection, avoid engagement, avoid or absorb damage/injury, and avoid destruction/death.

System: an integrated collection of facilities, parts, equipment, tools, materials, software, personnel, or techniques that produce an organized whole capable of performing or supporting some function (Stramler, 1993). A system can be physical or conceptual or a combination of both. An engineered system is designed to interact with an anticipated physical and operational environment to achieve specific goals.

Technology: techniques, tools, and machines created by humans to accomplish a specific purpose. Technologies include material technologies such as equipment and software as well as non-material technologies such as training techniques and operational concepts.

Trade Studies: research and analysis to identify and select the most viable option(s) from a set of alternatives, based on satisfaction of established criteria.

Traits: stable and enduring human characteristics and patterns of behavior manifested consistently across a wide range of circumstances (e.g., introversion versus extraversion).

Usability: the extent to which a system, product, or service can be used by the intended users to achieve specified goals with effectiveness, efficiency, and satisfaction in a given context of use (ISO 9241-220).

Use: interaction with a technology in the intended manner for which it was designed or in ways that can reasonably be foreseen to occur (e.g., projected misuse or errors that may occur during technology interaction).

User: any person who interacts with a system, product, or service. Users of a system, product, or service include people who operate the system, people who use of the output of the system, and people who support the system (ISO 9241-220). Support roles may involve logistics, maintenance, sustainability, security, and other roles dictated by system context.

User Needs: prerequisites identified as necessary for human users to accomplish the tasks within their assigned roles and achieve intended outcomes (ISO 9241-220). Human operator needs may be functional, task, cognitive, physical, or operational.

User Satisfaction: the extent to which the user's physical, cognitive, and emotional responses that result from interaction with a system, product, or service meet user needs and expectations (ISO 9241-220).

FOREWORD

This standard was developed by the Human Factors and Ergonomics Society (HFES), using the rules and procedures of the American National Standards Institute (ANSI). This edition is the first revision of *Human Readiness Level Scale in the System Development Process*.

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1.0 PURPOSE

Proper attention to human systems design during the development of technological systems is a significant factor in minimizing or preventing human error, which can account for 60% to 90% of accidents and incidents across a wide range of systems (Chen, Wall, Davies, Yang, Wang, & Chou, 2013; Ghasemi, Nasleseraji, Hoseinabadi, & Zare, 2013; Shappell, Detwiler, & Boquet, 2006; Vaurio, 2009). In addition, costs associated with system training, operations, and maintenance; which account for 35% to 70% of overall system costs; can be reduced when the human component of the system is addressed early and often throughout design and development (Balut, Gordon, Bishop, Cann, & Collins, 1999). A recent review indicated that operations and support costs account for 63% of total lifecycle costs for major air, land, and sea systems in the Department of Defense (DOD), with significant increases in costs over the past 20 years (Boito, Conley, Fleming, Ramos, & Anania, 2018). However, many system development programs have been deficient in applying established and scientifically-based human systems integration (HSI) processes, tools, guidance, and standards, resulting in suboptimal systems that degrade mission performance (Pew & Mavor, 2007). Approximately 70% of lifecycle costs are committed by the time the detailed design phase occurs, with costs of system modifications up to 60 to 100 times higher once the system design has been finalized (Gawron, Dennison, & Biferno, 1996; Pressman, 1992). Consequently, it is critical that human systems design issues be considered early during system design in order to reduce subsequent operations and maintenance costs, minimize accidents and incidents that negatively impact safety and costs, and improve the effectiveness of the combined human-system for achieving mission outcomes.

The purpose of this standard is to specify application of the Human Readiness Level (HRL) scale to evaluate, track, and communicate the readiness of a technology for safe and effective human use throughout design and development. This standard applies to any organization involved in the design and development of technologies and systems for multiple classes of intended human users. It is applicable to any type of technology under development in the military, government, federal agencies, industry, and academia. The HRL scale is designed to be applied by trained and knowledgeable human systems experts to ensure that human readiness is satisfactorily addressed throughout system design and development. Qualified human systems experts may tailor the specifications contained in this standard to their particular missions by following acceptable human systems engineering practices.

2.0 SCOPE

This standard defines the HRL scale and provides the guidance necessary for human systems experts to apply it. This standard uses the term “human readiness” to refer to the readiness of a technology for use by the intended human users in the intended operational environment. Addressing the current physical or mental readiness of human operators who will use the technology in order to accomplish their mission work is outside the scope of this standard. Further, this standard does not provide a detailed process for conducting HSI assessments. Existing HSI assessment processes and tools are critical to provide the foundation from which

HRL ratings can be derived; however, the purpose of the HRL scale is not to dictate the processes and tools that should be used or how they should be used. This type of information resides in standards such as SAE6906 *Standard Practice for Human Systems Integration* and in organization-specific HSI handbooks and guidance. Qualified human systems experts determine whether the elements in this standard have been satisfactorily addressed.

3.0 RELATED STANDARDS AND DOCUMENTS

This standard may be applied with other industry, national, and international standards and documents.

- ANSI/AAMI HE75:2009 *Human Factors Engineering: Design of Medical Devices*
- ANSI/HFES 100-2007 *Human Factors Engineering of Computer Workstations*
- *APA Handbook of Human Systems Integration* (2015)
- HF-STD-001 *FAA Human Factors Design Standard*
- HFES 200-2008 *Human Factors Engineering of Software User Interfaces*
- HFES 300-2004 *Guidelines for Using Anthropometric Data in Product Design*
- HF-STD-001 *Human Factors Design Standard* (Federal Aviation Administration)
- ISO 9241-220 *Ergonomics of Human-System Interaction Part 220: Processes for Enabling, Executing and Assessing Human-Centred Design within Organizations*
- Mil-Std-1472H *Department of Defense Design Criteria Standard: Human Engineering*
- Mil-Std-882 *Department of Defense Standard Practice: System Safety*
- NASA-STD-3001, Volumes 1 and 2, *NASA Space Flight Human System Standards*
- NUREG-0700 *Human-System Interface Design Review Guidelines*
- SAE6906 *Standard Practice for Human Systems Integration*
- *Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Program and Projects* (U.S. Government Accountability Office, 2020)

4.0 HUMAN READINESS LEVEL SCALE

4.1 Overview

The HRL scale is a simple nine-level scale developed as an adjunct to complement and supplement the existing Technology Readiness Level (TRL) scale widely used across government agencies and industry (Nolte, 2008). Whereas the TRL scale focuses on technical maturity, the HRL scale emphasizes the readiness of a developing technology for human use and safety. The HRL scale is intended to fully incorporate the human element of the system throughout design and development so that human systems issues can be captured and mitigated as early as possible when relevant decisions are being made (e.g., functionality, form, weight, layout, and automation). Early and proactive attention to the human element in the system design process significantly minimizes the cost and disruption associated with supporting effective

human, ultimately reducing human error in operational systems and promoting effective overall human-system performance.

The HRL scale provides organization and program management with a rating (ranging from 1 to 9) of the level of maturity of a technology with respect to its readiness for human use (see Table 4-1). The HRL scale focuses on the degree to which human systems activities and processes have been completed for a relevant technology or system in order to achieve desired mission outcomes. The goal of the HRL scale is to support management decision making with respect to investments of time and resources, guidelines, and testing considerations necessary to maximize readiness of the system for human use.

Table 4-1. Nine Levels of the HRL Scale

Phase	HRL Level
Basic Research and Development Scientific research, analysis, and preliminary development on paper and in the laboratory occur. This phase culminates in a validated proof of concept that addresses human needs, capabilities, limitations, and characteristics.	***HRL 1:*** Basic principles for human characteristics, performance, and behavior observed and reported ***HRL 2:*** Human-centered concepts, applications, and guidelines defined ***HRL 3:*** Human-centered requirements to support human performance and human-technology interactions established
Technology Demonstrations The technology is demonstrated at increasing levels of fidelity, first in the laboratory and later in relevant environments. This phase concludes with demonstration of a representative system in a high-fidelity simulation or actual environment, with evaluation of human systems designs provided by representative users.	***HRL 4:*** Modeling, part-task testing, and trade studies of human systems design concepts and applications completed ***HRL 5:*** Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design ***HRL 6:*** Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations
Full-Scale Testing, Production, and Deployment Final testing, verification, validation, and qualification occur, with human performance evaluations based on representative users. This phase concludes with operational use of the system and continued systematic monitoring of human-system performance.	***HRL 7:*** Human systems design fully tested and verified in operational environment with system hardware and software and representative users ***HRL 8:*** Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users ***HRL 9:*** System successfully used in operations across the operational envelope with systematic monitoring of human-system performance

4.2 HRL Scale Descriptions

Table 4-2 provides additional details to describe the primary intent for the evaluations that occur at each of the nine levels in the HRL scale. Like the TRL scale, the HRL scale begins at a basic exploratory level and concludes with operational use of the system by the intended users.

Table 4-2. Descriptions for Each HRL Level

HRL Level	Description
HRL 1: Basic principles for human characteristics, performance, and behavior observed and reported	This first level of human readiness observes and reports basic principles for human characteristics, performance, and behavior. It is a broad, high-level exploration of human capabilities and limitations and basic human-centered issues and risks relevant to a developing concept or proposed application.
HRL 2: Human-centered concepts, applications, and guidelines defined	As practical applications are being invented or identified, implications for human involvement are analyzed concurrently. Relevant human-centered concepts, applications, and guidelines are developed to begin identifying human use requirements and provide inputs for preliminary conceptual designs. While HRL 2 focuses on applied research, basic human research begun at HRL 1 may continue.
HRL 3: Human-centered requirements to support human performance and human-technology interactions established	Critical characteristics and functions of the initial proof of concept are demonstrated analytically or experimentally; however, individual components are not yet integrated or representative. Analyses of human operational, environmental, functional, cognitive, and physical needs are completed to understand requirements for supporting human user roles and meeting expected operational and system demands.
HRL 4: Modeling, part-task testing, and trade studies of human systems design concepts and applications completed	Human systems design concepts and applications are evaluated in basic laboratory environments or controlled field settings, using ad hoc modeling and part-task testing with low-fidelity prototypes and mockups that begin integrating key elements. Trade studies are conducted to analyze and identify viable human systems design options.
HRL 5: Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design	Human performance is evaluated via prototypes in mission-relevant part-task simulations or actual environments. The fidelity of key elements has increased significantly, and users participating in testing are independent from the design team and more representative of the target population. HRL 5 is the latest level to begin engaging more representative users during testing.
HRL 6: Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations	Human performance is evaluated with objective metrics in relevant high-fidelity simulated or actual environments, with a functional prototype and representative users. HRL 6 represents a major step up in demonstrated human readiness. The human-centered design is essentially finished, though minor modifications may still be made at subsequent levels.
HRL 7: Human systems design fully tested and verified in operational environment with system hardware and software and representative users	Human performance is evaluated for the full range of usage scenarios and tasks with the final development system in an operational environment. Recommended strategies to support human use and resolve human performance issues have been satisfactorily incorporated. The final development system conforms to key human-centered guidance and requirements.
HRL 8: Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users	Human performance is validated with the production system in a representative environment before full-rate production and final system fielding. HRL 8 represents the final opportunity to identify and incorporate elements to support human readiness before fielding and operational use. Any remaining human use issues are satisfactorily resolved.
HRL 9: System successfully used in operations across the operational envelope with systematic monitoring of human-system performance	The qualified system is fielded in the operational environment and operated by the intended users. Human systems experts continue to monitor the fielded system and resolve emerging issues. Systematic analysis of human performance issues, errors, and accidents occurs to identify enhancements.

5.0 RELATIONSHIP BETWEEN HRL AND TRL SCALES

5.1 Mapping the HRL Scale to the TRL Scale

The HRL scale has been intentionally designed to map 1:1 to the TRL scale. The alignment is primarily attributable to the need for human systems design and evaluation activities to keep pace with design and evaluation of the rest of the technological system, when critical decisions regarding provision of hardware, software, and functionality that impact human performance are made. Delays in the conduct of activities at each HRL generally result in suboptimal technology design decisions that can undermine later human interactions in the completed system.

Table 5-1 illustrates how the nine HRL levels map to the nine TRL levels used in the DOD TRL scale. In relation to the TRL scale, the HRL scale primarily focuses on a technology's maturity with respect to human systems integration. At lower TRLs, basic principles are discovered and early applications are considered. At TRL 4 and above, the focus shifts to assessing the integration of the technology within its intended system application. Elements of the HRL scale are worded in such a way to match this technology-to-system progression seen in the TRL scale.

Table 5-1. Mapping the HRL Scale to the DOD TRL Scale

Level	HRL	TRL
1	Basic principles for human characteristics, performance, and behavior observed and reported	Basic principles observed and reported
2	Human-centered concepts, applications, and guidelines defined	Technology concept and/or application formulated
3	Human-centered requirements to support human performance and human-technology interactions established	Analytical and experimental critical function and/or characteristic proof of concept
4	Modeling, part-task testing, and trade studies of human systems design concepts and applications completed	Component and/or breadboard validation in laboratory environment
5	Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design	Component and/or breadboard validation in relevant environment
6	Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations	System/subsystem model or prototype demonstration in a relevant environment
7	Human systems design fully tested and verified in operational environment with system hardware and software and representative users	System prototype demonstration in an operational environment
8	Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users	Actual system completed and qualified through test and demonstration
9	System successfully used in operations across the operational envelope with systematic monitoring of human-system performance	Actual system proven through successful mission operations

5.2 Assessing Program Risk Due to HRL-TRL Misalignment

Ideally, design and development activities occur such that the TRL and HRL levels remain aligned. Misalignment between the TRL and HRL ratings may generate varying levels of program risk, depending on the phase of development and the extent of the discrepancy. In general, the human systems work on a given program should be conducted in parallel with the technical work focused on maturing the technology. To minimize risk to successful program completion as well as risk to the system's human users, progression through the HRL scale should closely mirror progression through the TRL scale, as shown by the 1:1 mapping between the TRL and HRL scale in Table 5-1. In practice, however, one of two situations can potentially occur: (1) the HRL rating lags behind the TRL rating, or (2) the TRL rating lags behind the HRL rating. Figure 5-1 depicts a program risk matrix that takes these considerations into account.

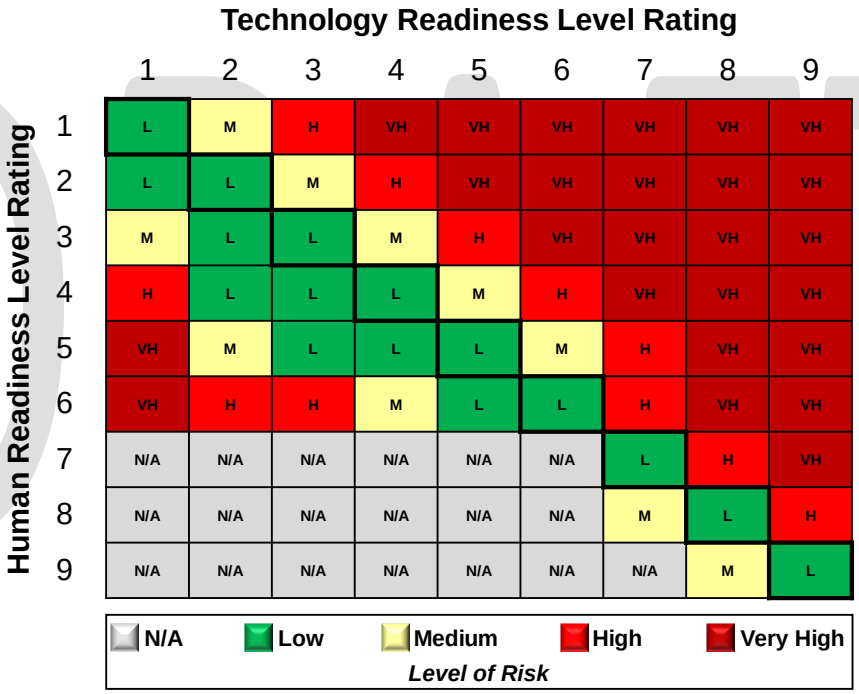

Figure 5-1. Program Risk Due to HRL-TRL Misalignment

HRL Rating Lags Behind TRL Rating. In the first situation, the HRL rating lags behind the TRL rating (the portion of Figure 5-1 above the diagonal). In this case, risk always increases whenever a discrepancy is present. Historically, when human systems work is neglected until the end of a program, human use requirements cannot be properly addressed because many technical constraints are in place that make needed changes too expensive or leave insufficient time in the schedule for the necessary rework. To properly address human systems needs, these human use requirements must be built into the system design from the beginning and thoroughly tested throughout the development process.

As illustrated in Figure 5-1, as long as the HRL and TRL are aligned, program risk due to improper human systems integration is minimized and is considered to be at a low (L) level (the top-to-bottom diagonal in the figure). At lower TRLs up through Level 5, program risk varies depending on the extent of the HRL lag:

- Risk is moderate (M, yellow) if the HRL rating lags behind the TRL rating by one level
- Risk is high (H, red) if the HRL rating lags behind the TRL rating by two levels
- Risk is very high (VH, dark red) if the HRL rating lags behind the TRL rating by three or more levels

Beginning at TRL 6, program risk becomes more pronounced if the HRL rating lags behind the TRL rating. In particular, a lag by a single level becomes a high risk (H, red), whereas a lag by two or more levels becomes a very high risk (VH, dark red). The rationale for this shift is a need to prepare at TRL/HRL 6 for the change in program focus that occurs at TRL 7. TRL 7 typically signals the end of development. The engineering design is essentially frozen at this level as the technology transitions from demonstrations focused on identifying further improvements to full-scale testing, production, and deployment. Therefore, program risk increases significantly if the HRL lags behind the TRL by this point.

TRL Rating Lags Behind HRL Rating. In the second situation, the TRL rating may lag behind the HRL rating (the portion of Figure 5-1 below the diagonal). This occurrence does not necessarily represent program risk. In some cases, human systems work may safely precede technology development efforts. For example, basic human research may be conducted at HRL 1 with no immediate goals to invent practical applications or technological solutions. Basic research is designed to expand the scientific knowledge base in a given area, advance theoretical foundations, or enhance understanding of human behavior and other phenomena. As another example, in software development, prototypes and other proxies may be used in place of fully functional technology to advance human systems testing through HRLs 4 and 5, providing inputs that inform maturation of system requirements and concept development for software that is still at TRL Levels 2 and 3. In this case, the HRL rating may safely exceed the TRL rating by one or two levels in the early stages of development. Generally, however, it will not be possible for HRL ratings to advance more than two levels ahead of technology development. Further, by definition, the HRL rating can never progress to Level 7 or higher without the presence of operational hardware and software, indicating the TRL rating must be at Level 7 at that point (gray N/A blocks in Figure 5-1). In the later TRL stages (7 to 9), the HRL rating may not safely exceed the TRL rating due to the need to incorporate fully functional operational hardware and software during human systems testing and evaluations. Accordingly, program risk increases to at least a moderate level at this point if the HRL rating is deemed completed on the basis of system hardware and software that is not sufficiently mature.

6.0 MAPPING THE HRL SCALE TO ACQUISITION FRAMEWORKS

6.1 Traditional Acquisition Processes

Because the HRL scale maps 1:1 to the TRL scale, its mapping to the systems acquisition framework also mirrors that of the TRL scale. Figure 6-1 shows the mapping to the traditional DOD acquisition process, and Figure 6-2 shows the mapping to the Department of Energy (DOE) acquisition process (Department of Defense, 2012; National Nuclear Security Administration, 2018). The DOD and DOE acquisition processes are similar with respect to the overall progression of activities during the development lifecycle from initial concept development through full quantity production and operations. They differ with respect to the terminology used. Appendix A provides additional information regarding DOD budget activity (BA) categories used to fund DOD research, development, testing, and evaluation (RDT&E) and their mapping to TRLs and HRLs.

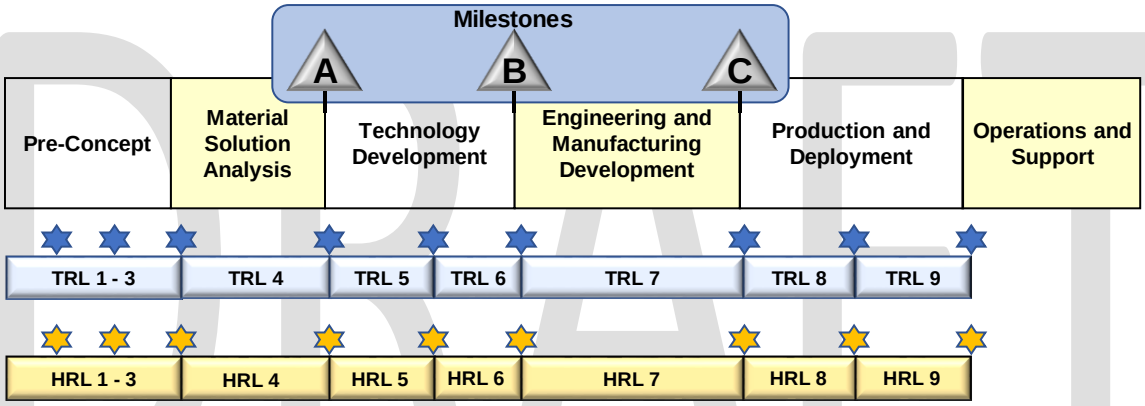

Figure 6-1. Mapping the HRL and TRL Scales to the DOD Systems Acquisition Framework

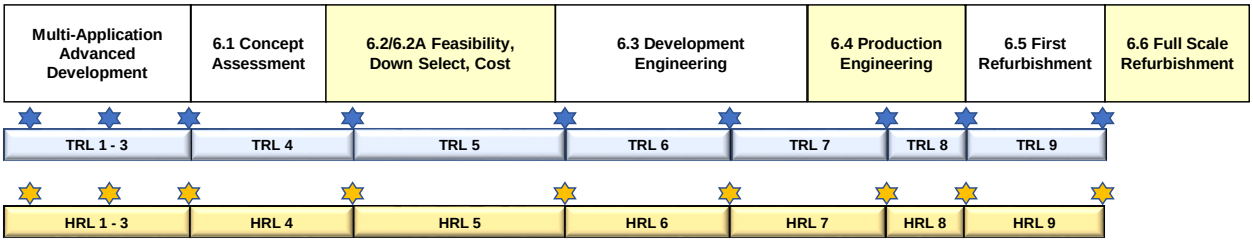

Figure 6-2. Mapping the HRL and TRL Scales to the DOE Systems Acquisition Framework

6.2 Adaptive Acquisition Framework Pathways

With the release of the updated DOD Instruction 5000.02 in January 2020, the Department of Defense restructured the traditional acquisition process to include five additional acquisition pathways that provide opportunities to match acquisition strategies and processes to the characteristics of the capability being acquired (Department of Defense, 2020b). Appendix B of this document maps the HRL scale to each of the alternative acquisition pathways described in the adaptive acquisition framework (AAF). Given that the DOD instruction constitutes new guidance, detailed information pertaining to applications of each of the individual pathways is

not yet available. Therefore, the HRL guidance in Appendix B is inherently preliminary in nature and will be revised as the standard is updated to incorporate additional information regarding the new pathways. HRL guidance for the new pathways is being included in this standard because human readiness is a critical element applicable to all acquisition pathways.

7.0 APPLYING THE HUMAN READINESS LEVEL SCALE

The purpose of this section of the standard is to identify actions that qualified human systems experts take to effectively apply the HRL scale, primarily throughout the design and development phases of the acquisition lifecycle. Tailoring may be applied to accommodate unique mission requirements. Recommendations to guide application of the HRL scale are provided in Appendix C, including suggested evaluation activities at each of the nine levels in order to determine whether human systems activities for the developing technology have been satisfactorily accomplished. Recommendations regarding the criteria and supporting evidence needed to exit each HRL level are also described in Appendix C. Applications of the HRL scale to examples representing both material and non-material solutions are covered in Appendix D.

7.1 HRL 1

Basic principles for human characteristics, performance, and behavior observed and reported.

As with TRL 1, work at this first level of human readiness is very conceptual, consisting of a broad, high-level exploration, primarily in the laboratory and on paper. HRL 1 focuses on observing and reporting basic human principles. At HRL1, basic human-centered research promotes improved understanding of human capabilities, limitations, performance, and behavior to expand the scientific knowledge base, advance theoretical foundations, or enhance understanding of human behavior and other phenomena. Research is also aimed at understanding potential concepts for enhancing human performance; developing methods, models, and measures related to aspects of human performance; and conducting initial identification of potential human interactions and human-related issues and risks relevant to a newly developing concept or proposed practical application. Human systems experts begin exploring human involvement for the developing concept or idea, identifying important characteristics of the people who might use this concept, and thinking about preliminary usage scenarios. HRL 1 research encompasses all the varieties of users who may potentially be part of an eventual system (e.g., decision makers, leaders, trainees, operators, maintainers, monitors, and inspectors) and may be focused on people as individuals or teams. Human systems experts also learn as much as possible about newly developing concepts and technologies to develop an understanding of potential roles and impacts on human users and lifecycle concepts.

7.2 HRL 2

Human-centered concepts, applications, and guidelines defined.

HRL 2 activities are intended to occur in conjunction with TRL 2 activities, which emphasize invention of practical applications for the developing concept or idea. Basic human research

begun at HRL 1 is transformed into applied research concepts that are more fully explored as additional information about proposed technologies and their application becomes available. As practical applications are identified, human systems experts analyze the implications for human involvement. Basic research is transformed into a determination of technology characteristics to support effective human use. Relevant human capabilities and limitations identified in HRL 1 may be further defined, based on improved knowledge of developing practical applications and use environments. In addition, potential user roles and tasks begin to be identified at HRL 2. Concepts, applications, and roles are still speculative at this point, and there may be no proof or detailed analysis to support the assumptions. However, preliminary task descriptions developed at HRL 2 serve as a basis for task analyses and human-machine function allocation decisions at higher HRL levels.

Guidelines for the design of systems and technologies to support safe and effective human interactions are developed, based on human characteristics, capabilities, and limitations discovered in HRL 1. Such guidelines provide the basis for establishing human-centered use requirements as well as inputs for preliminary conceptual designs. Human-centered principles, standards, and guidance may be used to create an overarching human systems interaction standard to establish consistency throughout later design and development.

Human performance analyses are a critical human-centered activity at HRL 2. First, human performance on legacy or comparable systems is analyzed to understand key human-technology interactions and potential sources of human error and misuse. Along these lines, relevant human performance data may be collected by interviewing current users for inputs or observing them complete key tasks with comparable systems. Historical documentation such as issue reports may also be analyzed, and highly controlled human-centered experiments may be conducted. Analysis of potential human errors and misuses at this early stage permits mitigation or prevention through identification of necessary design features.

Second, human systems experts begin identifying objective and subjective metrics that will signal the accomplishment of successful human performance for the proposed practical application. Human performance metrics encompass all relevant elements of human behavior that impact overall human-system performance and mission accomplishment. Metrics may include accuracy, response and completion times, error types and frequency, workload, situation awareness, user satisfaction, usability, fatigue, strain, risk of injury, reach, fit, layout, comfort, accessibility, learning rate, training demands, and manpower and personnel impacts. These metrics are initiated at HRL 2 for use in applied research so their feasibility can be addressed; they are later applied once an initial proof of concept is available at HRL 3. Metrics will be continuously reviewed and updated during testing and evaluation at higher HRL levels as programs mature.

7.3 HRL 3

Human-centered requirements to support human performance and human-technology interactions established.

HRL 3 activities are meant to coincide with TRL 3. At this level, critical characteristics and functions of the concepts that have been under development are examined analytically or experimentally in laboratory studies. Relevant analyses to establish human use requirements for developing concepts and applications are completed (e.g., function analyses, task analyses, cognitive task analyses, operational use analyses, training needs analyses, safety analyses, and other HSI domain analyses). Critical human performance issues for a developing technology or system are identified, and requirements for supporting human use in the developing system are determined, based on research, guidelines, and standards established in HRLs 1 and 2.

An initial proof of concept for developing human-centered concepts and applications via further study and experimentation may be created. The proof of concept is sufficient to support active contextualized human research and development such as analytical human-centered studies, limited complexity human-focused laboratory studies, and field observations to generate a broader understanding of human performance in complex systems. Human systems experts can use the proof of concept to begin understanding the demands the developing technology will impose on human users and to analyze human operational, environmental, functional, cognitive, and physical needs as well as their goals, strategies, and challenges. Human needs, capabilities, limitations, and characteristics are then mapped to the expected operational and system demands to establish perceptual, information, and decision requirements to support human user roles. With increased maturity of technology concepts, human systems experts can begin considering candidate human-machine function allocations to optimize performance. As part of updating usage scenarios and task descriptions, they are able to use the proof of concept to identify critical human performance issues that may impact achieving system goals and may therefore require additional rigor in the analysis.

With increased knowledge gained through the availability of a rough prototype, activities for each HSI domain begin at HRL 3. These domains include human factors; safety and occupational health; manpower, personnel, and training; environment; and the HSI domains of habitability and survivability if they are relevant for the given effort. For each relevant domain, preliminary requirements, risks, and implications are captured. In addition, possible tradeoffs among domains are evaluated to effectively support human operators and system lifecycle concepts within the trade space characterized by schedule, costs, and performance. For example, design features that simplify operations may be recommended to minimize future cost and schedule resources required for manpower and training. Along the same lines, maintenance and sustainment analyses are conducted to support early consideration of design features that will optimize human interactions during future maintenance and repair activities.

All of these analyses at HRL 3 guide the development of specific human-centered requirements that are flowed into higher-level system requirements. In addition, the proof of concept can be

used to evaluate feasibility and sufficiency of the metrics developed at HRL 2. Specific key performance parameters (KPP) to support successful human performance and lifecycle concepts are identified. Finally, human systems experts use all of the information gained to date to recommend preliminary design features that accommodate the capabilities, limitations, and needs of human users. An overarching human systems plan is completed at HRL 3 and incorporated into the broader system plan. Human systems experts with requisite expertise to support execution of the plan are identified and engaged. The number of human systems experts and their specialties will vary, depending on the exact nature of the design and development effort. A test plan for subsequent modeling and part-task testing with mockups at HRL 4 is begun.

7.4 HRL 4

Modeling, part-task testing, and trade studies of human systems design concepts and applications completed.

HRL 4 activities are intended to be completed concurrently with TRL 4 activities. Beginning at this level and continuing through Level 6, demonstrations and tests occur at increasing levels of fidelity, first in the laboratory and later in relevant environments. Fidelity of all key elements increases progressively over time—the technology, the environment, and the users. At this level, human systems experts use prototypes, analytical tools, and mockups to support modeling and part-task testing of human-centered design and lifecycle concepts. Analytical tools and models may be used to better understand particular aspects of human tasks or human systems interactions such as physical reach/fit for a new workstation, workload over different task and environmental conditions, time to complete tasks, and potential errors. Part-task testing of human systems designs provides human-centered evaluations in laboratory or controlled field settings. At HRL 4, these tests may include only partial mission complexity, parts of the technology, or limited elements of human systems interactions. Mockups may be simple static versions of displays or simple hardware facsimiles. Outcomes of these studies support trade studies of various candidate human systems design concepts and features to identify the most viable options to pursue. In addition, study outcomes are used to optimize development of procedures for human use. All of these activities serve as a basis to identify and recommend various strategies to support human use and lifecycle concepts, minimize human error, and optimize mission outcomes. Such strategies include the full range of engineered solutions, training, personnel selection, procedures, organizational and administrative solutions, and personal protective equipment (PPE) controls.

Key activities begun at HRL 3 continue during HRL 4. Namely, evaluations of each HSI domain and HSI tradeoffs continue in order to refine previous analyses, based on information gained through demonstrations of rapid prototypes, modeling, part-task testing, and trade studies. The preliminary human-machine function allocations and task analyses developed at HRL 3 are updated to incorporate emerging information and to optimize task flow and sequencing. Strategies to address human interactions during maintenance and sustainment are refined. Human systems experts collect and evaluate human performance data during modeling and part-task testing to determine whether human performance metrics and requirements are successfully met.

Human performance results may be compared against data from existing comparable systems to gauge the extent of any improvements or degradations and determine whether additional modifications are necessary. Human systems experts verify whether preliminary designs conform to human-centered guidelines and requirements established at earlier HRL levels. Finally, human systems experts finalize the test plan and generate a test report for human systems modeling and part-task testing activities completed at HRL 4. The test report includes recommended system design features and modifications. In addition, a draft test plan for subsequent human systems testing associated with HRL 5 activities is begun.

7.5 HRL 5

Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design.

At HRL 5, human systems design prototypes are developed or updated based on HRL 4 results. By HRL/TRL 5, the fidelity of key elements of the technology has increased significantly. Design and simulation of key user interface components and capabilities of the system, with realistic supporting elements, are sufficient for testing and demonstration in mission-relevant part-task simulations or actual environments. Portions of relevant missions are simulated to exercise the system and provide realistic user tasks and use conditions. Further, at this level, users participating in human-centered testing are independent from the design team. During earlier HRLs, human systems experts may work with various types of users, including surrogates and samples of convenience such as college students, non-experts, other members of the design team, colleagues, and retired subject matter experts. Representative users must be engaged no later than HRL 5 to interact with the technology during testing. They may not be fully representative of the intended target population, but they are much more similar in terms of basic characteristics and skills. Thus, at HRL 5, part-task evaluations of higher-fidelity prototypes in mission-relevant simulations by more representative users provide a basis for refined design recommendations. All of the evaluation activities completed at HRL 4, including those across all relevant HSI domains, are repeated at HRL 5 under these more representative conditions with the refined human systems design concept. Human systems experts finalize the HRL 5 test plan and generate a test report for human systems activities completed at HRL 5 that includes recommended system modifications. In addition, a draft test plan for subsequent HRL 6 human systems testing is begun.

7.6 HRL 6

Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations.

At HRL 6, human systems design prototypes are updated based on HRL 5 results. HRL 6 activities occur in conjunction with TRL 6, which represents a major step in a technology's demonstrated readiness and the final demonstration before verification and validation activities begin. At this level, a prototype or representative of the system is demonstrated in relevant environments such as a high-fidelity simulation or the actual environment with mission-level

complexity. High-fidelity simulations used at this stage provide realistic approximations of the intended final system with respect to form, fit, and function. Further, users participating in human-centered testing are fully representative of the target population with respect to the range of characteristics identified as relevant for the given technology. Human-centered testing encompasses the full range of usage scenarios and tasks, including emergency and non-normal events. Although subjective metrics continue to be informative at this level, testing emphasizes collection of objective metrics related to human performance and lifecycle concepts.

The evaluation activities completed at HRL 5, including those across all relevant HSI domains, are repeated at HRL 6 under these more representative conditions in high-fidelity simulations or actual environments with the evolved design concepts. Beginning at HRL 6, human systems experts also evaluate the effectiveness of a system designed to track and resolve human systems issues after fielding. This human systems issue tracking system may be an extension of an existing, broader issue tracking system or a completely new and separate system devoted solely to human systems issues.

At the completion of HRL 6, the majority of the human-centered design is essentially finished; however, modifications are still possible if critical issues or risks are identified during subsequent verification and validation testing in the production and deployment phase. The expectation is that any changes after TRL/HRL 6 should be more minor in extent than at previous levels. Human systems experts finalize the HRL 6 test plan and generate a test report for human systems activities completed at HRL 6 that includes recommended system modifications. In addition, a draft test plan for subsequent human systems testing associated with HRL 7 activities is begun.

7.7 HRL 7

Human systems design fully tested and verified in operational environment with system hardware and software and representative users.

HRL/TRL 7 represents the first level in the production and deployment phase and typically signals the end of development. At this time, the engineering design is essentially frozen. The final development system is evaluated in an operational environment with system hardware and software and representative users. Human-centered testing during HRL/TRL 7 demonstrations encompasses the full range of usage scenarios and tasks, including emergency and non-normal events and the proposed system to track, prioritize, and resolve human systems issues after fielding.

The evaluation activities completed at HRL 6, including those across all relevant HSI domains, are repeated at HRL 7, using the final development system in an operational environment. However, by this level, the primary task of human systems experts shifts from identification and recommendation of mitigation strategies to evaluation and verification that key recommended strategies have been successfully incorporated and work as intended to satisfactorily support the humans in the system. The presence of realistic environmental conditions in which the final

fielded system will be operated permits more thorough evaluation of the impacts of factors such as lighting, noise, vibration, stress, safety, and anomalous situations on human performance and behavior. Effectiveness of near-final user procedures, training approaches, and training manuals can also be evaluated at this level. Human systems experts verify whether (1) key human performance metrics and requirements established in earlier HRLs have been successfully met, (2) recommended strategies to support human use and lifecycle concepts have been satisfactorily incorporated in the final development system, and (3) the final development system conforms to key human-centered principles, standards, and guidance established at HRL 2. Human systems experts coordinate with systems engineering and design teams to resolve any remaining high-priority issues.

Human systems experts finalize the HRL 7 test plan and generate a test report for human systems activities completed at HRL 7 that includes recommended system modifications. In addition, a draft test plan for subsequent human systems testing associated with HRL 8 activities is begun.

7.8 HRL 8

Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users.

During HRL/TRL 8, the completed system hardware and software are fully tested with representative users and validated in mission operations. If testing is successful, the system is qualified and approved for full-rate production and fielding. For the DOD, TRL/HRL 8 testing activities may occur as part of developmental test and evaluation. HRL 8 represents the final opportunity to identify and incorporate elements to support human readiness before fielding and operational use. Therefore, human-centered testing during HRL/TRL 8 demonstrations encompasses the full range of usage scenarios and tasks, and all of the evaluation activities completed at HRL 7 are repeated at HRL 8, using the production system in mission operations. Effectiveness of the strategies used to address each HSI domain is evaluated with the production system. At this point, any remaining human systems issues should have been identified and satisfactorily resolved. If any high-priority items or KPPs have not been satisfactorily addressed, human systems experts work with the systems engineering and design teams to coordinate a mutually agreeable path forward. As a final check, conformance of the final production system to key human-centered principles, standards, and guidance identified as relevant at HRL 2 and requirements identified in HRL 3 is verified.

Human systems experts finalize the HRL 8 test plan and generate a test report for human systems activities completed at HRL 8. In addition, a draft plan for subsequent human systems evaluations at HRL 9 may be produced if testing such as operational test and evaluation is expected to occur. An overarching program report for the entire human systems program is also started and will be completed at this level if no more formal testing is planned.

7.9 HRL 9

System successfully used in operations across the operational envelope with systematic monitoring of human-system performance.

HRL 9 activities are intended to occur at the same time as TRL 9, which involves successful mission operations with the actual system. Accordingly, during this final level of human readiness, intended users operate the qualified system, as fielded in the operational environment. For the DOD, TRL 9 may occur during operational test and evaluation. Upon fielding, human systems experts systematically monitor the system to ensure the demonstrated human performance capability and lifecycle concepts are maintained. A critical aspect of continued monitoring is detection and resolution of emerging human systems issues, which may involve hardware, software, or process modifications. Systematic monitoring encompasses the comprehensive set of tasks and conditions comprising the intended mission, including training, operations, maintenance, and abnormal environments. Key elements for data collection and analysis at HRL 9 consist of human performance issues, errors, accidents, costs attributable to HSI concepts, and training effectiveness. Human systems experts may collect data via automated data collection, service databases, field observation, surveys, interviews, issue tracking systems, and error/accident reports. Lessons learned pertaining to both successes and failures are documented to support current and future applications. Finally, human systems experts participate during any planned system upgrades to evaluate human-system impacts and verify upgrades continue to support effective human performance and lifecycle concepts. Impacts of changes in user knowledge, skills, and abilities are also evaluated at this HRL level. Human systems experts finalize the HRL 9 plan and generate a test report, if applicable. If not accomplished during HRL 8, the overarching program report for the entire human systems program is finished.

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APPENDIX A: DOD BUDGET ACTIVITIES (INFORMATIVE)

The DOD originally established seven budget activity (BA) codes ranging from 6.1 to 6.7 to support funding of research, development, testing, and evaluation (RDT&E) work. Currently, an eighth category is being added to the list to fund software and digital technology pilot programs (Sargent, 2020). The new funding mechanism is intended to remove challenges program managers encounter when attempting to apply modern software development techniques like agile development (Department of Defense, 2020a).

Brief descriptions of the eight BA codes are provided in Table A-1 (Sargent, 2020). The DOD refers to funding in the BA 6.1 to 6.3 codes as the science and technology budget. The BA 6.4, 6.5, and 6.7 codes address funding for application of scientific and technical knowledge to meet current or near-term operational needs. BA 6.6 funds are for RDT&E management and may support work in any of the RDT&E budget accounts.

Table A-1. DOD RDT&E Budget Activity Codes

BA Code		Description
6.1	Basic Research	Systematic scientific study and experimentation to achieve greater knowledge or understanding of fundamental aspects of phenomena without specific applications or products in mind.
6.2	Applied Research	Systematic study to understand the means to meet a recognized and specific need by developing useful materials, devices, systems, or methods.
6.3	Advanced Technology Development	Development of subsystems and components and efforts to integrate them into prototypes for field experiments or tests in simulated environments. This effort provides proof of technological feasibility.
6.4	Advanced Component Development and Prototypes	Evaluation of integrated technologies, representative modes, or prototypes in high-fidelity and realistic operating environments. Efforts help expedite technology transition from the laboratory to operational use.
6.5	System Development and Demonstration	Engineering and manufacturing development tasks designed to meet validated requirements before full-rate production. Prototype performance is at or near planned operational system levels.
6.6	RDT&E Management Support	Management support and funds to sustain or modernize installations or operations required for general RDT&E.
6.7	Operational System Development	Development efforts to upgrade systems that have been fielded or have received approval for full-rate production (with the expectation that production funding will be received in the current fiscal year or next).
6.8	Software and Digital Technology Pilot Programs	Funding to cover agile development, test and evaluation, procurement and modification, and the operation and maintenance of pilot initiatives for software and digital technology.

Summarized from Sargent (2020)

Various interpretations of how the BA codes map to the TRLs exist. There are inconsistencies in the interpretations across different organizations, and overlaps between different BA codes may occur. Figure A-1 represents one interpretation (Atchison, 2013). In this view, RDT&E funding (BA 6.1 through 6.7 codes) ends at the conclusion of TRL 7 (Milestone C), at which time the engineering design is frozen, signaling the end of development. In this mapping, the BA 6.2 code does not begin until TRL 3. Defense Acquisition University (DAU) mappings, on the other hand, show RDT&E funding ending partway through TRL 9 with the BA 6.5 code (Figure A-2). In addition, the BA 6.2 code begins at the start of TRL 3 and extends midway through TRL 4 (Defense Acquisition University, 2018).

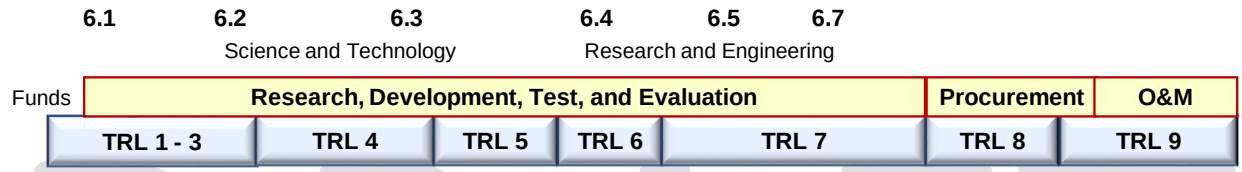

Figure A-1. One DOD Interpretation of a TRL-BA Mapping

(redrawn from Atchison, 2013)

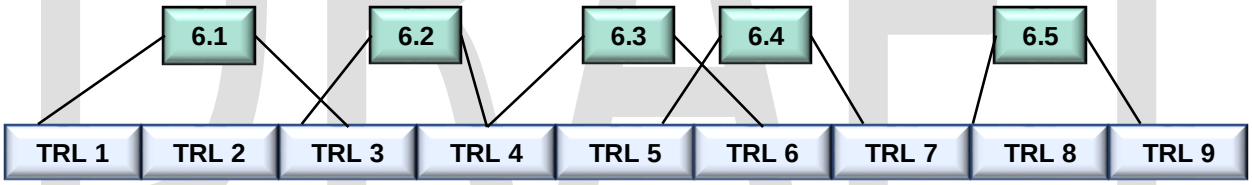

Figure A-2. One DAU Interpretation of a TRL-BA Mapping

(redrawn from Defense Manufacturing Management Guide for Program Managers, 2018)

Figure A-3 illustrates the TRL-HRL-BA mapping used in this standard. This mapping combines elements of existing TRL-BA mappings and aligns with the DOD and DOE systems acquisition framework mappings illustrated in Section 6.0 of this document. Existing TRL-BA mappings are readily extended to the HRL scale, given the intended 1:1 mapping between TRLs and HRLs.

- ***BA 6.1 (basic research)*** begins at TRL/HRL 1, during which basic research occurs in the laboratory and on paper. At this first level for technology/human readiness, fundamental scientific research occurs via analysis, observation, and experimentation. Examples include paper studies of a technology's basic properties and research investigating models of basic human capabilities, limitations, characteristics, and behaviors.
- ***BA 6.2 (applied research)*** begins at TRL/HRL 2 to coincide with the invention of practical applications and their implications for human involvement. Activities at TRL/HRL 2 move beyond basic research into applications and solutions. However, basic research elements of BA 6.1 activities may continue through TRL/HRL 2. Further, concepts, applications, and potential human roles are speculative at this point; there may not yet be proof or detailed analysis to support assumptions.

- ***BA 6.3 (advanced technology development)*** spans TRL/HRL 4 through TRL/HRL 6. These TRL and HRL levels emphasize repeated demonstration of the developing technology at increasing degrees of fidelity and user representativeness, first in the laboratory and later in simulations or actual environments. In accordance with BA 6.3, it is during these levels that true technology development occurs. Demonstration of the technology with increasingly realistic environments and users facilitates identification and implementation of additional design improvements throughout these TRL/HRL levels. By TRL/HRL 5 in particular, prototype development has progressed sufficiently to support participation of more representative users.
- ***BA 6.4 (advanced component development and prototypes)*** begins at TRL/HRL 5 and overlaps with both BA 6.3 and BA 6.5. BA 6.4 is viewed as beginning at TRL/HRL 5 when the fidelity and integration of key elements under development increases significantly, with demonstration in high-fidelity simulated or actual environments. During HRL 6, the human systems design is fully matured in preparation for follow-on verification, validation, and qualification activities.
- ***BA 6.5 (system development and demonstration)*** begins at TRL/HRL 7 at the start of the production and deployment phase of the lifecycle and continues through the initial stages of TRL/HRL 9. By TRL/HRL 7, the development version of the system is at or near the planned operational system, in preparation for final verification and validation tests funded at BA 6.5. At TRL/HRL 9, the qualified system is successfully used in operations across the operational envelope by the intended users.

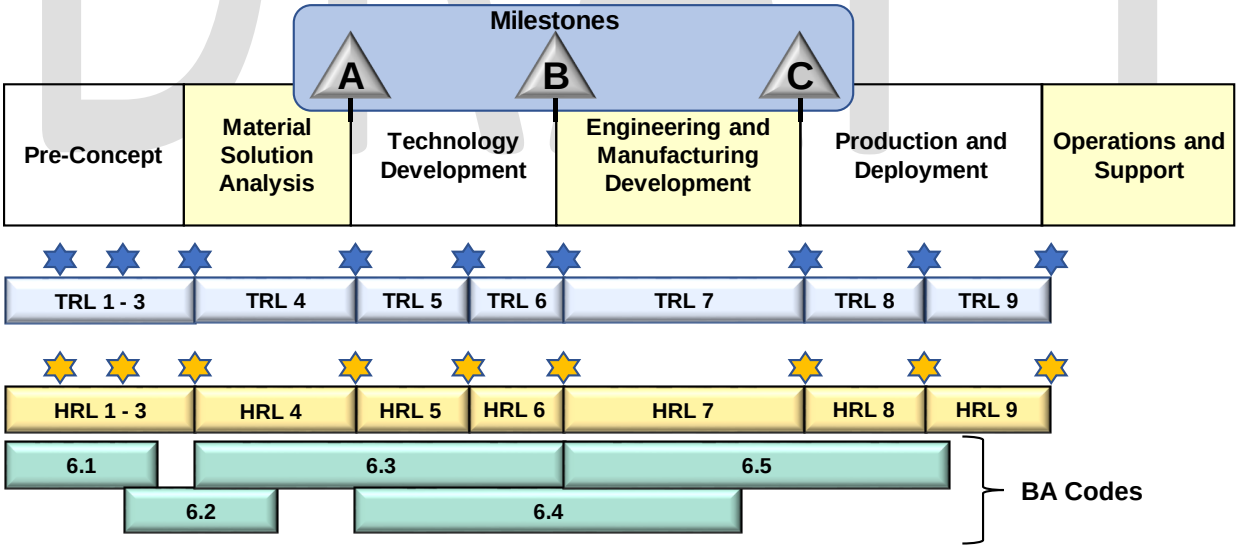

Figure A-3. TRL-HRL-BA Mapping Used in this Standard

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APPENDIX B: HRL-AAF MAPPING (INFORMATIVE)

This appendix maps the HRL scale to the acquisition pathways described in the adaptive acquisition framework (AAF) in DOD Instruction 5000.02 (Department of Defense, 2020b). The AAF was designed with the objective of delivering effective, suitable, survivable, sustainable, and affordable solutions to the end user in a timely manner. The AAF provides broad authority to plan and manage programs consistent with sound business practice while providing different acquisition strategies and processes that match the characteristics of the capability being acquired. Table B-1 describes the six pathways that identify multiple acquisition approaches to provide a capability to the user while capitalizing on advanced acquisition methods and improving the DOD's ability to benefit from commercial innovation. The third pathway listed in the table, Major Capability Acquisition, represents the traditional DOD acquisition process described in the main body of this standard.

Table B-1. Six Acquisition Pathways

Acquisition Pathway	Purpose	Features
Urgent Capability Acquisition	Field capabilities to fulfill urgent existing or emerging operational needs or quick reactions in less than two years	Acquisition processes are aggressively streamlined due to operational urgency
Middle Tier of Acquisition	Rapidly develop fieldable prototypes to demonstrate new capabilities or rapidly field production quantities of systems that require minimal development	Rapid prototyping supports a defined requirement that can be quickly demonstrated in an operational environment; rapid fielding supports production within six months
Major Capability Acquisition	Acquire and modernize military unique programs that provide enduring capability	Typically follows a structured approach of analysis, design, development, integration, testing, evaluation, production, and support
Software Acquisition	Facilitate rapid and iterative delivery of software capability (e.g., software-intensive systems or software-intensive components or subsystems) to the user	Integrates modern software development practices and small cross-functional team to deliver software rapidly and iteratively, meeting highest-priority user needs
Defense Business Systems (DBS) Acquisition	Acquire information systems that support DOD business operations.	Identifies existing commercial or government solutions that could be adopted to satisfy DOD needs with minimal customization
Defense Acquisition Services	Acquire services from the private sector, including electronics and communications, equipment, facilities, logistics, medical, and transportation services	Identifies required services, researches potential contractors, contracts for services, and manages performance

Regardless of which AAF pathway is chosen, HRL ratings should be determined and shortcomings addressed during system development. Pathways that have time constraints should

leverage technologies and system designs that have previously identified human-centric data and guidelines (i.e. HRL 1 and 2 completed). In understanding the impact of the different pathways on the timing of the HRL evaluations, it is helpful to consider the application of HRLs by phase of development (refer to Table 4-1 in the main body of this standard). HRLs can then be mapped to the different phases of the chosen pathway.

B.1 Pathway 1: Urgent Capability Acquisition

The purpose of this pathway is to field capabilities to fulfill urgent existing or emerging operational needs or quick reactions in less than two years. The acquisition, product support and sustainment processes, reviews, and documents are aggressively streamlined due to operational urgency. The goal is to plan for the capability in a few weeks, with development and production measured in months (Department of Defense, 2020b). This pathway typically involves mature technology components that pass through three major stages (Defense Acquisition University, 2020). Figure B-1 maps the HRLs to the three major stages of the pathway, and Table B-2 provides specific HRL guidance.

- ***Pre-Development*** assesses and selects a course of action to field a quick reaction capability and develop an acquisition approach. This stage maps to HRLs 1 to 3. Quick development of a human-centered concepts and applications must leverage existing data on human capabilities and performance requirements for HRLs 1 and 2. Emphasis is placed on analyzing human performance requirements for the system at HRL 3.
- ***Development*** includes assessment of performance, safety, suitability, survivability, and supportability plus software and lethality of the capability, if appropriate. Manpower, personnel selection, and training impacts should be assessed. This stage maps to HRLs 4 to 6. Integration of the human operator and performance evaluation should be assimilated into the streamlined reviews.
- ***Production and Deployment*** provides the warfighter with the needed capability, to include any required training, spares, and technical data such as known hazards and accepted mishap risks. This stage maps to HRLs 7 to 9. Final testing of the human systems design and performance validation occur in conjunction with total system testing.

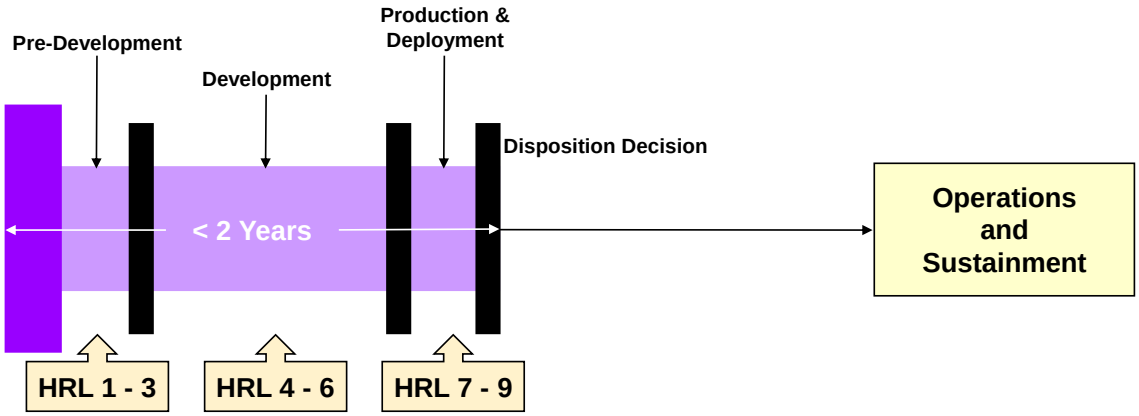

Figure B-1. HRL Mapping for the Urgent Capability Acquisition Pathway

Table B-2. HRL Guidance for Urgent Capability Acquisition

HRL	Guidance and Considerations
1	• HRLs 1 and 2 are confirmed to be already completed • Urgent capability acquisition is not suitable for very new technologies where human capabilities, limitations, and design guidelines are not yet established
2	
3	• Analysis of human performance requirements is emphasized and supports rapid development of an effective capability • Risk to human operators and maintainers is increased if there is insufficient analysis of user needs and failure modes due to compressed time scale
4	• Efforts to address these HRL levels may be condensed • Emphasis on rapid user testing and design iteration to support attainment of human-system performance objectives within the compressed effort
5	
6	
7	• User testing occurs in conjunction with total system testing • Compressed time scale may increase risk of instantiating systems with poor human systems development
8	
9	

B.2 Pathway 2: Middle Tier of Acquisition

The purpose of this pathway is to rapidly develop fieldable prototypes within an acquisition program to demonstrate new capabilities or rapidly field production quantities of systems that require minimal development. This pathway includes both rapid prototyping and rapid fielding activities: The objective of rapid prototyping is to field a prototype meeting defined requirements that can be demonstrated in an operational environment and provide for residual operational capability within five years of program start. The objective of rapid fielding is to begin production within six months and complete fielding within five years of program start (Department of Defense, 2020b). With this pathway, processes are tailored for rapid prototyping and fielding. These processes include lifecycle costs, issues of product support, logistics support and training, interoperability, and reduction of total ownership costs. Accordingly, consideration of HRLs 1 to 3 will be abbreviated to confirm human performance requirements at the onset of the acquisition activity. Figure B-2 maps the HRLs to the two major stages of the pathway, and Table B-3 provides specific HRL guidance.

- ***Rapid Prototyping*** provides for the use of innovative technologies to rapidly develop fieldable prototypes that demonstrate new capabilities and meet emerging military needs. This path maps to HRLs 3 to 6 for evaluation during rapid prototyping.
- ***Rapid Fielding*** provides for the use of proven technologies to field production quantities of new or upgraded systems with minimal development required. This path maps to HRLs 7 to 9 for evaluation during rapid fielding.

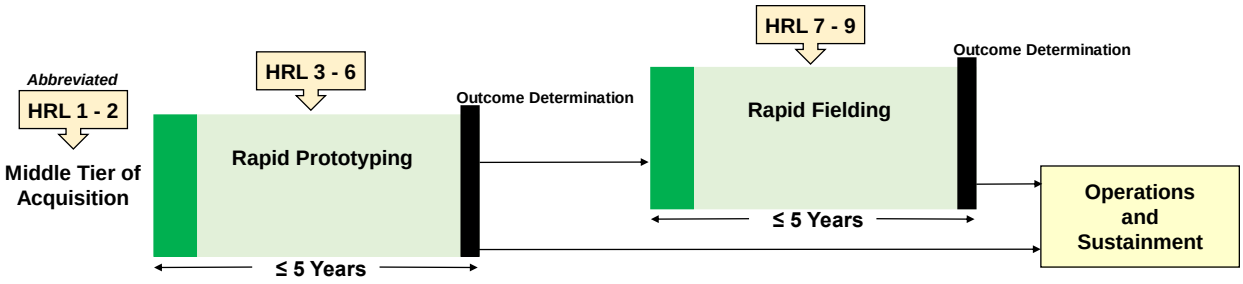

Figure B-2. HRL Mapping for the Middle Tier of Acquisition Pathway

Table B-3. HRL Guidance for Middle Tier of Acquisition

HRL	Guidance and Considerations
1	• HRLs 1 and 2 are confirmed to be already completed • Middle tier of acquisition is not suitable for very new technologies where human capabilities, limitations, and design guidelines are not yet established
2	
3	• Analysis of human performance requirements is emphasized and supports rapid development of an effective capability • Risk to human operators and maintainers is increased if there is insufficient analysis of user needs and failure modes due to compressed time scale
4	• Rapid prototyping/testing supports HRL evaluation • Emphasis on rapid user testing and design iteration to support attainment of human-system performance objectives within the compressed effort
5	
6	
7	• Rapid fielding supports HRL evaluation and incorporation of lessons learned into future iterations • Compressed time scale may increase risk of instantiating systems with poor human systems designs
8	
9	

B.3 Pathway 3: Major Capability Acquisition

Pathway 3 represents the traditional DOD acquisition process used to acquire and modernize military unique programs that provide enduring capability. These acquisitions typically follow a structured approach involving analysis, design, development, integration, testing, evaluation, production, and support. This process is designed to support major defense acquisition programs, major systems, and other complex acquisitions (Department of Defense, 2020b). For this pathway, all HRLs should be addressed in accordance with previous milestone alignment (refer to Figure 6-1 in the main body).

- ***Materiel Development Decision*** is the formal entry point into the major capability acquisition pathway and is informed by a validated requirements document that identifies a capability gap and determines that a material solution is needed. HRLs 1 to 3 should be addressed prior to this milestone.

- ***Milestone A*** is the decision point to pursue specific product or design concepts and to commit the resources required to mature the technology and reduce risks prior to development. HRL 4 should be addressed before this milestone.
- ***Milestone B*** is the decision point to enter development of a specific product with an associated budget, suppliers, contract terms, and schedule. Milestone B is generally considered the start of the program of record. HRLs 5 to 6 should be addressed prior to this milestone.
- ***Milestone C*** is the decision point based on results of developmental testing and operational assessment to enter low-rate initial production of the product. HRL 7 should be addressed before Milestone C.
- ***Initial Operational Capability*** is attained when selected organizations in the force structure receive a new product and have the ability to operate and maintain it. HRL 8 should be addressed prior to this milestone.
- ***Full Operational Capability*** is attained when all organizations in the force structure that are scheduled to receive a product have received it and have the ability to operate and maintain it. Full operational capability represents HRL 9.

B.4 Pathway 4: Software Acquisition

The purpose of this pathway is to facilitate rapid and iterative delivery of a software capability (e.g., software-intensive systems or software-intensive components or subsystems) to the user. This pathway integrates modern software development practices such as agile software development and lean practices. Small cross-functional teams consisting of users, developmental testers, software developers, and cybersecurity experts leverage enterprise services to deliver software rapidly and iteratively to meet the highest-priority user needs (Department of Defense, 2020b). This pathway follows through two major phases (Defense Acquisition University, 2020). Figure B-3 maps the HRLs to the two major phases of the pathway, and Table B-4 provides specific HRL guidance.

- ***Planning Phase*** focuses on understanding user needs and planning the approach to deliver software capabilities to meet those needs. HRLs 1 to 2 should be addressed during the planning stage to identify changes in human performance requirements incurred by the new software.
- ***Execution Phase*** focuses on first scoping, developing, and deploying a minimum viable product and minimum viable capability release to the warfighter/end user as quickly as possible and iteratively developing and deploying remaining capability thereafter. HRLs 3 to 6 should be addressed by the deployment of the minimum viable product as users provide new feedback during each cycle. HRL 7 is associated with the minimum viability capability release, and HRL 9 is associated with full release after the iterations are complete.

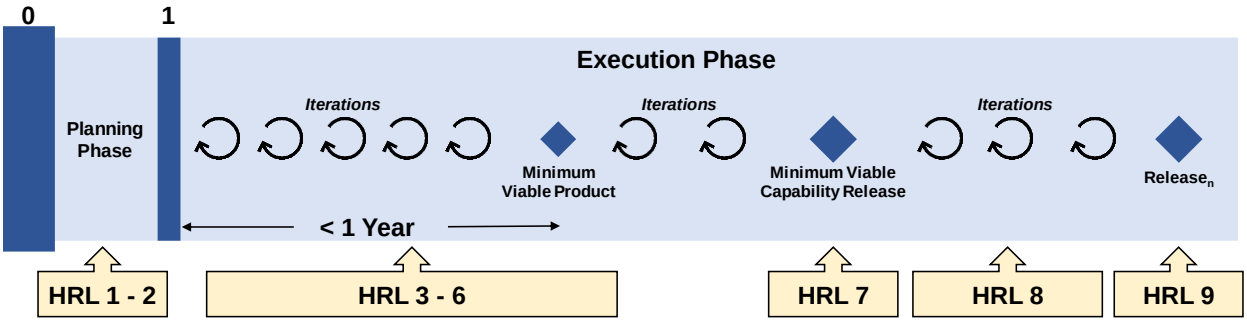

Figure B-3. HRL Mapping for the Software Acquisition Pathway

Table B-4. HRL Guidance for Software Acquisition

HRL	Guidance and Considerations
1 2	• Considered during the planning phase • Confirms human capabilities and limitation are known and design guidelines for software system are established
3	• User requirements determined • More upfront analysis of human performance requirements may be needed for complex and safety-critical systems • Cross-domain and cross-position information sharing requirements may need more extensive upfront analysis of user needs • Graphical user interface (GUI) design standards must be established and applied consistently across software iterations and design teams, enabled by human factors engineering and user experience style guides
4 5 6	• HRL evaluations should include objective testing to supplement agile testing, which is often subjective • HSI domain experts participate in cross-functional agile development teams • Testing must consider normal procedures and non-normal events • When software design is based on limited information on user requirements at each spiral, frequent and extensive software redesign and rework are common • Minimum viable product may be too limited for safety-critical system use and evaluations
7 8 9	• Minimum viable capability release occurs at HRL 7 • Final release occurs at HRL 9

B.5 Pathway 5: Defense Business Systems Acquisition

The purpose of this pathway is to acquire information systems that support DOD business operations. This pathway considers the business environment and identifies existing commercial or government solutions that could be adopted to satisfy DOD needs. The DOD reviews its business processes and revises them to align more closely with commercial or government

information technology best practices. Customization is minimal (Department of Defense, 2020b). This pathway transitions through five stages (Defense Acquisition University, 2020). Figure B-4 maps the HRLs to the five stages of the pathway, and Table B-5 provides specific HRL guidance.

- ***Capability Need Identification*** is based on the desired end state in a business mission area, the problems preventing it, and the future capabilities required to achieve it. HRLs 1 to 3 are completed at this stage to ensure human requirements are identified for the capability.
- ***Solution Analysis*** for future capabilities is based on reengineering the high-level future business processes that will deliver the capabilities. HRL 4 is completed at this stage to identify human considerations in the solution.
- ***Functional Requirements and Acquisition Planning*** covers how the business system will achieve the future business processes. HRLs 5 to 6 are evaluated at this stage to ensure user needs are included in the requirements.
- ***Acquisition, Testing, and Deployment*** address a detailed fit-gap analysis following the solution selection, based on the acquisition strategy. The fit-gap analysis is based on the known capabilities of commercial off-the-shelf and government off-the-shelf software in the selected business system solution. HRLs 7 to 8 are completed at this stage.
- ***Capability Support*** is a phase that provides support for the business capability, including continued cybersecurity readiness and enduring support for the business system as well as appropriate upgrades. HRL 9 is completed at this stage.

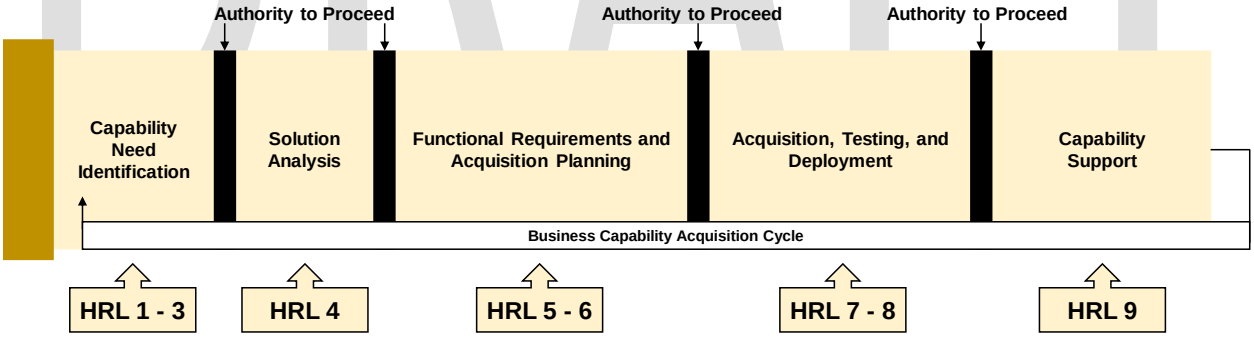

Figure B-4. HRL Mapping for the Defense Business Systems Pathway

B.6 Pathway 6: Defense Acquisition of Services

The purpose of this pathway is to acquire services from the private sector for electronics, communications, equipment, facilities, logistics, medical, and transportation services. This pathway is intended to identify the required services, research potential contractors, contract for the services, and manage performance (Department of Defense, 2020b). The seven steps of the pathway are grouped into three phases: Plan, Develop, and Execute. Figure B-5 maps the HRLs to the three major phases of the pathway, and Table B-6 provides specific HRL guidance.

- ***Plan*** is the phase in which the team is formed, the current strategy is reviewed, and market research is performed. HRLs 1 to 2 are partially addressed during planning.

- ***Develop*** is the phase in which requirements are defined and the acquisition strategy is developed. HRL 3 is completed during development.
- ***Execute*** is the phase in which the strategy is executed, and performance is managed. HRLs 4 to 9 are evaluated during execution.

Table B-5. HRL Guidance for Defense Business Systems Acquisition

HRL	Guidance and Considerations
1 2	• Completed as part of the capability need identification • Confirms known human capabilities and limitation and design guidelines
3	• Analysis of human performance requirements for the solution is completed • Systematic consideration of cross-position information flows and needs of multiple users is critical
4	• Emphasis is placed on user-centered designs • Support for user understanding of information and decision making is needed as well as task flow
5 6	• Frequent user testing should be included in acquisition contracts
7 8 9	• Focus on user testing during tests and evaluations and continued capability support

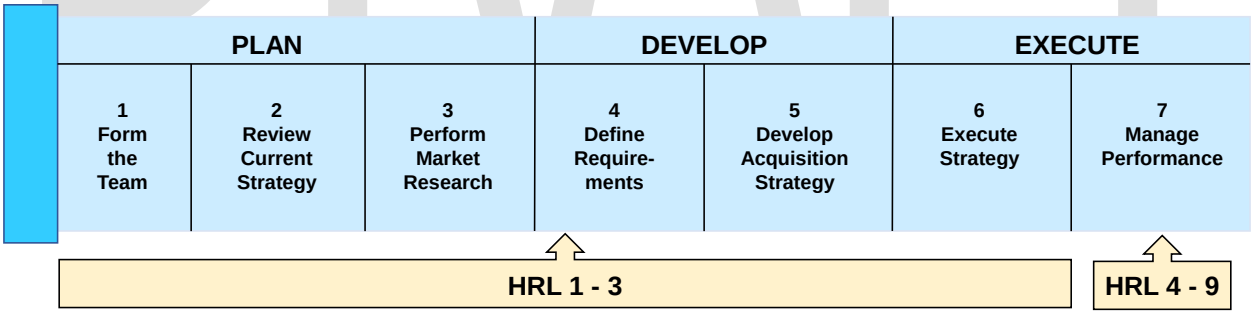

Figure B-5. HRL Mapping for the Defense Acquisition of Services Pathway

Table B-6. HRL Guidance for Defense Acquisition of Services

HRL	Guidance and Considerations
1	• Human systems experts should be part of the acquisition team to ensure the strategy, research, and requirements include user considerations
2	
3	
4	• User evaluation of interactions with services should be monitored and acted on to improve system performance
5	
6	
7	
8	
9	

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APPENDIX C: HRL GUIDANCE (INFORMATIVE)

This appendix provides additional guidance and considerations for each of the nine HRL levels described in Section 7.0. Many of the evaluation activities that occur across multiple HRLs to address human readiness are cyclical in nature. That is, certain core human-centered assessment activities occur repeatedly at increasing levels of system fidelity as technical maturity increases, particularly between HRLs 3 and 8 (see Table C-1). The HRL scale supports evaluation of multiple aspects of human-technology interactions and spans all HSI domains. Not all of the specified evaluation activities will be necessary or appropriate for every system. Therefore, at each level, human systems experts should use their expertise and experience to tailor the guidance in this standard appropriately and to specify which of the recommended questions must be answered positively in order to conclude that the given HRL level has been satisfactorily met.

Table C-1. Cyclical Nature of Evaluation Activities in the HRL Scale

Evaluation Activity	HRL 3	HRL 4	HRL 5	HRL 6	HRL 7	HRL 8
Usage scenarios	✓	✓	✓	✓	✓	✓
Human performance metrics	✓	✓	✓	✓	✓	✓
Human-machine allocations	✓	✓	✓	✓	✓	✓
Human factors engineering	✓	✓	✓	✓	✓	✓
Safety and occupational health	✓	✓	✓	✓	✓	✓
Manpower, personnel, training	✓	✓	✓	✓	✓	✓
Environment	✓	✓	✓	✓	✓	✓
Other relevant HSI domains	✓	✓	✓	✓	✓	✓
Maintenance and sustainment	✓	✓	✓	✓	✓	✓
Strategies for human use	✓	✓	✓	✓	✓	✓
Conformance to guidelines and principles		✓	✓	✓	✓	✓
User procedures		✓	✓	✓	✓	✓
Issue tracking system				✓	✓	✓

C.1 HRL 1 Evaluation Guidance

During HRL 1, basic principles for human characteristics, performance, and behavior are observed and reported. HRL 1 is characterized primarily by basic human research designed to understand human behaviors, capabilities, and limitations at a broad level, both for individuals and teams. HRL 1 activities may be related to human interaction with a developing concept or idea. Human systems experts should tailor the guidance in this section as needed and specify which of the recommended questions must be answered positively to conclude that HRL 1 has been satisfactorily met.

C.1.1 Evaluation Activities

Human systems experts should address the following questions during HRL 1, as applicable.

C.1.1.1 Have key human behaviors, capabilities, and limitations been identified? At HRL 1, basic human-centered research promotes improved understanding of human capabilities

and limitations to expand the scientific knowledge base, advance theoretical foundations, or enhance understanding of human behavior and other phenomena. Basic research into important characteristics of people are determined (e.g., strengths, capabilities, and limitations). Characteristics may include perceptual, cognitive, physical, and behavioral considerations and may encompass the effects of physical, cultural, social, organizational, and operational environments. Research may focus at the individual or team level and may include an examination of factors affecting individual differences and various levels of expertise. Research may be generic in nature or applied to human performance with respect to a developing technology concept or idea.

C.1.1.2 Have preliminary usage scenarios for potential users been identified? Basic research at HRL 1 may provide an initial identification of potential human activities or interactions with technologies or systems. High-level usage scenarios facilitate understanding the various types of human activities that may occur, including training, operations, maintenance, and sustainment. Identification of plausible usage scenarios can guide further development of future technologies and systems as programs mature.

C.1.1.3 Have potential key human performance issues and risks been identified and concomitant basic research conducted? At this very early conceptual stage, key human-centered issues requiring further investment in research and development may be identified. Exploring potential human-centered issues and risks provides an opportunity to consider each HSI domain with respect to possible implications for technologies, systems, operations, concepts, and support. The intent is to highlight areas that may warrant in-depth attention from a human systems perspective and begin planning approaches to mitigate or prevent those issues and risks.

C.1.1.4 Has basic human research relevant to a developing concept or application been conducted? At HRL 1, human systems experts begin understanding human performance and exploring human involvement for developing technologies, concepts, or ideas. Research can be driven by knowledge of a developing concept or idea in combination with identified characteristics of potential users, plausible usage scenarios, and potential critical human-centered issues and risks. Research may involve human interaction, physiology, psychology, sociology, behavioral economics, cognition, and other relevant fields. Any HSI domain may be a focus. Particular attention at this stage should be afforded to concerns impacting human factors engineering and safety or occupational health relevant to new technologies or systems. In this early stage, the focus of research may be on relevant human characteristics for a technology's operational user role, but research should also span all types of users who may potentially be part of future systems, including maintainers, inspectors, and other support personnel.

C.1.2 Guidance and Considerations

When addressing HRL 1, human systems experts should consider the following guidance:

- Basic research on human characteristics, behaviors, capabilities, and limitations in general or relevant to a developing concept is conducted at HRL 1.

- Human systems experts can begin addressing human involvement at a very high level to start identifying the characteristics of people who might use the concept and how.
- Human systems experts should learn as much as possible about developing technology concepts to understand the technological component of the system and its potential impacts on human users and lifecycle concepts.
- Involving human systems experts at HRL 1 may enhance the technical discovery efforts at TRL 1 and help guide a preliminary concept toward a tangible solution.

C.1.3 Exit Criteria

In order to exit HRL 1 and advance to the next level, human involvement relevant to the developing concept or proposed application should be identified and characterized at a basic level. Human systems experts should specify which of the recommended questions are relevant for the current effort and identify whether they have been answered positively in order to conclude that HRL 1 has been satisfactorily met.

C.1.4 Supporting Evidence

The following list identifies the types of supporting evidence that should be provided to indicate that HRL 1 has been satisfactorily addressed and exit criteria have been met:

- Document key human characteristics, performance, and behaviors.
- Document potential technology or concept usage scenarios at a high level.
- List potential key human performance issues and risks.
- Document basic human research findings.

C.2 HRL 2 Evaluation Guidance

During HRL 2, human-centered concepts, applications, and guidelines are defined, based on more detailed information associated with the settings in which human performance will occur. HRL 2 is characterized primarily by researching and establishing human-centered design and training principles, standards, and guidance relevant to the current effort. The human systems experts involved in the current effort should tailor the guidance in this section as needed and specify which of the recommended questions must be answered positively to conclude that HRL 2 has been satisfactorily met.

C.2.1 Evaluation Activities

Human systems experts should address the following questions during HRL 2, as applicable.

C.2.1.1 Has knowledge of relevant human characteristics, capabilities, and limitations been refined? The characteristics, capabilities, and limitations identified at HRL 1 are updated at HRL 2, based on improved knowledge of the developing technology or concept in applied settings. At HRL 2, a more detailed understanding of potential application domains, environments, tasks, and technologies is used to conduct relevant research on human

performance in applied settings. Human-centered concepts for augmenting performance or minimizing error are refined and tested in applied settings.

C.2.1.2 Have key human-centered design principles, standards, and guidance been established? Guidelines, principles, and standards regarding human-centered design, human capabilities, training, and human performance augmentation are developed, based on relevant basic and applied research. They are used to begin identifying human use requirements and provide inputs for preliminary conceptual designs. Human-centered principles, standards, and guidance may be used to create an overarching human systems interaction standard to establish consistency throughout later design and development. Examples of human-centered guidelines that may be applicable include designing for simplicity and consistency, minimizing memory requirements, enhancing system transparency to users, incorporating redundancy, using feedback to improve learning, and designing for fail-safe operations.

C.2.1.3 Have usage scenarios been updated to include basic task descriptions for user roles? The preliminary usage scenarios developed at HRL 1 are used to create initial high-level descriptions of key tasks for the range of expected user roles in identified domain applications. Technology concepts, applications, and roles are still high level and speculative at this point, based on a broad understanding of the settings in which human performance will occur. At this time, there may be no proof or detailed analysis to support the assumptions. Nevertheless, task descriptions at this stage are used to better understand potential concepts, technology interactions, and human performance issues. They serve as the basis for more detailed task analyses and human-machine function allocation decisions at higher HRL levels.

C.2.1.4 Has human performance on legacy or comparable systems been analyzed to understand key human-technology interactions, human behavior, and human performance issues? This type of information may be obtained by interviewing current users or observing them complete key tasks with comparable systems or in current settings. Historical documentation such as issue, accident, or incident reports may also be analyzed, and highly controlled human-centered experiments may be conducted. The intent is to understand how human interactions with legacy or comparable systems, with respect to both successes and failures, can inform design decisions for the current effort.

C.2.1.5 Have potential sources of human error and misuse been identified? Analysis of potential human errors and misuses of technologies at this early stage permits implementation of engineered design features that can mitigate or prevent the error or misuse entirely. Interviews with users of legacy or comparable systems and the application of human error taxonomies may be useful to identify potential types of error and possible mitigation strategies (Reason, 1990).

C.2.1.6 Are appropriate metrics for successful human performance being identified? Identification of appropriate objective and subjective metrics that will signal the accomplishment of successful human performance for the proposed practical application occurs at HRL 2. Human performance metrics encompass all relevant elements of human behavior that

impact overall human-system performance and mission accomplishment. Metrics may include accuracy, response and completion times, error types and frequency, workload, situation awareness, user satisfaction, usability, fatigue, strain, risk of injury, reach, fit, layout, comfort, accessibility, learning rate, training demands, and manpower and personnel impacts. These metrics are initiated at HRL 2 for use in applied research so their feasibility can be addressed; they are later applied once an initial proof of concept is available at HRL 3. Metrics will be continuously reviewed and updated during testing and evaluation at higher HRL levels as programs mature.

C.2.2 Guidance and Considerations

When addressing HRL 2, human systems experts should consider the following guidance:

- In HRL 2, additional information about the proposed technology or application settings becomes available. Focus begins to shift from basic to applied research.
- The implications of the emerging practical applications for human involvement and details of application conditions are analyzed for improved understanding of potential human user roles, usage scenarios, and tasks.
- Human performance analyses become a critical human-centered activity at HRL 2, first to understand human performance on legacy or comparable systems and second to begin identifying appropriate human performance metrics for the current effort.
- The goal of HRL 2 is to establish research-based guidelines, principles, and standards to support human performance and safety.

C.2.3 Exit Criteria

In order to exit HRL 2 and advance to the next level, key human-centered design and training principles, standards, and guidance for human interaction with the technology or for human performance augmentation should be established. Human systems experts should specify which of the recommended questions are relevant for the current effort and identify whether they have been answered positively in order to conclude that HRL 2 has been satisfactorily met.

C.2.4 Supporting Evidence

The following list identifies the types of supporting evidence that should be provided to indicate that HRL 2 has been satisfactorily addressed and exit criteria have been met:

- Document relevant human characteristics, capabilities, and limitations by user role.
- Document key human-centered design principles, standards, and guidance.
- Document high-level descriptions of key tasks by user role and scenario.
- Document current successes, problems, issues, and errors associated with legacy and comparable systems to guide design and development considerations.
- Document potential sources of human error or misuse.
- Define and document initial appropriate metrics for successful human performance.

C.3 HRL 3 Evaluation Guidance

During HRL 3, human-centered requirements to support human performance and human-technology interactions are established. HRL 3 is characterized primarily by analysis of human needs and operational/system demands to establish human-centered requirements that are flowed into higher-level system requirements. With the development of an initial proof of concept for the human-system interface or human augmentation system, HRL 3 represents the first opportunity to evaluate each HSI domain as well as possible tradeoffs among the domains to effectively support human operators and lifecycle concepts within the trade space characterized by schedule, costs, and performance. The human systems experts involved in the current effort should tailor the guidance in this section as needed and specify which of the recommended questions must be answered positively to conclude that HRL 3 has been satisfactorily met.

C.3.1 Evaluation Activities

Human systems experts should address the following questions during HRL 3, as applicable.

C.3.1.1 Have human systems experts with requisite expertise been engaged and funded to support the design and development effort? By HRL 3, human systems experts with requisite expertise and experience must be engaged and funded to ensure human systems considerations are identified and incorporated early and often as a development program begins to mature. The number of human systems experts and their specialties across HSI domains will vary depending on the exact nature of the design and development effort. Further, some experts may be needed full time, while others may be required only periodically at reduced levels of effort. Human systems experts who have been engaged to support the effort may need to educate other personnel on human factors engineering, HSI, and the various types of expertise that exist in the human systems arena.

C.3.1.2 Have usage scenarios been updated, based on human needs analyses for the proof of concept? With the additional realism provided by the initial proof of concept and understanding of the application domain, the usage scenarios developed at previous levels can be updated. The increased maturity in the proof of concept, coupled with information from human needs analyses completed at this level, provides more detail regarding the usage scenarios surrounding human-technology interactions. Updated usage scenarios support both design and continued evaluation and testing.

C.3.1.3 Have cognitive task analyses and detailed function and task analyses for each user role been completed? Detailed function and task analyses should be completed at HRL 3, based on knowledge from the proof of concept and application domain. In particular, by this stage of maturity, the initial proof of concept can be used to identify human user tasks that are particularly critical for achieving system goals and may therefore require additional rigor in the analysis throughout subsequent HRL levels. Cognitive task analyses that specify user goals, decisions, and situation awareness information requirements (basic situation and perceptual data, understanding/comprehension, and projection/prediction) for each decision for each user role should be completed to provide needed inputs for human interface designs. Detailed functional,

task, and cognitive task analyses are used to determine user goals, strategies, and challenges as well as perceptual, information, and decision requirements for each user role.

C.3.1.4 Have candidate human-machine function allocations been evaluated, based on the human needs analyses for the proof of concept? At HRL 3, the proof of concept and user needs analyses can be used to begin considering and evaluating candidate human-machine function allocations designed to optimize performance. Specific tasks that may require additional aiding from system automation should be identified. The need for dynamic and changing allocations over time, based on task conditions and other factors, should be considered. The allocations are preliminary at this point and may change over time. They provide a basis for future evaluations of human-machine function allocations as the program matures.

C.3.1.5 Have situation awareness information flow and sharing requirements across teams of human or automated system components been identified? Based on cognitive task analyses, function analyses, proof of concept, and environmental use conditions, requirements for situation awareness information sharing across human users (in different user roles or over space or time distributions) or between humans and automated/intelligent system components should be determined.

C.3.1.6 Have initial safety analyses for human users been completed? With increased knowledge gained through cognitive task analyses, function analyses, proof of concept, and environmental use conditions, initial evaluations for the HSI safety and occupational health domain should be completed. This domain is particularly important for new technologies and system upgrades to minimize the introduction of safety and occupational health hazards to humans. Preliminary requirements, risks, and implications for safety and occupational health are captured at HRL 3 in order to support the development of appropriate prevention and mitigation strategies, beginning at HRL 4. Activities for the HSI safety and occupational health domain focus on identifying hazards in order to minimize the risk of death, injury, acute or chronic illness, or disability to human users.

C.3.1.7 Have initial manpower, personnel, and training analyses been completed? Evaluations for the HSI manpower, personnel, and training domains begin at HRL 3. Although the three domains may be considered separately, they are highly interrelated, with a change in strategy for one domain generally impacting one or both of the other domains. Hence, this standard recommends managing the three domains concurrently. Preliminary requirements, risks, and implications for manpower, personnel, and training are captured at HRL 3. At this stage, it is important to begin evaluating how many qualified people may be needed to operate, maintain, and support the system (manpower); the knowledge, skills, abilities, and limitations of users in the target population (personnel); and the instruction, education, and on-the-job training that may be needed to provide the necessary knowledge, skills, and abilities to successfully perform user tasks. Any changes to current manpower and personnel requirements significantly impact follow-on workforce planning, personnel selection, and work allocation across the workforce. Training

requirements may impact the acquisition of training systems, curricula, training facilities, and staffing.

C.3.1.8 Have initial environmental conditions, constraints, and impacts been analyzed? Evaluations for the HSI environment domain begin at HRL 3 to understand the implications of the external context in which the developing technology will be operated, maintained, and sustained. The external context should be broadly construed to include air, land, sea, weather, acoustics, vibration, motion, pressure, radiation, and nuclear, biological, and chemical factors. Activities within this domain focus on supporting human performance within the anticipated operational environment. For example, usage scenario environments for human users are characterized in terms of the visual, auditory, and tactile environments in which tasks will occur as well as use conditions such as numbers of users, work posture, work and shift durations, pace of operations, timing of activities, and need for special clothing. Environmental factors such as luminance, glare, ambient noise, and vibration are explored. At this early stage, analysis may emphasize identifying the most critical environmental factors associated with the highest likelihood of occurrence or the most severe impacts on human users.

C.3.1.9 Have initial analyses for other relevant HSI domains been completed? Other HSI domains that may be relevant for a given development effort include habitability and force protection/survivability. The HSI habitability domain focuses on living and working conditions necessary to sustain morale, safety, health, quality of life, quality of work, and comfort of the target population. The HSI force protection and survivability domain facilitates operation and personnel safety during exposure to hostile situations or environments. Preliminary requirements, risks, and implications for these other HSI domains are captured at HRL 3.

C.3.1.10 Have initial analyses to address human interactions during maintenance and sustainment been completed? Maintenance and sustainment analyses begin at HRL 3 to support early consideration of design features such as accessibility that will optimize human interactions during future maintenance and repair activities. For example, human systems experts can use anthropometric data for the target population to begin addressing the ease of human interactions during item inspection, repair, or replacement.

C.3.1.11 Have characteristics of the target population been specified? User characteristics in terms of ranges of physical sizes, genders, visual and auditory capabilities, age ranges, job titles, languages, mobility, and other relevant characteristics (e.g., need to accommodate disabilities) should be identified for each system user role.

C.3.1.12 Are human capabilities, limitations, and needs being mapped to expected operational and system demands to identify human performance issues and system requirements? The initial proof of concept at HRL 3 is sufficient to begin understanding the operational and system demands that the developing technology will impose on human users. At the same time, the operational, environmental, functional, cognitive, and physical needs of human users are analyzed. Training needs analyses may be used to capture requirements for

training systems. With this foundation for both demands and needs, an initial mapping between the two is possible to identify human performance issues, gaps, and requirements.

C.3.1.13 Have relevant human performance data been collected and evaluated to determine the feasibility of appropriate metrics for successful human performance, based on the proof of concept? The proof of concept is used to evaluate the feasibility and appropriateness of human performance metrics developed at HRL 2. In addition, specific KPPs to support successful human performance and lifecycle concepts are identified. Evaluations with the proof of concept can be used to verify whether candidate human performance metrics will provide suitable indicators to gauge the success of human systems designs throughout the remaining HRL levels.

C.3.1.14 Have preliminary design features to accommodate human capabilities, limitations, and needs been investigated and recommended, based on the proof of concept? All of the information gained at HRL 3 is used to recommend preliminary design features that accommodate the capabilities, limitations, and needs of the target population.

C.3.1.15 Have requirements to support human performance been identified and included in system level requirements? All of the analyses that occur at HRL 3 help guide the development of human-centered requirements that are flowed into higher-level system requirements. Requirements should include reference to relevant human-centered standards and design guidelines as well as required information, functionality, technology attributes, and human performance outcomes (with clear, testable metrics).

C.3.2 Guidance and Considerations

When addressing HRL 3, human systems experts should consider the following guidance:

- Elements of the technology are available at this level but are not yet integrated or representative. Nevertheless, the proof of concept is sufficient to support improved understanding of the demands the developing technology will impose on human users.
- Activities at HRL 3 shift from basic research and exploration to establishing human-centered requirements to support human performance and human-technology interactions.
- With the availability of an initial rough proof of concept and understanding of the target domain and tasks, analysis of each HSI domain and tradeoffs among domains can begin. HSI domain analyses will continue through the remaining HRL levels.
- Analysis of maintenance and sustainment is critical at HRL 3 to support early consideration of design features that will optimize human interactions during future maintenance and repair activities.
- Concurrent analysis and mapping of human needs and operational/system demands identify issues, gaps, and requirements.
- Initial verification of the feasibility of candidate human performance metrics is possible at HRL 3 to identify the set of metrics by which the success of human systems designs will be gauged throughout the remaining HRL levels.

- Preliminary design features that accommodate human capabilities, limitations, and needs can be recommended at this early stage in design and development when they are inexpensive and easy to implement.
- Research and development to address any gaps identified in human-centered concepts and knowledge at this level should be planned and funded. Major gaps in understanding the impacts of technology and environment on human performance without a path for addressing them may prevent exiting HRL 3.

C.3.3 Exit Criteria

In order to exit HRL 3 and advance to the next level, required human-centered analyses are completed and human-centered requirements and KPPs are identified and flowed into high-level system requirements. Human systems experts should specify which of the recommended questions are relevant for the current effort and identify whether they have been answered positively in order to conclude that HRL 3 has been satisfactorily met.

C.3.4 Supporting Evidence

The following list identifies the types of supporting evidence that should be provided to indicate that HRL 3 has been satisfactorily addressed and exit criteria have been met:

- Document updated usage scenarios and function/task descriptions/analyses and identify tasks critical to system performance goals.
- Document cognitive task analyses with user goals, decisions, situation awareness information requirements, user strategies, and challenges.
- Describe preliminary human-machine function allocations.
- Document situation awareness information flow and sharing requirements across teams of human or automated system components.
- Document initial analyses for all relevant HSI domains.
- Document initial analyses of implications for human interactions during maintenance and sustainment.
- Document user characteristics of the target population for each user role.
- Describe human performance implications derived from mappings of human capabilities, limitations, and needs to expected operational and system demands.
- Document human interactions and performance with the key elements of the technology that have been demonstrated analytically or via laboratory studies of the proof of concept.
- Identify specific KPPs to support successful human performance.
- Document the human performance data used to show proof of concept and characterize the feasibility of identified human performance metrics.
- Describe recommended preliminary design features to accommodate human capabilities, limitations, and needs.
- Document requirements to support human use and flow into overall system requirements.
- Document expected level of effort and types of specialties required for human systems experts throughout the design and development effort.

- Complete an overarching human systems plan for the entire program and integrate within the broader system plan.
- Begin drafting a test plan for subsequent modeling and part-task testing with mockups that will occur at HRL 4.

C.4 HRL 4 Evaluation Guidance

During HRL 4, modeling, part-task testing, and trade studies of human systems design concepts and applications are completed. HRL 4 represents the first level in the technology demonstration phase. Demonstrations and tests occur at increasing levels of fidelity with respect to the technology, the environment and the users. Key human-centered evaluation activities begun at HRL 3 continue during HRL 4, using relatively low-fidelity rapid prototypes wherein key elements have been integrated. The human systems experts involved in the current effort should tailor the guidance in this section as needed and specify which of the recommended questions must be answered positively to conclude that HRL 4 has been satisfactorily met.

C.4.1 Evaluation Activities

Human systems experts should address the following questions during HRL 4, as applicable.

C.4.1.1 Have analytical tools, models, and prototypes for human systems design concepts or applications been developed for each class of user to support assessment of critical human performance issues? Analytical tools and models should be created to reflect particular aspects of human tasks or human systems interactions (e.g., physical reach and fit for a new workstation, workload over different task and environmental conditions, time to complete tasks, and potential errors). Mockups and rapid prototypes of the human-centered technology concept or the human interface to the system (e.g., physical displays/controls, GUI screens, simulations of system functionality, or other representations) should be created to represent the emerging system design being developed to meet the requirements identified in HRL 3. At HRL 4, representations may include only parts of the technology or human systems interactions. Initial mockups may be simple (e.g., static versions of displays or simple hardware facsimiles) and evolve in complexity at succeeding HRLs (e.g., computer simulations with realistic representations of system functionality). Analytical tools, models, and the evolving prototype support evaluations of the human interface as well as other HSI activities throughout the system development process.

C.4.1.2 Have usage scenarios been updated, based on modeling and part-task testing? Modeling and part-task testing at HRL 4 are used to update the usage scenarios developed at previous levels with additional details regarding human behavior and human-technology interactions. Updated usage scenarios provide more detailed and realistic representations of user tasks to support refinement of task analyses. Updated usage scenarios further support both design and continued evaluation and testing at this and higher HRL levels.

C.4.1.3 Have task analyses been updated based on the developing prototype and optimized for human performance, using modeling and part-task testing? Task analyses developed at previous HRL levels are updated to incorporate emerging information from analytical modeling and the design of the prototype. Modeling and part-task testing with rapid prototypes can be used to design for optimization of task flow and sequencing, where appropriate, and for accomplishment of dynamically changing mission goals (e.g., organization of information around goals and decisions). Metrics to gauge optimization may include subjective reviews, task accuracy, task completion time, workload, and situation awareness. Information gained from updated task analyses supports procedure design at this and subsequent HRL levels as well as activities for the HSI manpower, personnel, and training domains.

C.4.1.4 Have human-machine teaming and function allocations been updated, based on modeling and part-task testing? The increased maturity of the rapid prototypes available at HRL 4 supports modeling and part-task testing, which provide data to update the preliminary human-machine function allocations created at HRL 3. The effectiveness of strategies for human-automation teaming should be identified and evaluated. The effectiveness of human-machine function allocations and support for transitions in allocations across changing task, environmental, and human states (including both normal and non-normal conditions) should be evaluated to support updates to human-machine teaming and function allocation design decisions. Strategies should be evaluated for their feasibility and effectiveness via analytical models and the developing prototype system in each succeeding HRL.

C.4.1.5 Have strategies to mitigate safety implications for human users been identified and recommended? The HSI safety domain analyses begun at HRL 3 and the use of analytical models and rapid prototypes at HRL 4 provide a foundation to develop strategies to manage identified safety and occupational health risks. Strategies to minimize risk may include engineering and design recommendations that eliminate the hazard, administrative or physical controls that mitigate the hazard, environmental limits and controls, or recommended issuance of PPE to mitigate impacts from the hazard. Error prevention, error tolerance, and error mitigation strategies should be considered. Strategies to address all safety considerations should be identified at HRL 4 to avoid limiting possible options at later stages of technology development. Strategies should be evaluated for their feasibility and effectiveness via analytical models and the developing prototype system in each succeeding HRL.

C.4.1.6 Have strategies to accommodate manpower, personnel, and training concerns been identified and recommended? Analytical models and rapid prototypes at HRL 4 should be used to develop strategies to manage identified risks for the HSI manpower, personnel, and training domains. Methods to reduce lifecycle costs and provide systems that will be operable with known manpower, personnel, and training constraints should be optimized. Tradeoffs between manpower, personnel, and training should be considered. For example, design features that simplify operations may be recommended to minimize future cost and schedule resources required for manpower and training. Strategizing at this stage fosters appropriate technology use and reduces the likelihood of disuse and misuse. Strategies should be evaluated

for their feasibility and effectiveness via analytical models and the developing prototype systems in each succeeding HRL.

C.4.1.7 Have strategies to address environmental constraints and impacts been identified and recommended? Strategies to manage the human performance and safety implications of the external context in which the developing technology will be operated, maintained, and sustained should be developed at HRL 4. Evaluations of strategy options may be prioritized to focus on the most critical environmental factors with the highest likelihood of occurrence or the most severe impacts (e.g., lighting, acoustics, temperature, chemical, or biological factors). Strategies to mitigate environmental effects and constraints should be identified at HRL 4 to avoid limiting possible options at later stages of technology development. Strategies should be evaluated for their feasibility and effectiveness via analytical models and the developing prototype system in each succeeding HRL.

C.4.1.8 Have strategies to address other relevant HSI domains been identified and recommended? Strategies to address human performance and safety concerns in other HSI domains such as habitability and force protection/survivability that may be relevant for a given development effort should be identified at HRL 4. As with other HSI domains, strategies should be identified at HRL 4 to avoid limiting possible options at later stages of technology development. Strategies should be evaluated for their feasibility and effectiveness via analytical models and the developing prototype system in each succeeding HRL.

C.4.1.9 Have strategies to address human interactions during maintenance and sustainment been identified and recommended? Strategies to address human interactions during maintenance and sustainment throughout the lifecycle should be identified and recommended at HRL 4. Strategies may consist of recommendations for engineered design features to support ease of human interactions during such activities as inspection, repair, and replacement. Such strategies should be identified at HRL 4 to avoid limiting possible options at later stages of technology development. Strategies should be evaluated for their feasibility and effectiveness via analytical models and the developing prototype system in each succeeding HRL.

C.4.1.10 Is modeling and part-task testing being used to design procedures for human user roles throughout the lifecycle? Outcomes from modeling and part-task testing are used to provide initial inputs intended to optimize procedures for human performance for tasks requiring formal procedures. Optimization involves incorporating elements to support procedure readability, usability, and reliability for the target population. Design features to minimize procedure complexity and support procedure performance should be identified and incorporated into system design. Strategies for supporting human performance in implementing procedures should be evaluated for their feasibility and effectiveness via analytical models and the developing prototype system in each succeeding HRL.

C.4.1.11 Have analyses been completed to support system-wide trade studies for features affecting human performance? At HRL 4, system design features are fluid. Analyses, models, and data collection should be conducted to contribute human performance data to ongoing trade studies as system design features are determined. For example, the effects of system hardware or functionality trades on human performance requirements and outcomes should be determined.

C.4.1.12 Have relevant human performance data been collected and evaluated to determine whether human performance metrics are successfully met, based on modeling and part-task testing? Using the analytical tools, models, and rapid prototypes, human performance data are collected and evaluated during part-task testing to determine whether human performance requirements are being successfully met. It may not be possible to collect all relevant metrics at HRL 4, given the maturity of the developing technology and limited representations of human systems interfaces. Frequently, at lower levels of technical maturity, evaluation may be limited to subjective feedback or model output. As the system matures, increased focus on objective human performance metrics should be emphasized. Human performance results may be compared against data from existing comparable systems to gauge the extent of any improvements or degradations in human performance. In addition, a comparison of results to human performance requirements in HRL 3 should be used to determine additional system design modifications that are necessary. Collected data are used to support trade studies comparing competing system design solutions. A positive response to this question signifies that the relevant data have been collected, evaluated, *and* deemed satisfactory by qualified human systems experts, given current and anticipated levels of technical maturity. For example, if NASA-TLX workload ratings are collected during part-task testing, those subjective ratings must be considered to lie within an acceptable range before the human readiness level can advance.

C.4.1.13 Have strategies to support human use been identified and recommended, based on modeling, part-task testing, and trade studies? All of the information gained at HRL 4 is used to recommend system design improvements and strategies that will effectively support human interactions with the developing technology and address key human-centered challenges identified at this and previous HRL levels. Such strategies include the range of engineered, administrative, and PPE controls. Given the ease with which design modifications can be made at this stage of development, engineered design features that eliminate an identified risk or human performance issue altogether are preferred.

C.4.1.14 Has conformance of preliminary designs to human performance requirements, design principles, standards, and guidance been verified? Conformance of preliminary designs to the human performance requirements, design principles, standards, and guidance established at earlier HRL levels is evaluated. Any discrepancies are analyzed to identify appropriate actions for resolution.

C.4.2 Guidance and Considerations

When addressing HRL 4, human systems experts should consider the following guidance:

- Development of analytical models, tools, and relatively low-fidelity rapid prototypes wherein key elements of the evolving human systems designs have been represented supports human-centered part-task testing and evaluation of initial design concepts. Testing representing partial mission complexity may occur in laboratory environments or controlled field settings.
- Outcomes of modeling and part-task testing support trade studies of various candidate human systems design concepts and system design features to identify the most viable options to pursue.
- Initial strategies for supporting human systems considerations for each HSI domain are developed and evaluated.
- Human performance data obtained from modeling and part-task testing are used to determine whether human performance metrics are being successfully met.

C.4.3 Exit Criteria

In order to exit HRL 4 and advance to the next level, human interactions and performance are evaluated and characterized, using analytical tools, modeling, and part-task testing with rapid prototypes and mockups. Task analyses and human-machine function allocations are updated. Human systems designs, HSI domain strategies, and human performance results must be deemed satisfactory by qualified human systems experts. Human systems experts should specify which of the recommended questions are relevant for the current effort and identify whether they have been answered positively in order to conclude that HRL 4 has been satisfactorily met.

C.4.4 Supporting Evidence

The following list identifies the types of supporting evidence that should be provided to indicate that HRL 4 has been satisfactorily addressed and exit criteria have been met:

- Document evolving human-centered concept or human systems design in models, mockups, or prototypes.
- Document updated usage scenarios.
- Document results of updated task analyses, trade studies, and implications for system design.
- Document updated human-machine function allocations and human-machine teaming support strategies and provide the rationale.
- Document strategies to mitigate concerns related to all relevant HSI domains.
- Document strategies to mitigate concerns related to human interactions during maintenance and sustainment.
- Document strategies and key observations for procedure development.
- Document analyses to support system-wide trade studies.
- Document human interactions and performance, based on analytical tools, modeling, and part-task testing with rapid prototypes and mockups.
- Document the human performance data collected during modeling and part-task testing with rapid prototypes and mockups and evaluations of the ability of solutions to meet requirements for successful human performance.

- Describe recommended strategies to support human use.
- Characterize conformance of preliminary designs to human performance requirements, design principles, standards, and guidance established at previous HRL levels.
- Complete the HRL 4 test plan.
- Complete the HRL 4 test report to document the results of human systems modeling and part-task testing activities at HRL 4.
- Begin drafting a test plan for subsequent human systems testing associated with HRL 5.

C.5 HRL 5 Evaluation Guidance

During HRL 5, human-centered evaluation of prototypes in mission-relevant part-task simulations are completed to inform design. Human systems design prototypes are developed or updated, based on HRL 4 results. The fidelity of key elements of the technology has increased significantly at this level. Users participating in human-centered testing are independent from the design team and more representative of the intended target population. Part-task evaluations of higher-fidelity prototypes in mission-relevant simulations by more representative users provide a basis for refined design recommendations. All of the human-centered evaluation activities completed at HRL 4 are repeated during HRL 5 under these more representative conditions with a more mature human systems design concept and representation of system technology and functionality. The human systems experts involved in the current effort should tailor the guidance in this section as needed and specify which of the recommended questions must be answered positively to conclude that HRL 5 has been satisfactorily met.

C.5.1 Evaluation Activities

Human systems experts should address the following questions during HRL 5, as applicable.

C.5.1.1 Have functioning prototypes of the human-system interface and simulations of mission tasks and conditions been developed to support assessment of critical human performance issues? Functioning prototypes of human-centered technology concepts or human interfaces to the system should be created that represent the emerging human systems design, as refined by activities in the prior HRL. Simulations should incorporate realistic representations of system functionality and allow for collection of relevant human performance metrics in realistic simulations of user tasks.

C.5.1.2 Have usage scenarios been updated, based on prototype testing in mission-relevant part-task simulations? Prototype testing of the emerging human systems design in mission-relevant part-task simulations at HRL 5 is used to update the usage scenarios developed at previous levels. Additional details regarding human behavior and human-technology interactions provide more realistic representations of user tasks to support refinement of task analyses. Updated usage scenarios further support both design and continued evaluation and testing at this and higher HRL levels.

C.5.1.3 Have task analyses been updated, based on prototype testing in mission-relevant part-task simulations? The tasks analyses developed and updated at earlier HRL levels are further refined at HRL 5 to incorporate emerging information. For example, with increased technical maturity, more realistic environments and scenarios, and the participation of more representative users, it is possible to derive improved estimates of task durations and optimal sequences. Recommendations for further design improvements to optimize task performance are documented.

C.5.1.4 Has the suitability of human-machine teaming strategies and human-machine function allocations been determined, based on prototype testing in mission-relevant part-task simulations? With the increased maturity of the prototypes used in mission-relevant part-task simulations at HRL 5, the efficacy of preliminary human-automation teaming strategies, human-machine function allocations, and support for transitions of functions across humans and automation can be evaluated and modified as needed. The capabilities of humans and automation to perform in both normal and non-normal conditions across changing task, environmental, and human states are assessed, based on evaluations with increased system representativeness and mission realism. Recommendations for needed system design modifications are documented.

C.5.1.5 Have strategies to mitigate safety implications for human users been updated, based on prototype testing in mission-relevant part-task simulations? The initial strategies to manage safety and occupational health risks that were identified at HRL 4 are refined, based on human-centered evaluations with prototypes at an increased level of maturity. Assumptions in safety analyses are verified or updated. Recommendations for needed system design modifications are documented.

C.5.1.6 Have strategies to accommodate manpower, personnel, and training concerns been updated, based on prototype testing in mission-relevant part-task simulations? The initial strategies to manage the HSI domains of manpower, personnel, and training that were identified at HRL 4 are refined, based on human-centered evaluations with prototypes at an increased level of maturity. Recommendations for needed system design modifications or revisions to the manpower, personnel, and training strategies are documented.

C.5.1.7 Have strategies to address environmental constraints and impacts been updated, based on prototype testing in mission-relevant part-task simulations? The initial strategies to manage environmental hazards that were identified at HRL 4 are refined, based on human-centered evaluations with prototypes at an increased level of maturity. Recommendations for needed system design modifications and other strategies are documented.

C.5.1.8 Have strategies to address implications for other relevant HSI domains been updated, based on prototype testing in mission-relevant part-task simulations? The initial strategies to address implications for other HSI domains that were identified at HRL 4 are refined, based on human-centered evaluations with prototypes at an increased level of maturity.

Recommendations for needed system design modifications and updates to HSI domain analyses and strategies are documented.

C.5.1.9 Have strategies to address human interactions during maintenance and sustainment been updated, based on prototype testing in mission-relevant part-task simulations? The initial strategies to address human interactions during maintenance and sustainment that were identified at HRL 4 are refined, based on human-centered evaluations with prototypes at an increased level of maturity. Recommendations for needed system design modifications and strategies are documented.

C.5.1.10 Has prototype testing in mission-relevant part-task simulations been used to update procedures for human user roles? The initial procedures and procedure support strategies generated at HRL 4 are refined, based on human performance evaluations with more representative users completing tasks during prototype testing in mission-relevant part-task simulations. With participation of more representative users, issues such as complexity, readability, clarity, accuracy, and sufficiency of procedure support strategies can be more fully assessed. Recommendations for needed system design and procedure modifications are documented.

C.5.1.11 Have analyses been completed to support system-wide trade studies on features affecting human performance? Analyses, models, and data collection contribute human performance data to ongoing trade studies as system design features are refined.

C.5.1.12 Have relevant human performance data been collected and evaluated to determine whether human performance metrics are successfully met, based on prototype testing in mission-relevant part-task simulations? Using TRL 5 prototypes, human performance data are collected and evaluated during mission-relevant part-task simulations to determine whether human performance metrics and requirements are being successfully met. Both objective human performance metrics (e.g., task performance times, errors, situation awareness, workload, muscle strain, learning time, and learning retention) and subjective data (e.g., usability surveys and stress ratings) are collected. Human performance results may be compared against data from existing comparable systems to gauge the extent of any improvements or degradations in human performance. In addition, a comparison of results to human performance requirements established in HRL 3 should be used to determine additional system design modifications that are necessary. Collected data are used to support trade studies to compare competing system design solutions. A positive response to this question signifies that the relevant data have been collected, evaluated, *and* deemed satisfactory by qualified human systems experts, given current and anticipated levels of technical maturity.

C.5.1.13 Have strategies to support human use been identified and recommended, based on prototype testing in mission-relevant part-task simulations? All of the information gained at HRL 5 is used to recommend system design improvements and strategies that will effectively support human interactions with the developing technology and address key human-

centered challenges identified at this and previous HRL levels. Such strategies include the range of engineered, administrative, and PPE controls. Given the ease with which design modifications can be made at this stage of development, engineered design features that eliminate an identified risk or human performance issue altogether are preferred.

C.5.1.14 Has conformance of system prototypes to human performance requirements, design principles, standards, and guidance been verified? Conformance of TRL 5 prototypes to the human performance requirements, design principles, standards, and guidance established at earlier HRL levels is evaluated. Any discrepancies are analyzed to identify appropriate actions for resolution.

C.5.2 Guidance and Considerations

When addressing HRL 5, human systems experts should consider the following guidance:

- All of the human-centered evaluation activities completed at HRL 4 are repeated at HRL 5, using a more detailed and functional human systems prototype with realistic mission tasks and conditions and representative users.
- The fidelity of key elements of the technology has increased significantly, integrating key components and capabilities with realistic supporting elements and at least simulated system functionality.
- Testing and demonstration occur in mission-relevant part-task simulations or actual environments.
- Users participating in human-centered testing are independent from the design team, providing more informative and unbiased assessments. Up to this point, test participants may have been solicited from various samples of convenience. HRL 5 represents the latest level to begin engaging more representative users to interact with the technology during testing. They may not be fully representative of the intended target population, but they should be similar in terms of basic characteristics and skills.

C.5.3 Exit Criteria

In order to exit HRL 5 and advance to the next level, human interactions and performance with developing system prototypes are evaluated and characterized in the context of more realistic mission-relevant part-task simulations with higher fidelity and users independent from the design team. Human performance results must be deemed satisfactory by qualified human systems experts. Human systems experts should specify which of the recommended questions are relevant for the current effort and identify whether they have been answered positively in order to conclude that HRL 5 has been satisfactorily met.

C.5.4 Supporting Evidence

The following list identifies the types of supporting evidence that should be provided to indicate that HRL 5 has been satisfactorily addressed and exit criteria have been met:

- Document evolving human-centered concepts or human systems designs in the form of a functional prototype.

- Document updated usage scenarios.
- Document results of updated task analyses, trade studies, and implications for system design.
- Describe updated human-machine function allocations and human-machine teaming support strategies and provide the rationale.
- Document strategies to mitigate concerns related to all relevant HSI domains.
- Document strategies to mitigate concerns related to human interactions during maintenance and sustainment.
- Document strategies and key observations for procedure development.
- Document human interactions and performance, based on functional prototype testing in mission-relevant part-task simulations.
- Document the human performance data collected during prototype testing in mission-relevant part-task simulations and evaluations of the ability of solutions to meet metrics and requirements for successful human performance.
- Describe recommended strategies to support human use.
- Characterize conformance of prototypes to human performance requirements, design principles, standards, and guidance established at earlier HRL levels.
- Complete the HRL 5 test plan.
- Complete the HRL 5 test report to document the results of human-centered prototype testing in mission-relevant part-task simulations.
- Begin drafting a test plan for subsequent human systems testing associated with HRL 6.

C.6 HRL 6 Evaluation Guidance

During HRL 6, the human systems design is fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations. This level represents a major step in a technology's demonstrated readiness and the final demonstration before verification and validation activities begin in the production and deployment phase. Users participating in human-centered testing are representative of the target population with respect to the range of characteristics identified as relevant for the given technology. Human-centered testing features a more mature representation of the system and encompasses the full range of usage scenarios and tasks, including emergency and non-normal events, training, maintenance, and sustainment. Although subjective metrics continue to be informative at this level, testing emphasizes the collection of objective metrics related to human performance and lifecycle concepts. The human-centered evaluation activities completed at HRL 5 are repeated during HRL 6 under these more representative conditions in high-fidelity simulations or actual environments with the evolved system design concepts. The human systems experts involved in the current effort should tailor the guidance in this section as needed and specify which of the recommended questions must be answered positively to conclude that HRL 6 has been satisfactorily met.

C.6.1 Evaluation Activities

Human systems experts should address the following questions during HRL 6, as applicable.

C.6.1.1 Have the functioning prototype of the human-system interface and simulations of mission tasks and conditions been fully developed to support assessment of critical human performance issues? Functioning prototypes of the human-centered technology concept or the human interface to the system should be updated to represent emerging human systems designs, as refined by activities in the prior HRL. Simulations should incorporate realistic representations of system functionality and a representative range of mission tasks and conditions that allow for collection of relevant human performance metrics in realistic simulations of user tasks.

C.6.1.2 Has the full range of user scenarios and tasks been tested in high-fidelity simulated or actual environments? Because HRL 6 represents the final demonstration before verification and validation activities begin, it is important to evaluate the full range of usage scenarios under the more representative conditions that characterize high-fidelity simulated or actual environments. In addition to normal usage and tasks, the full range of scenarios and tasks includes emergency and non-normal events to support evaluation of human interactions and performance in conditions that occur infrequently or without warning. The full range also includes tasks that permit evaluation of human interactions and performance during training, maintenance, and sustainment activities.

C.6.1.3 Have task analyses been updated, based on testing in high-fidelity simulated or actual environments? The tasks analyses developed and updated at earlier HRL levels are further refined at HRL 6 to represent the final system design. Given that the technology development phase is nearing its conclusion at TRL/HRL 6, task analyses should be near final in preparation for production and deployment activities that will begin at HRL 7.

C.6.1.4 Have human-machine teaming strategies and human-machine function allocations been updated, based on testing in high-fidelity simulated or actual environments? The efficacy of human-automation teaming strategies, human-machine function allocations, and support for transitions of functions across humans and automation that were identified and updated at previous HRL levels are verified and fully refined, based on testing in high-fidelity simulated or actual environments. Given that the technology development phase is nearing its conclusion at TRL/HRL 6, these strategies should be near final in preparation for production and deployment activities that will begin at HRL 7. Final system design modifications are documented and incorporated.

C.6.1.5 Has a system to track and resolve human systems issues after fielding been developed and evaluated in high-fidelity simulated or actual environments? The human systems issue tracking system may be an extension of an existing, broader issue tracking system, functionality built into the system itself to unobtrusively track performance, or a completely new and separate system devoted solely to human systems issues. The effectiveness of the system to

track and resolve human-related issues is evaluated, beginning at HRL 6. This evaluation may be accomplished by running scenarios in which human errors are deliberately induced for entry and follow-through in the tracking system. A key factor for evaluation is whether the tracking system provides a comprehensive set of categories for accurately diagnosing root causes of the error. For example, many issues attributed to human error have root causes in basic system designs poorly suited for people to use.

C.6.1.6 Have strategies to mitigate safety implications for human users been updated, based on testing in high-fidelity simulated or actual environments? The strategies to manage safety and occupational health risks that were identified and updated at previous HRL levels are verified and fully refined, based on testing in high-fidelity simulated or actual environments. Given that the technology development phase is nearing its conclusion at TRL/HRL 6, these strategies should be near final in preparation for production and deployment activities that will begin at HRL 7. Any remaining assumptions in safety analyses are verified or updated. Final system design modifications and safety strategies are documented and incorporated into the system design.

C.6.1.7 Have strategies to accommodate manpower, personnel, and training concerns been updated, based on testing in high-fidelity simulated or actual environments? The strategies to manage the HSI domains of manpower, personnel, and training that were identified and updated at previous HRL levels are verified and fully refined, based on testing in high-fidelity simulated or actual environments. Given that the technology development phase is nearing its conclusion at TRL/HRL 6, these strategies should be near final in preparation for production and deployment activities that will begin at HRL 7. Final system design modifications and updated to manpower, personnel, and training systems are documented and incorporated.

C.6.1.8 Have strategies to address environmental constraints and impacts been updated, based on testing in high-fidelity simulated or actual environments? The strategies to manage environmental hazards that were identified and updated at previous HRL levels are verified and fully refined, based on testing in high-fidelity simulated or actual environments. Given that the technology development phase is nearing its conclusion at TRL/HRL 6, these strategies should be near final in preparation for production and deployment activities that will begin at HRL 7. Final system design modifications, environmental hazard strategies, and updates to the occupational safety and health plan, if applicable, are documented and incorporated.

C.6.1.9 Have strategies to address implications for other relevant HSI domains been updated, based on testing in high-fidelity simulated or actual environments? The strategies to address human performance issues for other HSI domains that were identified and updated at previous HRL levels are verified and fully refined, based on testing in high-fidelity simulated or actual environments. Given that the technology development phase is nearing its conclusion at TRL/HRL 6, these strategies should be near final in preparation for production and deployment

activities that will begin at HRL 7. Final system design modifications and updates to HSI strategies and plans, if applicable, are documented and incorporated.

C.6.1.10 Have strategies to address human interactions during maintenance and sustainment been updated, based on testing in high-fidelity simulated or actual environments? The strategies to address human interactions during maintenance and sustainment that were identified and updated at previous HRL levels are verified and fully refined, based on testing in high-fidelity simulated or actual environments. Given that the technology development phase is nearing its conclusion at TRL/HRL 6, these strategies should be near final in preparation for production and deployment activities that will begin at HRL 7. Final system design modifications and updates to maintenance and sustainment systems are documented and incorporated.

C.6.1.11 Has testing in high-fidelity simulated or actual environments been used to finalize procedures for human user roles throughout the lifecycle? The procedures and procedure support strategies that were generated and updated at previous HRL levels are verified and fully refined, based on inputs provided by representative users completing the full range of usage scenarios and tasks during testing in high-fidelity simulated or actual environments. With participation of representative users, issues such as readability, clarity, and accuracy can be fully addressed and resolved in preparation for final verification and validation activities.

C.6.1.12 Have relevant human performance data been collected and evaluated to determine whether human performance metrics are successfully met, based on testing in high-fidelity simulated or actual environments? Human performance data are collected and evaluated during testing in high-fidelity simulated or actual environments to determine whether human performance metrics and requirements are successfully met. Both objective performance metrics and subjective data should be collected to document whether human performance requirements and human systems goals can be successfully accomplished; however, testing at HRL 6 begins emphasizing collection of objective metrics. Human performance data are used to support remaining system trade studies. A positive response to this question signifies that the relevant data have been collected, evaluated, *and* deemed satisfactory by qualified human systems experts, given that the technology development phase is nearing its conclusion. Final system design modifications are documented and incorporated.

C.6.1.13 Have strategies to support human use been identified and recommended, based on testing in high-fidelity simulated or actual environments? All of the information gained at HRL 6 is used to finalize strategies that will effectively support human interactions with the developing technology and address key human-centered challenges identified at this and previous HRL levels. Such strategies include the range of engineered, administrative, and PPE controls. Given that TRL/HRL 6 represents the end of the technology development phase, this level is the final point at which design modifications that eliminate identified risks or issues can be made without incurring excessive costs or schedule delays. Final system design modifications are documented and incorporated.

C.6.1.14 Has conformance of functional prototypes to human performance requirements, design principles, standards, and guidance been verified? Conformance of the TRL 6 prototype to the human performance requirements, design principles, standards, and guidance established at earlier HRL levels is evaluated and confirmed. Any remaining discrepancies are analyzed to identify appropriate actions for resolution. If any high-priority human-centered guidelines deemed critical by the qualified human systems experts involved in the effort have not been met by HRL 6, a resolution approach must be coordinated and established before progressing to HRL 7. Final system design modifications are documented and incorporated.

C.6.2 Guidance and Considerations

When addressing HRL 6, human systems experts should consider the following guidance:

- All of the human-centered evaluation activities completed at HRL 5 are repeated at HRL 6.
- Testing and evaluation occur using a highly functional prototype representative of the system design in high-fidelity simulated or actual environments with users who are representative of the target population.
- The full range of usage scenarios and tasks is evaluated to support full maturation of human systems designs. The full range includes emergency and non-normal events and activities associated with training, maintenance, sustainment, and tracking of human systems issues.
- Strategies to address each relevant HSI domain should be near final at this level in preparation for production and deployment activities that will begin at HRL 7.
- Any required human user procedures should be finalized in preparation for follow-on verification and validation activities.
- Although subjective metrics continue to be informative at HRL 6, testing emphasizes collection and evaluation of objective human performance metrics.
- The human systems design is essentially completed at HRL 6; however, modifications are still possible if critical issues or risks are identified during subsequent verification and validation testing in the production and deployment phase. Any changes after TRL/HRL 6 should be more minor in extent than at previous levels.
- Given that TRL/HRL 6 represents the end of the technology development phase, this level is the final point at which design modifications that eliminate identified risks or human performance issues can be easily made without incurring excessive costs or schedule delays.
- Before progressing to HRL 7, human systems experts should establish a mutually agreeable resolution plan for any critical human-centered recommendations or guidelines that have not yet been met.

C.6.3 Exit Criteria

In order to exit HRL 6 and advance to the next level, human interactions and performance are evaluated and characterized in the context of high-fidelity simulated or actual environments with a functional and realistic prototype, representative users, and the full range of usage scenarios and tasks. Human performance results must be deemed satisfactory by qualified human systems experts. Human systems experts should specify which of the recommended questions are

relevant for the current effort and identify whether they have been answered positively in order to conclude that HRL 6 has been satisfactorily met.

C.6.4 Supporting Evidence

The following list identifies the types of supporting evidence that should be provided to indicate that HRL 6 has been satisfactorily addressed and exit criteria have been met:

- Document completed human-centered concept or human systems design in a functional, representative system prototype.
- Document usage scenarios and tasks tested with a functional prototype in high-fidelity simulated or actual environments.
- Document results of updated task analyses, trade studies, and system design recommendations.
- Document human-machine function allocations and human-machine teaming support strategies.
- Document the proposed system that will be used to track and resolve human systems issues after fielding.
- Document strategies to mitigate concerns related to all relevant HSI domains.
- Document strategies to mitigate concerns related to human interactions during maintenance and sustainment.
- Document procedure support strategies and completed human user procedures.
- Document human interactions and performance, based on testing in high-fidelity simulated or actual environments.
- Document the human performance data used during testing in high-fidelity simulated or actual environments and evaluations of the ability of solutions to meet metrics and requirements for successful human performance.
- Document recommended strategies to support human use.
- Characterize conformance of functional prototypes to human performance requirements, design principles, standards, and guidance established at earlier HRL levels.
- Complete the HRL 6 test plan.
- Complete the HRL 6 test report to document the results of human-centered testing in high-fidelity simulated or actual environments.
- Begin drafting a test plan for subsequent human systems testing associated with HRL 7.

C.7 HRL 7 Evaluation Guidance

During HRL 7, the human systems design is fully tested and verified in an operational environment with system hardware and software and representative users. This level represents the first level in the production and deployment phase and typically signals the end of development. The engineering design is essentially frozen. Human-centered testing encompasses the full range of usage scenarios and tasks, including emergency and non-normal events and activities associated with training, maintenance, sustainment, and tracking of human systems issues. All of the human-centered evaluation activities completed at HRL 6 are repeated during

HRL 7, using the final development system in an operational environment. By this level, the primary task of human systems experts shifts from identification and recommendation of mitigation strategies to evaluation and verification that key recommended strategies have been successfully incorporated and work as intended to satisfactorily support the humans in the system. Any remaining required modifications should be recommended and incorporated into the final system. The human systems experts involved in the current effort should tailor the guidance in this section as needed and specify which of the recommended questions must be answered positively to conclude that HRL 7 has been satisfactorily met.

C.7.1 Evaluation Activities

Human systems experts should address the following questions during HRL 7, as applicable.

C.7.1.1 Has the range of user scenarios and tasks been tested with the final development system in an operational environment? The final functional and integrated development system (including hardware and software) is evaluated in the full range of usage scenarios and tasks in representative conditions by representative system users in an operational environment. The full range of scenarios and tasks includes emergency and non-normal events to support evaluation of human interactions and performance in conditions that occur infrequently or without warning. The full range also includes tasks that permit evaluation of human interactions and performance during training, maintenance, and sustainment activities. Final required modifications are documented.

C.7.1.2 Have task analyses been updated with the final development system in an operational environment? The tasks analyses developed and updated at earlier HRL levels are further refined at HRL 7 to ensure they represent the final development system. Given that HRL 7 represents the beginning of the production and deployment phase, evaluations at this stage serve to verify task analyses adequately represent user tasks, as performed with the final development system in an operational environment.

C.7.1.3 Have human-machine teaming strategies and human-machine function allocations been evaluated with the final development system in an operational environment? The efficacy of human-automation teaming strategies, human-machine function allocations, and support for transitions of functions across humans and automation that were identified and updated at previous HRL levels is verified at HRL 7. Use of the final development system by representative users permits evaluation under realistic conditions in an operational environment to gauge effectiveness. Any remaining required modifications are documented.

C.7.1.4 Has a system to track and resolve human systems issues after fielding been evaluated with the final development system in an operational environment? The effectiveness of the system to track and resolve human systems issues is evaluated in representative conditions in an operational environment. Targeted scenarios in which human errors are deliberately induced may be implemented to evaluate entry and follow-through of

identified human-related issues in the tracking system. Final required modifications are documented.

C.7.1.5 Has the effectiveness of strategies to mitigate safety implications for human users been evaluated with the final development system in an operational environment? At HRL 7, activities to address the HSI domain of safety and occupational health focus on verifying the effectiveness of previously recommended strategies to manage identified safety and occupational health risks. Use of the final development system by representative users permits evaluation under realistic conditions in an operational environment to gauge effectiveness. Final required modifications are documented.

C.7.1.6 Has the effectiveness of strategies to accommodate manpower, personnel, and training requirements been evaluated with the final development system in an operational environment? At HRL 7, activities to address the HSI domains of manpower, personnel, and training focus on verifying the effectiveness of previously recommended strategies and systems to support identified manpower, personnel, and training requirements. Training and use of the final development system by representative users permits evaluation under realistic conditions in an operational environment to gauge effectiveness. Final required modifications are documented.

C.7.1.7 Has the effectiveness of strategies to address environmental constraints and impacts been evaluated with the final development system in an operational environment? At HRL 7, activities to address the HSI environment domain focus on verifying the effectiveness of previously recommended strategies to manage identified environmental constraints and impacts. Use of the final development system by representative users permits evaluation under realistic conditions in an operational environment to gauge effectiveness. For example, impacts of realistic operational environment conditions such as light, noise, vibration, temperature, and stress on human performance and behavior should be evaluated. Any remaining required modifications are documented.

C.7.1.8 Has the effectiveness of strategies to address implications for other relevant HSI domains been evaluated with the final development system in an operational environment? At HRL 7, activities to address other relevant HSI domains such as habitability and force protection/survivability focus on verifying the effectiveness of previously recommended strategies to manage any identified risks. Use of the final development system by representative users permits evaluation under realistic conditions in an operational environment to gauge effectiveness. Any remaining required modifications are documented.

C.7.1.9 Has the effectiveness of strategies to address human interactions during maintenance and sustainment been evaluated with the final development system in an operational environment? At HRL 7, activities to address human interactions maintenance and sustainment focus on verifying the effectiveness of previously recommended strategies to manage maintenance and sustainment activities throughout the lifecycle. Use of the final

development system by representative users permits evaluation under realistic conditions in an operational environment to gauge effectiveness. Any remaining required modifications are documented.

C.7.1.10 Have human user procedures been tested with the final development system in an operational environment? The procedures that were generated, updated, and refined at previous HRL levels are fully evaluated by representative users completing the full range of usage scenarios and tasks during testing with the final development system in an operational environment. Any remaining procedure modifications to correct issues with complexity, understandability, readability, clarity, and accuracy can be implemented and verified with representative users. Any remaining required modifications are documented.

C.7.1.11 Have relevant human performance data been collected and evaluated to determine whether human performance metrics are successfully met, based on testing with the final development system in an operational environment? Human performance data are collected and evaluated during testing with the final development system in an operational environment to determine whether human performance metrics and requirements are successfully met. A positive response to this question signifies that the relevant data have been collected, evaluated, *and* deemed satisfactory by qualified human systems experts, given that the technology is essentially frozen at this level. Although subjective metrics may continue to be collected and evaluated, HRL 7 testing emphasizes objective metrics related to human performance and lifecycle concepts to document whether human performance requirements and human systems goals can be successfully accomplished. Any remaining required modifications are documented.

C.7.1.12 Have recommended strategies to support human use been satisfactorily incorporated into the final development system? All of the information gained at HRL 7 is used to determine whether recommend strategies designed to effectively support human interactions with the technology and address key human-centered challenges have been satisfactorily incorporated into the final development system. Given that the engineering design is normally frozen at TRL/HRL 7, any critical modifications that must be implemented to fully support human-centered systems designs at this point will incur additional costs or schedule delays. Human systems experts must coordinate with systems engineering and design teams to resolve issues that have not been satisfactorily addressed, providing a rationale and explicitly identifying the consequences of failure to address the issue. Any remaining required modifications are documented.

C.7.1.13 Has conformance of the final development system to human performance requirements, design principles, standards, and guidance been verified? Conformance of the TRL 7 final development system to the human performance requirements, design principles, standards, and guidance established at earlier HRL levels is evaluated. Any discrepancies are analyzed to identify appropriate actions for resolution. If any high-priority human-centered guidelines deemed critical by the qualified human systems experts involved in the effort have not

been met by HRL 7, a resolution approach must be coordinated and established before progressing to HRL 8. Human systems experts must coordinate with the design team to resolve any discrepancies that have not been satisfactorily addressed, providing a rationale and explicitly identifying the consequences of failure to address the discrepancy. Any remaining required modifications are documented.

C.7.2 Guidance and Considerations

When addressing HRL 7, human systems experts should consider the following guidance:

- All of the human-centered evaluation activities completed at HRL 6 are repeated at HRL 7. However, human-centered activities shift from identification and recommendation of mitigation strategies to evaluation and verification that key recommended strategies have been successfully incorporated and work as intended to satisfactorily support the humans in the system. The intent is to verify the final development system supports human use.
- Testing and evaluation occur using the final development system in an operational environment with representative users.
- The full range of usage scenarios and tasks is evaluated to support full testing and verification of human systems designs. The full range includes emergency and non-normal events and activities associated with training, maintenance, sustainment, and tracking of human systems issues.
- The effectiveness of recommended strategies to address each relevant HSI domain is evaluated and verified at HRL 7.
- The effectiveness of human user procedures is verified with representative users applying the procedures in realistic scenarios and tasks in an operational environment.
- Although subjective metrics continue to be collected and evaluated at HRL 7, testing emphasizes objective metrics related to human performance and lifecycle concepts.
- Given that the engineering design is normally frozen at TRL/HRL 7, any critical modifications that must be implemented to fully support human-centered designs at this point will incur additional costs or schedule delays.
- Before progressing to HRL 8, human systems experts should establish a mutually agreeable resolution plan for any critical human-centered recommendations or guidelines that have not yet been met.

C.7.3 Exit Criteria

In order to exit HRL 7 and advance to the next level, human interactions and performance are evaluated and characterized in an operational environment with the final development system, representative users, and the full range of usage scenarios and tasks. Human performance results must be deemed satisfactory by qualified human systems experts. Human systems experts should specify which of the recommended questions are relevant for the current effort and identify whether they have been answered positively in order to conclude that HRL 7 has been satisfactorily met.

C.7.4 Supporting Evidence

The following list identifies the types of supporting evidence that should be provided to indicate that HRL 7 has been satisfactorily addressed and exit criteria have been met:

- Document usage scenarios and tasks tested with the final development system in an operational environment.
- Document results of updated task analyses.
- Document the effectiveness of human-machine function allocations and human-machine teaming support strategies.
- Document the effectiveness of the system to track and resolve human systems issues after fielding.
- Document the effectiveness of strategies to mitigate concerns related to all relevant HSI domain.
- Document the effectiveness of strategies to mitigate concerns related to human interactions during maintenance and sustainment.
- Document the effectiveness of human user procedures.
- Document human interactions and performance, based on testing with the final development system in an operational environment.
- Document the human performance data used during testing with the final development system in an operational environment and evaluations of the ability of solutions to meet metrics and requirements for successful human performance.
- Document the incorporation of recommended strategies to support human use.
- Document conformance of the final development system to human performance design requirements, principles, standards, and guidance established at earlier HRL levels.
- Complete the HRL 7 test plan.
- Complete the HRL 7 test report to document the results of human-centered testing with the final development system in an operational environment.
- Begin drafting a test plan for subsequent human systems testing associated with HRL 8.

C.8 HRL 8 Evaluation Guidance

During HRL 8, total human-system performance is fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users. If testing is successful, the system is qualified and approved for full-rate production and fielding. For the DOD, TRL 8 testing activities may occur as part of developmental test and evaluation. Human-centered testing encompasses the full range of usage scenarios and tasks, and all of the human-centered evaluation activities completed at HRL 7 are repeated during HRL 8, using the production system in mission operations. HRL 8 represents the final opportunity to identify and incorporate elements to support human readiness before fielding and operational use. The human systems experts involved in the current effort should tailor the guidance in this section as needed and specify which of the recommended questions must be answered positively to conclude that HRL 8 has been satisfactorily met.

C.8.1 Evaluation Activities

Human systems experts should address the following questions during HRL 8, as applicable.

C.8.1.1 Has the range of user scenarios and tasks been tested with the production system in mission operations? The full range of usage scenarios and tasks is evaluated with the production system in mission operations. The full range of scenarios and tasks includes emergency and non-normal events to support evaluation of human interactions and performance in conditions that occur infrequently or without warning. The full range also includes tasks that permit evaluation of human interactions and performance during training, maintenance, and sustainment activities. Final required modifications are documented.

C.8.1.2 Have task analyses been updated with the production system in mission operations? HRL 8 provides the final opportunity to verify task analyses adequately represent user tasks before the system is fielded for operational use. Observations and analyses should focus on identifying and understanding any deviations between tasks as planned versus tasks as performed with the production system in mission operations.

C.8.1.3 Have human-machine teaming strategies and human-machine function allocations been evaluated with the production system in mission operations? The efficacy of human-automation teaming strategies, human-machine function allocations, and support for transitions of functions across humans and automation that were identified and updated at previous HRL levels is validated at HRL 8. Use of the final production system by representative users permits evaluation under realistic conditions in mission operations to gauge effectiveness. Final required modifications are documented and implemented.

C.8.1.4 Has a system to track and resolve human systems issues after fielding been finalized and tested with the production system in mission operations? The effectiveness of the system to track and resolve human systems issues is evaluated with the production system in mission operations. Targeted scenarios in which human errors are deliberately induced may be implemented to evaluate entry and follow-through of identified human systems issues in the tracking system. Final required modifications are documented.

C.8.1.5 Has the effectiveness of strategies to mitigate safety implications for human users been evaluated and successfully demonstrated with the production system in mission operations? At HRL 8, human systems experts verify successful demonstration of the effectiveness of strategies to mitigate any identified risks in the HSI domain of safety and occupational health. Use of the final production system by representative users permits evaluation during realistic mission operations to gauge effectiveness. Strategies that have not been adequately incorporated or that are evaluated as ineffective must be fully documented for coordination and resolution. Final required modifications are documented.

C.8.1.6 Has the effectiveness of strategies to accommodate manpower, personnel, and training concerns been evaluated and successfully demonstrated with the production system in mission operations? At HRL 8, human systems experts verify successful demonstration of the effectiveness of strategies and systems to address the HSI domains of manpower, personnel, and training. Use of the completed manpower, personnel, and training system and the final production system by representative users permits evaluation during realistic mission operations to gauge effectiveness. Strategies that have not been adequately incorporated or that are evaluated as ineffective must be fully documented for coordination and resolution. Final required modifications are documented and implemented.

C.8.1.7 Has the effectiveness of strategies to address environmental constraints and impacts been evaluated and successfully demonstrated with the production system in mission operations? At HRL 8, human systems experts verify successful demonstration of the effectiveness of strategies to address the HSI environment domain. Use of the final production system by representative users permits evaluation during realistic mission operations to gauge effectiveness. Strategies that have not been adequately incorporated or that are evaluated as ineffective must be fully documented for coordination and resolution. Final required modifications are documented and implemented.

C.8.1.8 Has the effectiveness of strategies to address implications for other relevant HSI domains been evaluated and successfully demonstrated with the production system in mission operations? At HRL 8, human systems experts verify successful demonstration of the effectiveness of strategies to address other relevant HSI domains. Use of the final production system, including relevant support systems (e.g., survivability support system and PPE), by representative users permits evaluation during realistic mission operations to gauge effectiveness. Strategies that have not been adequately incorporated or that are evaluated as ineffective must be fully documented for coordination and resolution. Final required modifications are documented and implemented.

C.8.1.9 Has the effectiveness of strategies to address human interactions during maintenance and sustainment been evaluated and successfully demonstrated with the production system in mission operations? At HRL 8, human systems experts verify successful demonstration of the effectiveness of strategies for human interactions during maintenance and sustainment throughout the lifecycle. Use of the final production system by representative users completing maintenance and sustainment tasks permits evaluation during realistic mission operations to gauge effectiveness. Strategies that have not been adequately incorporated or that are evaluated as ineffective must be fully documented for coordination and resolution. Final required modifications are documented and implemented.

C.8.1.10 Have human user procedures been tested and found acceptable to meet task demands with the production system in mission operations? Human user procedures and procedure support systems are fully evaluated by representative users completing the full range of usage scenarios and tasks during testing with the production system in mission operations.

Any required procedure modifications to correct issues with complexity, understandability, readability, clarity, and accuracy can be implemented at this level and verified with representative users. Final required modifications are documented and implemented.

C.8.1.11 Have relevant human performance data been evaluated to determine whether human performance metrics are successfully met, based on qualification of the production system in mission operations? Human performance data are collected and evaluated during testing with the production system in mission operations to determine whether human performance metrics and requirements are successfully met. A positive response to this question signifies that the relevant data have been collected, evaluated, *and* deemed satisfactory by qualified human systems experts, given that the technology is essentially frozen at this level. Although subjective metrics may continue to be collected and evaluated, testing emphasizes objective metrics related to human performance and lifecycle concepts to document whether human performance requirements and human systems goals can be successfully accomplished. Final required modifications are documented and implemented.

C.8.1.12 Have human use issues been satisfactorily resolved, as evidenced by qualification of the production system in mission operations? All of the information gained at HRL 8 is used to determine whether human use issues have been satisfactorily resolved. Any critical modifications that must be implemented to fully support human-centered designs at this point will incur significant costs or schedule delays. Human systems experts must coordinate with systems engineering and design teams to resolve high-priority issues that have not been satisfactorily addressed, providing a rationale and explicitly identifying the consequences of failure to address the issue. Final required modifications are documented and implemented.

C.8.1.13 Has conformance of the final production system to human performance requirements, design principles, standards, and guidance been verified? Conformance of the TRL 8 production system to the human performance requirements, design principles, standards, and guidance established at earlier HRL levels is verified. Any discrepancies are analyzed to identify appropriate actions for resolution. If any high-priority human-centered guidelines deemed critical by the qualified human systems experts involved in the effort have not been met by HRL 8, a resolution approach must be coordinated and established before progressing to HRL 9. Human systems experts must coordinate with systems engineering and design teams to resolve any discrepancies that have not been satisfactorily addressed, providing a rationale and explicitly identifying the consequences of failure to address the discrepancy. Final required modifications are documented and implemented.

C.8.2 Guidance and Considerations

When addressing HRL 8, human systems experts should consider the following guidance:

- All of the human-centered evaluation activities completed at HRL 7 are repeated at HRL 8.
- Testing and evaluation occur using the production system in mission operations with representative users. For the DOD, testing at this level may occur as part of developmental test and evaluation.

- The full range of usage scenarios and tasks is evaluated to support full testing, validation, and approval of total human-system performance in mission operations. The full range includes emergency and non-normal events and activities associated with training, maintenance, sustainment, and tracking of human systems issues.
- HRL 8 represents the final opportunity to identify and incorporate elements to support human readiness before fielding and operational use. Any design changes at this point are the minimum required to bring the system up to specification.
- The effectiveness of strategies to address each relevant HSI domain is evaluated with the production system at HRL 8.
- The acceptability of human user procedures is tested with representative users applying the procedures in realistic scenarios and tasks with the production system in mission operations.
- Although subjective metrics continue to be collected and evaluated at HRL 8, testing emphasizes objective metrics related to human performance and lifecycle concepts.
- Any critical modifications that must be implemented to fully support human-centered designs at this point will incur significant costs or schedule delays.
- Before progressing to HRL 9, human systems experts should establish a mutually agreeable resolution plan for any critical high-priority human-centered recommendations or guidelines that have not yet been satisfactorily met. Final recommended modifications must be identified and incorporated.

C.8.3 Exit Criteria

In order to exit HRL 8 and advance to the next level, human interactions and performance are evaluated and characterized with the production system in mission operations during the full range of usage scenarios and tasks completed by representative users. Human performance results must be deemed satisfactory by qualified human systems experts. Human systems experts should specify which of the recommended questions are relevant for the current effort and identify whether they have been answered positively in order to conclude that HRL 8 has been satisfactorily met.

C.8.4 Supporting Evidence

The following list identifies the types of supporting evidence that should be provided to indicate that HRL 8 has been satisfactorily addressed and exit criteria have been met:

- Document usage scenarios and tasks tested with the production system in mission operations.
- Document results of updated task analyses.
- Document the effectiveness of human-machine function allocations and human-machine teaming support strategies.
- Document the effectiveness of the system to track and resolve human systems issues after fielding.
- Document the effectiveness of strategies to mitigate concerns related to any relevant HSI domain.
- Document the effectiveness of strategies to mitigate concerns related to human interactions during maintenance and sustainment.

- Document the effectiveness of human user procedures.
- Document human interactions and performance, based on testing with the production system in mission operations.
- Document the human performance data used during testing with the production system in mission operations and evaluations of the ability of solutions to meet metrics and requirements for successful human performance.
- Document resolution of any remaining human use issues.
- Document conformance of the final production system to human performance requirements, design principles, standards, and guidance established at earlier HRL levels.
- Complete the HRL 8 test plan.
- Complete the HRL 8 test report to document the results of human-centered testing with the final development system in an operational environment.
- Begin drafting an overarching program report for the entire human systems program.
- Develop a test plan for subsequent HRL 9 activities (if applicable) and continued systematic monitoring after the system is fielded.

C.9 HRL 9 Evaluation Guidance

During HRL 9, the system is successfully used in operations across the operational envelope with systematic monitoring of human-system performance. For the DOD, final TRL 9 testing activities may occur during operational test and evaluation, if required. Human systems experts systematically monitor the system to ensure the required human performance capability is realized. A critical aspect of continued monitoring is detection and resolution of emerging human systems issues. Systematic monitoring encompasses the comprehensive set of tasks and conditions comprising the intended mission, including training, operations, maintenance, and abnormal environments. Human systems experts recommend future modifications to enhance human systems performance. The human systems experts involved in the current effort should tailor the guidance in this section as needed and specify which of the recommended questions must be answered positively to conclude that HRL 9 has been satisfactorily met.

C.9.1 Evaluation Activities

Human systems experts should address the following questions during HRL 9, as applicable.

C.9.1.1 Has the qualified system been fielded in the operational environment for the intended users? Use of the actual system in successful mission operations signals the beginning of TRL/HRL 9. For the DOD, initial operational use may occur in the form of operational test and evaluation, if required. However, if final operational test and evaluation is not required, the system can achieve TRL 9 by performing in a live operational mission. By this level, the system has been fully tested, verified, validated, and qualified for its intended mission and is now fielded for the full range of operational mission tasks.

C.9.1.2 Are human systems performance data and lessons learned being documented for recommended systems improvements and future applications? Lessons learned pertaining to both successes and failures are documented not only to maintain or improve the human performance capability for the current system but also to provide recommendations for future systems improvements and to support future applications involving similar technologies.

C.9.1.3 Does the system designed to track and resolve human systems issues in the fielded system fully support these activities? Human systems experts evaluate the efficacy of the human systems issue tracking and resolution system during HRL 9. Modifications may be suggested to enhance the ability to track issues that specifically involve the human component of the system and expedite resolution.

C.9.1.4 Are human systems mitigations to improve performance in the fielded system being identified and implemented? Human systems experts systematically monitor the fielded system to detect and resolve emerging human systems issues. Systematic monitoring encompasses the full range of mission tasks and conditions, including training, operations, maintenance, and abnormal environments. Collected data may consist of human performance issues, errors, and accidents. Data collection may involve field observation, surveys, interviews, issue tracking systems, and error/accident reports. The intent is to support early detection and resolution of human systems issues to maintain or improve human performance and prevent future, potentially catastrophic, system errors.

C.9.1.5 Is user training for operation of the fielded system being evaluated for required modifications? As part of monitoring the fielded system, human systems experts evaluate all forms of user training to assess effectiveness and identify improvements—initial classroom training, hands-on training in the field, periodic refresher training, and instruction associated with upgrades or change notifications.

C.9.1.6 Are potential upgrades to the fielded system being evaluated to address human systems issues and impacts? Whenever upgrades to the fielded system are planned, it is critical to involve human systems experts to evaluate potential human systems impacts and verify upgrades continue to support effective human performance. At the same time, human systems experts evaluate any changes in user knowledge, skills, and abilities that have occurred since initial fielding and may impact interactions with the upgraded system. Upgrades to an existing system are typically managed under a new development effort, potentially with a new team of human systems experts who leverage human systems reports from the initial development effort during evaluation of upgrades.

C.9.2 Guidance and Considerations

When addressing HRL 9, human systems experts should consider the following guidance:

- Human systems evaluation does not end once the system is fielded. Continued systematic monitoring is necessary to ensure the human performance capability achieved during verification, validation, and qualification is maintained.
- New human systems issues may emerge after fielding that require detection and mitigation. Resolution may involve hardware, software, or process modifications.
- Recommendations for future system upgrades, based on human performance issues encountered during operations, should be provided.
- Human systems experts should be consulted when any system upgrades are proposed to analyze the modifications for potential human systems impacts. At the same time, human systems experts must evaluate any changes in user knowledge, skills, and abilities that have occurred since initial fielding and may impact interactions with proposed system upgrades.
- Documentation of lessons learned can support resolution of issues impacting the current system and provide guidance to avoid similar problems with comparable future technologies.

C.9.3 Exit Criteria

Like TRL 9, HRL 9 does not have a distinct or well-defined conclusion. A fielded system continues to be monitored, tested, and evaluated to ensure it supports the mission as intended. Human systems experts should evaluate the fielded system in the operational environment with the actual users and provide recommendations to sustain the human performance capability.

C.9.4 Supporting Evidence

The following list identifies the types of supporting evidence that should be provided to indicate that HRL 9 is being satisfactorily addressed. The system will remain at TRL/HRL 9 indefinitely as long as it is being used. Because the program office that was responsible for design and development may be disbanded soon after fielding, a separate team of human systems experts may have primary responsibility for continued monitoring of the fielded system.

- Document customer acceptance and operational use of the qualified system.
- Document ongoing human systems evaluations of the existing system and proposed upgrades through observations, tests, and issue analysis and resolution.
- Document results and lessons learned.
- Complete the HRL 9 test report if a formal event like operational test and evaluation was involved.
- Complete the overarching human systems program report, if not accomplished during HRL 8.

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APPENDIX D: APPLICATION EXAMPLES (INFORMATIVE)

This appendix provides six examples illustrating how to apply the HRL scale for material and non-material solutions:

- Helmet-mounted display
- Traditional software development
- Agile software development
- Robot repurposing
- Leadership training
- System upgrade

D.1 Helmet-Mounted Display Example

A helmet-mounted display (HMD) projects visual text and icons onto a transparent visor worn by a user that overlays on top of information viewed in the natural world. This type of display is also referred to as augmented reality. In this example, the technology for presenting information via an HMD was developed and then incorporated into a military aircraft cockpit. Accordingly, in this example, while the aircraft system is a relatively mature technological concept, the HMD is a new technology for which human readiness is evaluated, beginning with HRL1.

D.1.1 HRL 1: Basic principles for human characteristics, performance, and behavior observed and reported

- Potential HMD scenarios and usage cases identified.
- Preliminary analysis completed to identify potential physical, cognitive, and perceptual performance issues and risks for HMDs, including risks of injury due to HMD weight.
- Research conducted to determine optical characteristics needed for accurate perception of HMD information, required field of view, and methods to provide sufficient contrast with diverse backgrounds.
- Research conducted to determine effects of tracking lags and vibration on human performance.
- Research conducted to determine effect of HMDs on depth perception, visual illusions, and spatial disorientation.
- Research conducted to determine impact of HMDs on neck injuries during G-loading and on ejection and evacuation safety.
- Human head dimensions established to identify anthropometric capabilities and limitations of potential users.

D.1.2 HRL 2: Human-centered concepts, applications, and guidelines defined

- Design guidelines established for HMD optics to support human perceptual performance across a range of illumination and background contrast conditions.
- Design guidelines established for HMD tracking performance and vibration limitations required for human performance.
- Design guidelines established for methods to minimize visual illusions and spatial disorientation with HMDs.

- Design guidelines established for HMD weights, form factors, and mountings that will promote comfort and prevent neck injuries during G-loading, ejection, and evacuation procedures.
- Design guidelines established to ensure the 5th to the 95th percentiles of human head dimensions are accommodated.
- Design guidelines established for integrating HMD information with traditional display hardware in cockpits to allow concurrent viewing.
- Design guidelines established for supporting ease of human interactions during HMD maintenance and sustainment.
- Concepts defined to use an HMD to replace current head-up displays for fighter aircraft pilots.
- Initial task descriptions for relevant roles (user and maintainer) developed.
- Human performance on legacy head-up displays analyzed to leverage lessons learned for HMD development.
- Legacy system operators interviewed to identify potential sources of human error and misuse.
- Appropriate human performance metrics identified, based in part on performance metrics used to evaluate legacy head-up displays.

D.1.3 HRL 3: Human-centered requirements to support human performance and human-technology interactions established

- Target population specified (95% of male and female military personnel) and user characteristics identified.
- Human systems experts (human factors, safety, survivability, environment, manpower, personnel, and training) identified to support the design and development effort.
- Usage scenarios updated to characterize tasks that will be performed while wearing the HMD.
- Cognitive task analyses conducted to identify information and decision-making needs in target aircraft missions.
- Operational and system demands for using an HMD in target aircraft identified.
- User capabilities, limitations, and needs mapped to expected operational and system demands to identify human performance issues.
- Function allocation conducted to determine information and functions to be supported on the HMD.
- HSI domains for safety and survivability analyzed.
- HSI domain for environment analyzed to identify relevant environmental use conditions such as lighting and vibration affecting performance with the HMD.
- Initial manpower, personnel, and training analyses conducted to determine potential changes needed to accommodate addition of HMD to aircraft system.
- Requirements established for the design of HMDs to provide necessary information and allow for the performance of required tasks under the specified operational use conditions.

- Requirements established for the design of HMDs to meet design guidelines specified in HRL 2.
- Requirements established for the HMD design to provide specified levels of human performance on relevant tasks, to include manageable levels of workload and accurate situation awareness when the HMD is used within the target aircraft system.
- Requirements established for HMD fit and comfort.
- Requirements established for maximum loading on the neck during G-loading and ejection activities.
- Requirements established for maximum time requirements to perform basic and advanced maintenance tasks on the HMD.
- Preliminary HMD design features recommended to accommodate user capabilities, limitations, and needs.

D.1.4 HRL 4: Modeling, part-task testing, and trade studies of human systems design concepts and applications completed

- Additional analysis for the HSI domains of safety and survivability conducted to recommend potential mitigation strategies for identified risks.
- Strategies to accommodate needed manpower, personnel, and training changes due to incorporation of HMD identified and recommended.
- Strategies to support human interactions during HMD maintenance and sustainment identified.
- Physical modeling of HMD designs for target populations conducted using Jack modeling tool. Analysis of form and fit for design options conducted for users and maintainers. Comfort and muscle fatigue issues identified and solutions recommended.
- Impact of HMD design options on center of mass and impact on biomechanical loading on the neck under mission conditions and G-loading conducted. Issues and recommended solutions identified.
- Graphical prototypes of HMD iconography and text developed and evaluated to maximize situation awareness during operations, optimize pilot workload, and minimize training requirements across mission tasks and timelines.
- Prototype displays modeled in graphics software. Subjective testing of designs conducted to determine needed modifications.
- Improved Performance and Research Integration Tool (IMPRINT) for workload modeling used to analyze impacts of HMD information on pilot workload. Issues and recommended solutions identified.
- Sample text and graphics projected on prototype HMD optical hardware and visual acuity tested against representative backgrounds under representative environmental conditions such as lighting and vibration. Issues and recommended solutions identified.
- Automation and information fusion needed to support situation awareness and minimize pilot workload identified. Human-automation integration strategy identified to include appropriate levels of automation across functions, methods for shifting control, and methods for human override. Methods for sharing information across human and automation identified.

- Task analyses updated to optimize task flow and sequencing during key HMD tasks such as targeting and weapon cueing.
- Initial procedures for HMD use designed, leveraging procedures historically used for head-up displays.
- Conformance of HMD design to requirements and guidelines established at earlier HRL levels assessed and needed modifications identified.

D.1.5 HRL 5: Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design

- Higher-fidelity HMD prototype that incorporates draft symbology and text displays developed.
- Analyses for the HSI domains of safety and survivability updated based on more complete understanding of risks from prototype evaluations and potential mitigation strategies identified.
- Sled tests conducted with representative prototypes and manikins to assess crash impact on human safety. Safety problems and modifications identified.
- Strategies to accommodate manpower, personnel, and training changes due to incorporation of HMD updated and recommended.
- Strategies to support human interactions during HMD maintenance and sustainment updated and recommended.
- HMD prototype tested with pilot subjects completing relevant tasks in aircraft simulators with representative part-mission scenarios. Human performance with the system (time to perform tasks and errors) evaluated along with pilot workload (subjective ratings and physiological measures), situation awareness (objective scores), and ergonomics factors such as fit and comfort.
- Potential negative environmental effects such as fatigue, motion sickness, vibration, and display lags evaluated.
- HMD hardware, software and display design modifications recommended to improve human performance, optimize workload, and maximize situation awareness when using the system.
- Human-automation integration strategy tested and required changes identified.
- Task analyses further refined to optimize task flow and sequencing during key HMD tasks such as targeting and weapon cueing.
- Procedures for HMD use refined, based on prototype testing in mission-relevant part-task simulations.
- Conformance of system design to requirements and design guidelines established at earlier HRL levels assessed and needed modifications identified.

D.1.6 HRL 6: Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations

- HMD hardware, software, and system displays modified and integrated into functional prototype design and evaluated in full-motion cockpit simulation.

- Human performance testing conducted in high-fidelity mission simulations with pilot users across range of mission scenarios and tasks.
- Analyses for the HSI domains of safety and survivability updated to demonstrate the validity of any assumptions and successful mitigation of risks.
- Manpower, personnel, and training requirements updated and design changes identified.
- Strategies to support human interactions during HMD maintenance and sustainment refined and needed modifications identified.
- Procedures for HMD use finalized, based on testing in high-fidelity simulated or actual environments.
- Near-miss reporting and accident analysis system evaluated to address effectiveness for HMD data.
- Objective evaluation metrics collected on human-system performance, workload, and situation awareness with prototype designs. HMD fit and comfort evaluated via pilot feedback and ratings.
- Conformance to design guidelines and human-system performance requirements established at earlier HRL levels verified.

D.1.7 HRL 7: Human systems design fully tested and verified in operational environment with system hardware and software and representative users

- System hardware, software, and displays integrated into aircraft cockpit and tested with representative pilot users across the full range of mission scenarios and tasks in operational environment.
- Near-miss reporting and accident analysis system evaluated to address effectiveness for HMD data.
- Effectiveness of strategies to mitigate safety issues tested and safety analysis updated to provide risk mitigation as needed.
- Effectiveness of strategies to accommodate manpower, personnel, and training concerns evaluated. Any remaining issues identified and mitigated.
- Effectiveness of HMD to perform across lighting and vibration conditions in operational environment evaluated. Any remaining issues identified and mitigated.
- Effectiveness of strategies to support human interactions during HMD maintenance and sustainment evaluated. Any remaining issues identified and mitigated.
- HMD user procedures tested with final development system in operational environment. Any required modifications verified with representative pilot users.
- Objective evaluation metrics collected on human-system performance, workload, and situation awareness with final HMD design.
- HMD modifications needed to fully support pilot use identified.
- Conformance to design guidelines and human-system performance requirements established at earlier HRL levels verified.

D.1.8 HRL 8: Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users

- Final production-ready HMD integrated into aircraft cockpit and tested with representative pilot users performing the full range of representative scenarios and mission tasks.
- Near-miss reporting and accident analysis system evaluated to address effectiveness for HMD data.
- User procedures tested and found acceptable to meet task demands with the production system in operational environment.
- Effectiveness of strategies to mitigate safety issues evaluated and successfully demonstrated in operational environment.
- Effectiveness of strategies to mitigate manpower, personnel, and training concerns evaluated and successfully demonstrated in operational environment.
- Effectiveness of strategies to support human interactions during HMD maintenance and sustainment evaluated and successfully demonstrated in operational environment.
- HMD user procedures tested and fully evaluated by representative pilot users. Any required modifications verified with representative pilot users.
- Objective evaluation metrics collected on human-system performance, workload, and situation awareness with final HMD design.
- Remaining HMD human use issues satisfactorily resolved.
- Conformance to design guidelines and human-system performance requirements established at earlier HRL levels demonstrated.

D.1.9 HRL 9: System successfully used in operations across the operational envelope with systematic monitoring of human-system performance

- HMD fielded and used in operational aircraft system by intended pilot users.
- Observations and interviews conducted to identify emerging issues for resolution and ensure demonstrated human performance capability is maintained.
- Potential upgrades evaluated to address human systems issues and impacts.
- Near-miss reporting and accident analysis system monitored and analyzed to identify potential problems with HMD operations in practice and changes needed.
- Human mitigation efforts, work arounds, and lessons learned recorded.
- Recommendations made for future system upgrades.
- User manpower, personnel, and training system in operational use and evaluated for potential improvements.

D.2 Traditional Software Development Example

The software example presented here is based on a call management and vehicle dispatch system that transitioned from a manual to a software-based system. This system is used to receive requests for emergency response vehicles, identify the appropriate resource for the request, notify the appropriate vehicle, and provide routing information from the vehicle's current location to the requested location. The system includes both communication and information

systems as well as geographic map overlays. This example assumes that a traditional software development process is followed (Section D.3 presents a comparable example for agile software development). Software development represents one case where the HRL rating may frequently surpass the TRL rating as the HSI efforts provide detailed requirements and graphical user interface (GUI) prototypes that can be used to inform the design of the software.

D.2.1 HRL 1: Basic principles for human characteristics, performance, and behavior observed and reported

- Human characteristics for perception of visual displays and interaction with keyboards, mice, and touchscreens conducted.
- Potential limitations due to user memory capacities (leading to information overload and stress) or visual deficiencies such as color blindness (leading to reduced ability to use certain color-coded displays) identified.
- Basic use cases for system operation and interactions with users created.
- Preliminary analysis completed that identifies potential performance risks for the system such as multitasking and decision making under uncertainty.
- Research conducted to determine effective presentation of time-sensitive information to users.

D.2.2 HRL 2: Human-centered concepts, applications, and guidelines defined

- Task descriptions for relevant system user roles developed; e.g., call takers, resource allocators, and dispatchers.
- Relevant contexts of use identified (emergency vehicle, control center, and mobile applications).
- Design guidelines for human-computer interaction established.
- Design guidelines to minimize negative impacts due to color blindness established.
- Design guidelines to minimize negative impacts due to stress, information overload, multitasking, and decision making under uncertainty established.
- GUI standard established for look/feel, interaction paradigms, and alarms to guide consistent design across different roles and contexts.
- Legacy and comparable systems analyzed for robust understanding of user needs and potential sources of user errors.
- Baseline performance metrics for response time, accuracy, and usability identified.

D.2.3 HRL 3: Human-centered requirements to support human performance and human-technology interactions established

- GUI standard updated as necessary.
- Personnel with expertise in human factors, human systems integration, and the HSI domains of manpower, personnel, training, environment, and safety identified to serve as development team members or consultants.
- Cognitive task analysis conducted to identify goals, decisions, and specific information needs in call management and dispatch operations.

- Communication needs identified across user scenarios and tasks.
- Task analysis conducted to identify workflow requirements in call management and dispatch operations.
- Operational analysis conducted to identify use patterns under high operational tempo that may impact system performance.
- Automation needs identified to facilitate workflow and response time requirements.
- Functional allocation of system components established based on communication and information needs.
- Initial estimates of number of personnel (manpower), types of users (personnel knowledge, skills, abilities, and limitations), and training needs identified.
- Safety and occupational health analyses conducted to minimize user risks (e.g., in-vehicle use of software).
- Operational conditions analysis conducted to identify environmental factors (e.g., illumination, noise, interruptions) that may affect both system operation and GUI design.
- Initial analyses of human interactions during system maintenance and sustainment activities completed.
- Requirements for human system GUI design established and flowed into system level requirements. Requirements include adherence to design guidelines established in HRL 2, response time and accuracy requirements, and the provision of information and functionality to support operations, based on HRL 3 analyses.
- Initial human performance data used to evaluate feasibility of metrics indicating whether human performance is successful.

D.2.4 HRL 4: Modeling, part-task testing, and trade studies of human systems design concepts and applications completed

- GUI standard updated as necessary.
- Initial display prototypes for each user role and context designed to maximize situation awareness, minimize error, and support timely decision making.
- Interaction design for system response to user inputs defined.
- Prototype displays modeled in graphics software (static).
- Strategies to mitigate identified safety and occupational health risks identified and recommended.
- Strategies to accommodate manpower and personnel needs identified such as modifying the GUI to accommodate different personnel types.
- Training requirements for different user roles identified.
- Strategies to address environmental impacts from factors such as lighting and noise identified and recommended.
- Strategies to optimize human interactions during maintenance and sustainment activities identified and recommended (e.g., ease of correction of software bug or integration of new software modules in the future).
- User performance data analyzed to determine whether human performance metrics are successfully met, based on initial design. Initial subjective evaluation of GUI designs by

subject matter experts completed to determine consistency, understandability, usability, format, and completeness.
- Initial evaluation of GUI for adherence to design principles conducted.

D.2.5 HRL 5: Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design

- GUI standard updated as necessary.
- Safety analysis updated based on preliminary user testing results. Potential user errors based on GUI or system interaction design identified and resolution strategies developed.
- GUI prototype updated, based on modifications identified during HRL 4.
- Prototype tested with subject matter experts completing relevant tasks in representative part-mission scenarios with low and high call volumes.
- Gaps in communication or information flow across teammates identified, based on realistic scenarios, and strategies for resolution developed.
- Implications of environment and connectivity on system performance noted and strategies for resolution developed.
- Simulations including increasing communication and information loads conducted to identify potential human-system failures.
- Task analyses updated, based on mission-relevant part-task simulations, to optimize task flow and sequencing.
- Areas of difficulty for human performance noted (e.g., dealing with interruptions, background noise, and multitasking) and strategies for resolution developed.
- User performance data analyzed to determine whether human performance metrics are successfully met, based on current prototypes. Human performance metrics may include response time, accuracy, workload (subjective ratings and physiological measures), situation awareness (objective scores), and usability. Tasks associated with high workload, low situation awareness, high errors or response times, or poor usability identified and strategies for resolution developed.
- Conformance of system design to design guidelines established at earlier HRL levels evaluated and needed modifications identified.

D.2.6 HRL 6: Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations

- GUI design, as modified based on HRL 5 results, programmed into functional production software, with integrated communication and information system protocols.
- Human performance testing conducted in high-fidelity mission simulation with call center and emergency vehicle personnel across the full range of mission scenarios, tasks, and operational conditions.
- Successful completion of user workflows verified, with all information needs met.
- Near-miss reporting and accident analysis system evaluated to address effectiveness for computerized dispatch system data.
- Testing in high-fidelity simulated or actual environments used to finalize user procedures

- Strategies to support successful human use identified and recommended.
- Manpower, personnel, and training requirements updated as needed.
- Automated performance monitoring system data requirements identified.
- Objective human performance metrics collected and evaluated with prototype designs, including response time, accuracy, workload, situation awareness, and usability. Acceptable performance levels established for each system display and task across user types and contexts.

D.2.7 HRL 7: Human systems design fully tested and verified in operational environment with system hardware and software and representative users

- Final development system (hardware and software) tested with representative call center and emergency vehicle users with anticipated communication and information loads in an operational environment. Non-normal events and activities associated with training, maintenance, sustainment, and tracing of human-related issues are evaluated.
- Final development system (hardware and software) tested with realistic environmental variables, including moving vehicles, information loads, communication dead zones, global positioning system (GPS) failures, and inaccurate vehicle locations.
- User procedures tested in operational environment with representative users. Any remaining issues identified and mitigated.
- Effectiveness of strategies to mitigate safety issues tested and safety analysis updated to provide risk mitigation as needed.
- Systems for manpower, personnel, and training updated based on human performance data. Any remaining issues identified and mitigated.
- Objective evaluation metrics collected on human-system performance (response time and accuracy), workload, situation awareness, and usability.
- Conformance of the final development system to human performance requirements and design guidelines established at earlier HRL levels verified. Necessary modifications identified and incorporated into system hardware and software.

D.2.8 HRL 8: Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users

- Production system tested with a range of current call center and emergency vehicle users, with actual communication and information loads in multiple field settings.
- Production system tested in mission operations with realistic factors such as communication dead zones and inaccurate vehicle location as well as naturally occurring weather and road conditions.
- User procedures tested and found acceptable to meet actual operational tempo of system use.
- Effectiveness of strategies to mitigate safety issues tested with the production system and safety analysis updated to provide risk mitigation as needed.
- Systems for manpower, personnel, and training evaluated in mission operations and found to perform successfully.

- Objective evaluation metrics collected on human-system performance (response time and accuracy), workload, situation awareness, and usability to confirm system performance in mission operations.
- Conformance to human performance requirements and design guidelines established at earlier HRL levels demonstrated.

D.2.9 HRL 9: System successfully used in operations across the operational envelope with systematic monitoring of human-system performance

- System fielded and used successfully for call center, in-vehicle, and mobile operations.
- User errors and problems analyzed for resolution.
- System failures and performance logs monitored for troubleshooting and redress.
- Potential upgrades evaluated to address human systems issues and impacts.
- Recommendations made for future system upgrades based on lessons learned.
- Observations and interviews conducted to identify emerging issues for resolution and ensure demonstrated human performance capability is maintained.

D.3 Agile Software Development Example

The emergency call center and vehicle dispatch system described in Section D.2 was implemented via a traditional software development process. The software could also be developed using an agile software development process. In this case, all of the activities described in Section D.2 must still be conducted at each HRL. However, for agile software development, the activities in HRLs 3, 4, 5, and 6 are conducted for small logical subsets of the system (functionality and information displays) and integrated into production software (Figure D-1). These subsets are often called minimum viable products. This process is conducted iteratively, with additional subsets of the system added at each repetition of the cycle. In such a case, the HRL of the system may be represented as the percentage of the overall system at each HRL. For example, during software development, 30% of the system may be at HRL 6, 20% at HRL 5, 10% at HRL 4, 25% at HRL 3, and 15% at HRL 2. In a well-executed agile development program, the HRL and TRL of the system are often tightly interlinked. In an agile software development process, a minimum viable capability release is rolled out to users in the field at some point. The minimum viable capability release corresponds to HRL 7.

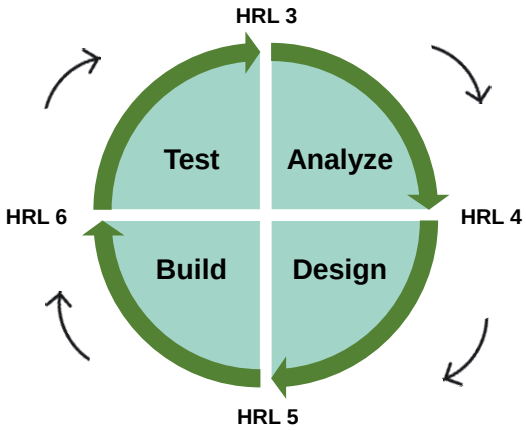

Figure D-1. HRLs and Minimum Viable Products in Agile Software Development

D.4 Robot Repurposing Example

In this example, a robot that had previously been developed and used for a specific mission was adapted to allow it to crawl across the surface of an aircraft and provide remote viewing for detailed human visual inspection for metal fatigue. Thus, the HRLs are applied to a technology that is fairly mature, but it is being used for a new purpose and mission. In addition, comprehensive human systems evaluations were not incorporated when the existing capability was initially developed. Accordingly, the HRL of the system is significantly lower than the current TRL, and new work is needed to develop the GUI for the robot's new application. As in other examples, while much of the basic research applicable to HRL 1 may have already been conducted and relevant design guidelines for HRL 2 developed by the time the program begins, a key first step will be to ensure that this work is adequate and sufficient for the current project and to use this information to determine relevant gaps and areas of focus for the current HSI development effort. In this repurposing effort, all of the HRL levels will be completed, though it may be possible to expedite some levels if any previous human systems work can be leveraged.

D.4.1 HRL 1: Basic principles for human characteristics, performance, and behavior observed and reported

- Potential scenarios and use cases for an aircraft inspection robot identified.
- Preliminary analysis completed to identify potential physical, cognitive, and perceptual performance risks for the robot, including risks of the robot falling, missing areas of damage, and inadequate visual information.
- Research conducted to identify challenges for human-robot interaction such as poor situation awareness due to problems with spatial orientation, localization, and poor sensory data (uneven lighting, limited field-of-view camera, poor video resolution and contrast). Potential high workload associated with camera panning and zooming and maintaining awareness of task progress identified.
- Research conducted to determine optimal methods for robot interaction and control.

- Research conducted to determine visual and task characteristics affecting human visual performance in aircraft inspection tasks.
- Research conducted to identify capabilities and limitations of potential users (i.e., robot operators, robot maintainers, and aircraft inspectors).

D.4.2 HRL 2: Human-centered concepts, applications, and guidelines defined

- Design guidelines established for remote visual inspection to support human perceptual performance across a range of illumination and background contrast conditions.
- Design guidelines established for human-robot interaction, displays, and controls required to support human performance during aircraft inspection.
- Design guidelines established to support human interactions during maintenance and sustainment of visual inspection robots.
- Concepts defined to use robot for remote inspection of aircraft body for metal fatigue and damage.
- Initial tasks descriptions for relevant roles established (e.g., robot operators, robot maintainers, and aircraft inspectors).
- Human performance on legacy and comparable systems for automated aircraft inspection analyzed to leverage lessons learned for the current robot development effort.
- Potential sources of human error and misuse identified. Users of current comparable systems may be interviewed to collect relevant data.
- Appropriate performance metrics identified, based in part on performance metrics used to evaluate legacy and comparable systems.

D.4.3 HRL 3: Human-centered requirements to support human performance and human-technology interactions established

- Target population specified (95% of males and females in the population) and user characteristics identified.
- Human systems experts (human factors, safety, survivability, environment, manpower, personnel, and training) identified to support the design and development effort.
- Usage scenarios updated to characterize tasks that will be performed with the robot.
- Cognitive task analysis conducted to identify information and decision-making needs in aircraft visual inspection and robot operation.
- Task analysis conducted to identify tasks that will be performed during aircraft visual inspection and robot operation.
- Operational conditions analysis conducted to identify relevant lighting, moisture, and other environmental use conditions affecting performance with the robot.
- Operational and system demands for operations with robot (including visual inspection) identified.
- User capabilities, limitations, and needs mapped to expected operational and system demands to identify human performance issues.
- Function allocation conducted to determine information and functions to be performed by the robot.

- Safety analysis conducted to identify risks and potential mitigation strategies.
- Requirements established for the design of robot displays to provide necessary information and allow for the performance of required tasks under the specified operational use conditions (robot control and visual inspection).
- Requirements established for the design of robotic visual inspection system to meet design guidelines specified in HRL 2.
- Requirements established for the system design to provide specified levels of human performance on tasks, to include manageable levels of workload and accurate situation awareness when maneuvering and performing visual inspection with the system.
- Initial manpower, personnel, and training analyses conducted to determine number and qualifications of personnel needed to perform robot-assisted visual inspection.
- Preliminary robot design modifications recommended to accommodate user capabilities, limitations, and needs for the purposes of the aircraft visual inspection mission.

D.4.4 HRL 4: Modeling, part-task testing, and trade studies of human systems design concepts and applications completed

- Additional safety analysis conducted to recommend potential mitigation strategies for identified risks.
- Graphical prototypes of visual displays developed to maximize situation awareness during robot operations, optimize operator workload, and minimize training requirements across inspection tasks and timelines.
- Prototype displays modeled in graphics software. Subjective testing of designs conducted to determine needed modifications.
- Visual imagery from cameras and other system sensors tested to determine visual inspection performance across a range of visual conditions and robot orientations. Issues and recommended solutions identified.
- IMPRINT workload modeling tool used to determine robot operator and aircraft inspector workload across tasks and functions. Issues and recommended solutions identified.
- Automation needed to support situation awareness and minimize robot operator workload identified. Human-automation integration strategy identified to include appropriate levels of automation across functions, methods for shifting control, and methods for human override. Methods for sharing information across human and automation identified.
- Strategies to support manpower, personnel, and training changes due to use of remote robot-assisted aircraft inspection identified and solutions recommended.
- Strategies to support human interactions during maintenance and sustainment of robot visual inspection system identified.
- Task analyses updated to optimize task flow and sequencing during key robot operation and aircraft inspection tasks.
- Initial procedures for robot operation and robot-assisted aircraft inspection designed, leveraging procedures historically used for similar operations.
- Conformance of system design to requirements and design guidelines identified in earlier HRL levels assessed and needed modifications identified.

D.4.5 HRL 5: Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design

- Safety analysis updated based on more complete understanding of risks from preliminary testing and potential mitigation strategies identified.
- Operator-robot GUI developed with prototyping software.
- Robot GUI prototype tested with human subjects completing relevant robotic control and inspection tasks in simulated task environment with representative part-mission scenarios.
- Robot hardware, software, and display designs modified based on evaluations conducted to improve human performance, optimize workload, maximize situation awareness, and support usability when using the system.
- Human-automation integration strategy tested and required changes identified.
- Robot control tests conducted with hardware prototypes to assess impact on human safety and control issues. Safety problems identified and modifications identified.
- Impacts of relevant environmental factors such as lighting and moisture evaluated and modifications identified.
- Strategies to accommodate manpower, personnel, and training changes due to use of remote robot-assisted aircraft inspection updated and needed changes recommended.
- Strategies to support human interactions during maintenance and sustainment of system updated and needed changes recommended.
- Task analyses further refined to optimize task flow and sequencing during key robot operation and visual inspection tasks.
- Procedures for robot operation and robot-assisted aircraft inspection refined, based on prototype testing in mission-relevant part-task simulations.
- Human performance with the system (time to perform tasks and errors) evaluated along with workload (subjective ratings and physiological measures), situation awareness (objective scores), and usability.
- Conformance of system design to requirements and design guidelines established at earlier HRL levels assessed, and needed modifications identified.

D.4.6 HRL 6: Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations

- Robot hardware, software, and system displays modified and integrated into prototype design based on results from HRL 5 activities.
- Human performance testing conducted in high-fidelity simulations across a range of mission scenarios and tasks, including emergency and non-normal events, training, maintenance, and sustainment.
- Safety analysis updated to demonstrate the validity of any assumptions and successful mitigation of risks.
- User procedures for robot operation and robot-assisted aircraft inspection finalized, based on testing with high-fidelity simulations and strategies for successful performance identified.
- Automated performance monitoring system data requirements identified.
- Manpower, personnel, and training requirements updated and design changes identified.

- Strategies to support human interactions during maintenance and sustainment of aircraft inspection robots updated and evaluated. Needed modifications identified.
- Objective evaluation metrics collected on human-system performance, workload, situation awareness, and usability with prototype designs.
- Conformance to design guidelines and human-system performance requirements established at earlier HRL levels demonstrated.

D.4.7 HRL 7: Human systems design fully tested and verified in operational environment with system hardware and software and representative users

- System hardware, software, and displays integrated and tested with representative aircraft inspection personnel completing the full range of representative aircraft inspection scenarios and tasks in operational environment.
- Effectiveness of robot system to support aircraft inspection performance across variations in lighting and moisture in operational conditions evaluated. Any remaining issues identified and mitigated.
- User procedures tested in operational environment. Any remaining issues identified and mitigated.
- Automated performance monitoring system evaluated to address effectiveness for robot-assisted aircraft inspection near misses and accidents.
- Effectiveness of strategies to mitigate safety issues tested and safety analysis updated to provide risk mitigation as needed.
- Systems for manpower, personnel, and training updated and evaluated. Any remaining issues identified and mitigated.
- Systems to support human interactions during maintenance and sustainment of robot system implemented and evaluated. Any remaining issues identified and mitigated.
- Objective evaluation metrics collected on human-system performance, workload, and situation awareness with final development system.
- Modifications to system needed to achieve compliance with human-system requirements and design guidelines established in earlier HRL levels identified and incorporated into robot system.

D.4.8 HRL 8: Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users

- Final production ready robotic aircraft inspection system, as modified through HRL 7, tested with representative aircraft inspection personnel in representative aircraft inspection tasks in mission operations.
- Automated performance monitoring system evaluated to address effectiveness for robot-assisted aircraft inspection near misses and accidents.
- User procedures tested and found acceptable to meet task demands with the production system in operational environment.
- Effectiveness of strategies to mitigate safety issues tested in operational environment and safety analysis updated to provide risk mitigation as needed.

- Systems for manpower, personnel, and training evaluated in operational environment and found to perform successfully.
- Systems to support human interactions during maintenance and sustainment of robot system evaluated in operational environment and found to perform successfully.
- Objective evaluation metrics collected on human-system performance, workload, and situation awareness with final robot system design.
- Remaining human use issues for robot control and aircraft inspection satisfactorily resolved.
- Conformance to design guidelines and human-system performance requirements established in earlier HRL levels demonstrated.

D.4.9 HRL 9: System successfully used in operations across the operational envelope with systematic monitoring of human-system performance

- Robot system fielded and used in aircraft maintenance and inspection tasks.
- Observations and interviews conducted to identify emerging issues for resolution and ensure demonstrated human performance capability is maintained.
- Potential upgrades evaluated to address human systems issues and impacts.
- Aircraft inspection performance system monitored and analyzed to identify potential problems with robot system in practice and changes needed.
- Human mitigation efforts, work arounds, and lessons learned recorded.
- Recommendations made for future system upgrades.
- User manpower, selection, and training system in operational use and being evaluated for potential improvements.

D.5 Leadership Training Example

In this example, a system for training new Army officers in leadership skills is developed. Unlike other examples, the focus is not on developing human-centered designs for a new technology but on providing novel solutions for achieving improved human performance as a whole, in a manner that transcends technologies and situations. The focus in the early HRLs is on basic human research to determine effective human performance enhancement principles and techniques. The focus in the later HRLs is to design, develop, and validate solutions for delivering those enhancements.

D.5.1 HRL 1: Basic principles for human characteristics, performance, and behavior observed and reported

- Research conducted to determine characteristics of effective and ineffective leadership styles and behaviors.
- Research conducted to determine effectiveness of strategies and tools for delivering leadership training.

D.5.2 HRL 2: Human-centered concepts, applications, and guidelines defined

- Design guidelines established for instructional system design.
- Leadership training principles established.
- Concepts defined to provide improved leadership training to new Army officers.
- Initial task descriptions for relevant roles established (e.g., instructors, facilitators, students).
- Lessons learned from existing leadership training programs leveraged to determine benefits and limitations of current approaches.
- Potential sources of human error and misuse identified. Trainees in current comparable training programs may be interviewed to collect relevant data.
- Appropriate performance metrics identified, based in part on performance metrics used to evaluate legacy and comparable training programs.

D.5.3 HRL 3: Human-centered requirements to support human performance and human-technology interactions established

- Target population specified (100% of male and female officer candidates) and characteristics identified.
- Human systems experts (human factors, manpower, personnel, and training) identified for the program development team.
- Training needs analysis conducted, to include learner profiles, constraints, needs, and tasks.
- Requirements established for training system design to meet instructional system design, leadership training needs, and design guidelines specified in HRL 2.
- Initial manpower, personnel, and training analyses conducted to determine potential changes needed to accommodate new leadership training program.

D.5.4 HRL 4: Modeling, part-task testing, and trade studies of human systems design concepts and applications completed

- Leadership training program designed to include measurable objectives, instructional strategy and plans, needed resources, and prototype specifications.
- Draft storyboards, scripts, and exercises developed and reviewed by military training experts to determine understandability and suitability for target population.
- Trainee instructions and procedures designed.
- Strategies to accommodate any needed manpower, personnel, and training changes due to new leadership training program determined and recommended.
- Strategies to achieve maintenance and sustainment of leadership training program over time identified (e.g., to incorporate changes in instructional material or modes of instruction).
- Conformance of system design to requirements and design guidelines identified in earlier HRL levels assessed and needed modifications identified.

D.5.5 HRL 5: Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design

- Software prototype of training program developed.
- Subjective evaluation of software prototype with training personnel and naïve subjects conducted (formative evaluation).
- Tests and trainee evaluation metrics incorporated into software prototype.
- Initial evaluation of trainee performance on leadership training scenarios and tests conducted.
- Trainee instructions and procedures updated.
- Strategies to accommodate any needed manpower, personnel, and training changes due to new leadership training program updated.
- Strategies to achieve maintenance and sustainment of leadership training program over time updated.
- Conformance of system design to requirements and design guidelines identified in earlier HRL levels assessed and needed modifications identified.

D.5.6 HRL 6: Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations

- Leadership training software updated with changes identified in initial testing and matured to provide full suite of functionality identified in HRL 3.
- Performance on leadership training program scenarios and tests conducted with larger group of instructors and potential trainees. Problems and errors identified. Recommendations for improvements collected.
- Automated performance monitoring system data requirements identified.
- Trainee instructions and procedures finalized.
- Manpower, personnel, and training requirements updated and design changes identified.
- Strategies to achieve maintenance and sustainment of leadership training program incorporated and evaluated. Needed modifications identified.
- Conformance to design guidelines and performance requirements established at earlier HRL levels demonstrated.

D.5.7 HRL 7: Human systems design fully tested and verified in operational environment with system hardware and software and representative users

- Completed leadership training program tested with officer candidates in schoolhouse environment. Evaluation metrics collected on trainee subjective comments and objective performance (formative evaluation).
- Effectiveness of leadership training course evaluated to determine additive value by comparing trainee performance in leadership tasks to control group who did not receive the leadership training course (summative evaluation).
- Modifications to leadership training course identified and incorporated.
- Trainee instructions and procedures tested with officer candidates in schoolhouse environment.

- Systems for manpower, personnel, and training updated to include needed changes and evaluated. Any remaining issues identified and mitigated.
- Systems for maintenance and sustainment of leadership training program implemented and evaluated. Any remaining issues identified and mitigated.
- Conformance to requirements and design guidelines established in earlier HRL levels identified and incorporated.

D.5.8 HRL 8: Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users

- Final leadership training course implemented in officer training program. Objective evaluation metrics collected on trainee performance and transfer of training.
- Trainee instructions and procedures tested and found acceptable for use in training environment.
- Training syllabus modified to incorporate new leadership training course.
- Systems for manpower, personnel, and training evaluated and found to perform successfully.
- Systems for maintenance and sustainment of leadership training course evaluated in training environment and found to perform successfully.
- Conformance to requirements and design guidelines established at earlier HRL levels demonstrated.

D.5.9 HRL 9: System successfully used in operations across the operational envelope with systematic monitoring of human-system performance

- Leadership training program fielded and used in regular training syllabus.
- Observations and interviews conducted to identify emerging issues for resolution and ensure the demonstrated training capability is maintained.
- Potential upgrades evaluated to address human systems issues and impacts.
- Training program performance monitored.
- Human mitigation efforts, work arounds, and lessons learned recorded.
- Recommendations made for future training program upgrades.
- User manpower, personnel, and training system in operational use and being evaluated for potential improvements.

D.6 System Upgrade Example

In this example, the HMD originally developed in Section D.1 is later upgraded to provide enhanced capabilities. Specifically, a matured system (TRL/HRL 9) is modified with new hardware (improved optics) and new functionality (additional information displays), based on both technology improvements and lessons learned from its use in flight operations. Work at each HRL will consist of updates needed to incorporate and evaluate the impact of the proposed changes on human performance and relevant HSI domains. Previously existing analyses and tools can be leveraged to shorten the time and effort required to advance the system through each HRL, beginning with HRL 1 where any new issues will be identified and researched, as needed.

Any required updates to the manpower, personnel, and training systems will be evaluated and incorporated as needed throughout the process, based on both the new technology and on lessons learned in current operations.

D.6.1 HRL 1: Basic principles for human characteristics, performance, and behavior observed and reported

At HRL 1, human systems experts consider whether the upgrades introduce any new issues or risks. For example, with additional information displays, there may be a risk of increased workload that was not present with the original design. In addition, the upgrades might lead to a requirement to perform scenarios that were not completed with the original HMD design. These new scenarios must be identified and characterized at HRL 1. Finally, human systems experts verify that the relevant capabilities and limitations of the target population have not changed significantly in the interim.

D.6.2 HRL 2: Human-centered concepts, applications, and guidelines defined

At HRL 2, human systems experts verify whether there are any new design guidelines applicable to the upgrades that must be established. Human performance on the current HMD (without the upgrades) is reviewed and analyzed to leverage lessons learned for implementation of the upgrades. At the same time, lessons learned may be used to identify whether other improvements unrelated to the current upgrades are possible at this time, without detracting from the current purpose. Task descriptions for the current HMD are analyzed to identify modifications due to the upgrades. Pilots who use the current version of the HMD are interviewed to identify potential issues with the upgrades. Human performance metrics used for the current HMD are reviewed for their adequacy to evaluate the upgrades.

D.6.3 HRL 3: Human-centered requirements to support human performance and human-technology interactions established

Key activities during HRL 3 are to update usage scenarios, cognitive task analyses, and function allocations that were previously performed to include the new information displays. Human systems experts verify the target population remains the same (i.e., 95% of male and female military personnel). HMD operational and system demands are reviewed to identify any impacts from the upgrades. HSI domain analyses are reviewed and updated as needed. The HSI domain for safety and occupational health is analyzed to identify any new risks associated with the updates. With respect to the HSI environment domain, the effects of vibration may differ with the new optics. The HSI domains of manpower, personnel, and training may need to be updated to accommodate the new information displays. Previously established HMD requirements are reviewed to determine whether modifications are needed to address the upgrades. For example, workload and situation awareness may be altered with the addition of information displays. Maintaining the improved optics system may take longer.

D.6.4 HRL 4: Modeling, part-task testing, and trade studies of human systems design concepts and applications completed

Human systems experts develop graphical prototypes of new information displays to evaluate response time, accuracy, workload, and situation awareness. Sample text and graphics are projected onto the improved optics hardware, and visual acuity is tested against representative backgrounds under representative environmental conditions such as lighting and vibration. Subjective testing of designs is conducted to determine needed modifications. IMPRINT is used for workload modeling to analyze impacts of the new information displays specifically on pilot workload. Issues and recommended solutions are identified. Existing procedures are reviewed and required updates to incorporate the upgrades are begun. Strategies to support human interactions during maintenance and sustainment of the upgraded HMD are identified. Previously implemented strategies for each HSI domain are reviewed for continued effectiveness and updated as needed.

D.6.5 HRL 5: Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design

At HRL 5, an HMD prototype that incorporates the updates, including drafty symbology and text for the new information displays, is tested with pilot subjects completing relevant tasks in aircraft simulators with representative part-mission scenarios. Human performance with the system (time to perform tasks and errors) is evaluated along with pilot workload (subjective ratings and physiological measures) and situation awareness (objective scores). Any changes to fit and comfort due to the upgrades are also evaluated. Any additional modifications needed to the upgrades to improve human performance, optimize workload, and maximize situation awareness are recommended. Updated procedures are further refined, based on prototype testing in mission-relevant part-task simulations. Previously implemented strategies for each HSI domain are reviewed for continued effectiveness and updated as needed.

D.6.6 HRL 6: Human systems design fully matured as influenced by human performance analyses, metrics, prototyping, and high-fidelity simulations

At HRL 6, the updated HMD hardware, software, and system displays are modified, integrated into a functional prototype design, and evaluated in full-motion cockpit simulation. Human performance testing is conducted with pilot users across the range of mission scenarios and tasks, including maintenance and sustainment of the improved optics system. Procedure updates are finalized. Objective evaluation metrics are collected on human-system performance, workload, and situation awareness with functional prototype designs. Any changes to fit and comfort due to the upgrades are also evaluated. The existing system for near-miss reporting and accident analysis is evaluated to determine whether any modifications are needed to accommodate the HMD upgrades. Updated strategies for each HSI domain are further refined as needed.

D.6.7 HRL 7: Human systems design fully tested and verified in operational environment with system hardware and software and representative users

System hardware, software, and displays for the updated HMD are integrated into the aircraft cockpit and tested with representative pilot users across the full range of mission scenarios and

tasks, including maintenance and sustainment, in an operational environment. Updated procedures are tested to identify any additional modifications. Objective evaluation metrics are collected on human-system performance, workload, and situation awareness with functional prototype designs. Any changes to fit and comfort due to the upgrades are also evaluated. The existing system for near-miss reporting and accident analysis is evaluated to determine whether any modifications are needed to accommodate the HMD upgrades. Updated strategies for each HSI domain are evaluated for effectiveness and further refined as needed.

D.6.8 HRL 8: Total human-system performance fully tested, validated, and approved in mission operations, using completed system hardware and software and representative users

The final production-ready upgraded HMD is integrated into the aircraft cockpit and tested with representative pilot users performing the full range of representative scenarios and mission tasks, including maintenance and sustainment. Updated procedures are tested and found acceptable to meet task demands with the production system in mission operations. Objective evaluation metrics are collected on human-system performance, workload, and situation awareness with functional prototype designs. Any changes to fit and comfort due to the upgrades are also evaluated. The system for near-miss reporting and accident analysis is evaluated to address effectiveness for the upgraded HMD. Updated strategies for each HSI domain are evaluated for effectiveness and successfully demonstrated. Any remaining HMD human use issue are satisfactorily resolved at this level. Conformance to any new design guidelines and human-system performance requirements established at earlier HRL levels is demonstrated.

D.6.9 HRL 9: System successfully used in operations across the operational envelope with systematic monitoring of human-system performance

The updated HMD is fielded and used in operational aircraft systems by intended pilot users. Observations and interviews are conducted to identify emerging issues for resolution and ensure the demonstrated human performance capability with the upgraded system is maintained. Potential future upgrades will be evaluated similarly to address human systems issues and impacts. Lessons learned for the current upgrade are documented to support future upgrades. The near-miss reporting and accident analysis is monitored and analyzed to identify potential problems with the updated HMD and any necessary changes. The user manpower, personnel, and training system in operational use for the updated HMD is evaluated for potential improvements.

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