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A Guide for Evaluating Spacecraft Environmental Control & Life Support Systems (ECLSS) Technology Developments

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Environmental Control and Life Support Systems (ECLSS) are the core of any human spacecraft or habitat and are key to the astronaut's survival during missions. NASA continues to invest in the development of ECLSS technology that more efficiently recycle air, water, and waste. These advancements are needed to enable longer duration Artemis missions to the Moon or Mars and reduce dependency on Earth. Objectively evaluating the content of a technical portfolio is critical to identifying and advancing the most technically relevant and/or promising technology solutions, particularly in limited resource scenarios. Here we define four types of technical portfolio evaluations: 1) Technology Down-Selects where one or more technologies are selected over others within the same trade space (for development or flight), 2) Technology Continuation Reviews where a technology's relevance and development progress is weighed against stand-alone metrics and the risks of continued development, 3) Technology Flight Necessity Assessments to determine whether a flight demonstration is required to meet critical performance goals, and 4) Flight Demonstration Readiness Assessments to determine whether the technology is technically ready to be considered for flight demonstration. Historically, the processes used to evaluate technologies within the ECLSS portfolio have varied from project to project. Therefore, an assessment was performed to improve consistency and transparency of ECLSS technology evaluation processes within NASA. This involved evaluating the processes employed on historical NASA projects, and those used in industry and other government agencies to identify the most relevant and useful aspects of each. The product is a guide to quantitatively and objectively evaluate ECLSS technology, and case studies were performed using the new guide on previous ECLSS technology development projects. The outcomes were compared, and the findings are reported.

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Nomenclature

AD²	=	Advance Degree of Difficulty
AFRL	=	U.S. Air Force Research Lab
CHP	=	Crew Health and Performance
CHX	=	Cabin Heat Exchanger
DOD	=	U.S. Department of Defense
DOE	=	U.S. Department of Energy
ECLSS	=	Environmental Control and Life Support Systems
GAO	=	U.S. Government Accountability Office
ISS	=	International Space Station
KDP	=	Key Decision Point
KPP	=	Key Performance Parameters
NASA	=	National Aeronautics and Space Administration
PDR	=	Preliminary Design Review
PBS	=	Produce Breakdown Structure
SME	=	Subject Matter Expert
SOA	=	State of the Art
SRR	=	System Readiness Review
TDT	=	Technical Discipline Team
TRA	=	Technology Readiness Assessment
TRAR	=	Technology Readiness Assessment Report
TRL	=	Technical Readiness Level

I. Introduction

The Environmental Control and Life Support Systems (ECLSS) on spacecraft and habitats provides the capabilities to enable human exploration. These systems include technologies that supply breathable air, clean water, humidity control, carbon dioxide removal, regulate cabin pressure, and remove waste. NASA relied on consumable based ECLSS technologies, which are used once then discarded, for past spaceflight programs like Gemini and Apollo. Though these technologies are feasible for short duration missions, ECLSS technologies that regenerate, or recycle, air, water, carbon dioxide and waste trade more favorably for sustaining longer duration missions.

The International Space Station (ISS) uses regenerative ECLSS technology, but systems with improved efficiency and reliability are necessary to support Artemis missions to the Moon and Mars. NASA continues to invest in ECLSS regenerative technology and improvements to ISS heritage technology. Further, the ISS is often used to demonstrate these capabilities in a space environment. Prior to a flight demonstration, these technologies undergo a series of technical evaluations to assess the technical maturity and readiness. These technical portfolio evaluations include:

1) **Technology Down-Selects** – where one or more technologies are selected over others within the same trade space (for development or flight)
2) **Technology Continuation Reviews** – where a technology's relevance and development progress are weighed against stand-alone metrics and the risks of continued development
3) **Technology Flight Necessity Assessments** – to determine whether a flight demonstration is required to meet critical performance goals
4) **Flight Demonstration Readiness Assessments** – to determine whether the technology has made sufficient developmental progress to warrant a flight demonstration

Technology Readiness Assessments (TRA) are used throughout NASA agency to evaluate the maturity of a technology. However, the TRA processes used for the portfolio evaluations are less transparent and inconsistent across the agency, and low-quality TRA can have significant cost, schedule, or technical impacts. The NASA Technical Readiness Level[1] (TRL) is often used as a starting point for a TRA as shown in Figure 1, but the TRA process and definitions on how to meet the TRL or mature the technology to the next TRL is left up to interpretation. For instance, some projects relied on the developer to determine the TRL while others relied on a subject matter expert (SME) within the NASA agency. Objectively evaluating the content of a technical portfolio is critical to identifying and advancing the most technically relevant and/or promising technology solutions, particularly in limited resource scenarios.

Therefore, the NASA Engineering and Safety Center (NESC) ECLSS Technical Discipline Team (TDT) conducted an assessment to evaluate existing TRA processes and developed a guide on how to qualitatively and objectively conduct an ECLSS portfolio evaluation. Workshops were held over four days to complete most of the assessment, which included reviewing existing TRA used at NASA and other government agencies. The commonalties and best practices were identified and used to develop a tailored ECLSS TRA processes guide for each of the technical portfolio evaluations. Case studies were performed using the new TRA process on previously completed technology development projects, and the outcomes were compared. This paper will discuss the findings, conclusions, and recommendations from the assessment.

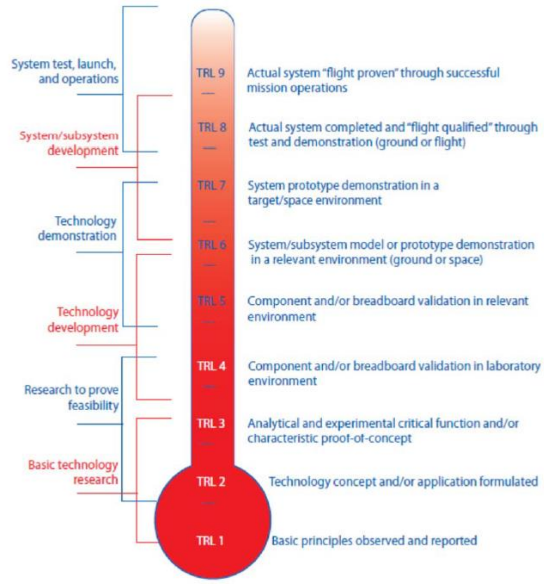

Figure 1. NASA Technical Readiness Levels (TRL) from the NASA Systems Engineering Handbook[1]

II. Review of Existing Technology Readiness Assessments (TRA) Processes

The assessment team reviewed the TRA process that are publicly available from NASA, the U.S. Department of Defense (DOD)[4], the U.S. Department of Energy (DOE)[5], and U.S. Government Accountability Office (GAO)[3]. The team found that TRA processes are a common concern across the government agencies. Each of the agencies have conducted studies and developed best practices for conducting TRA. Some of the common best practices amongst the agencies are as follows:

1. Develop a TRA plan and establish the criteria, requirements, and definitions needed to complete the assessment
2. Start the TRA at the beginning of a project and repeat before each milestone, phase, gate, or Key Decision Point
3. Determine a technology's TRL using a Product Breakdown System (PBS) to break down the technology into components, and assign an overall TRL based on the component with the lowest TRL
4. The TRA should include an Advancement Degree of Difficulty (AD^2) assessment to evaluate the risk or degree of difficulty of advancing a technology to the next TRL
5. Refine the TRA, TRL and AD^2 processes and definitions as the technology matures through development
6. A non-advocate or independent Subject Matter Expert (SME) is recommended to conduct the TRA using objective, relevant, and trustworthy data, analysis, and information
7. Create a Technology Readiness Assessment Report (TRAR) at the completion of each TRA and disseminate the information to the stakeholders and community

A. NASA Technology Readiness Assessment (TRA) Process

Guidance on how to perform TRA is described in Appendix G of the NASA Systems Engineering Handbook[2]. The process involves the developer or a SME within the agency performing the TRA at Key Decision Points (KDP) as shown in Figure 2. TRA includes determining the technology's current maturity level via the NASA TRL[1], and establishing what is required to mature a technology from one TRL to the next via the AD^2. The TRA is recommended to be performed at the earliest stage of a project, and continue until KDP-C, where the technology is evaluated to be infused into the flight program just prior to a Preliminary Design Review (PDR). The technical recommendations from the TRA should be documented in a TRAR.

The NASA TRL has been commonly used on TRAs to define a technologies maturity level, but the process can be challenging. The descriptions for each TRL are intended to be broad so the TRL can be applied to all engineering disciplines, but the problem is that it leaves the TRL definitions open to interpretation. For instance, the differences between TRL 4 and 5 are the environment in which the technology or component will be tested, the fidelity of the hardware (“breadboard” vs “brassboard”), and scaling definitions. In each case, subtle differences in the environments or hardware make interpretation highly subjective. Like the TRL, determining a technologies AD^2 can be a challenge and definitions can vary from project to project. Thus, programs or projects are often undertaken without fully understanding the technology maturity level or appreciating the technical risk to advance the technology.

Gate	Product
KDP A—Transition from Pre-Phase A to Phase A	Requires an assessment of potential technology needs versus current and planned technology readiness levels, as well as potential opportunities to use commercial, academic, and other government agency sources of technology. Included as part of the draft integrated baseline. Technology Development Plan is baselined that identifies technologies to be developed, heritage systems to be modified, alternative paths to be pursued, fallback positions and corresponding performance descopes, milestones, metrics, and key decision points. Initial Technology Readiness Assessment (TRA) is available.
KDP B—Transition from Phase A to Phase B	Technology Development Plan and Technology Readiness Assessment (TRA) are updated. Incorporated in the preliminary project plan.
KDP C—Transition from Phase B to Phase C/D	Requires a TRAR demonstrating that all systems, subsystems, and components have achieved a level of technological maturity with demonstrated evidence of qualification in a relevant environment.

Figure 2. NASA Technology Assessment at Key Decision Points (KDP) from the NASA Systems Engineering Handbook[1]

The NASA Systems Engineering handbook[2] provides a method for determining the TRL, which is to break down the technology into components using the Product Breakdown Structure (PBS) as shown in Figure 3. The TRL for each component is determined, and the technology’s overall TRL based on the component with the lowest TRL. Like the TRL, AD^2 is performed on each component using the PBS, and the overall difficulty based on component with the most technical risk. Therefore, clear definitions of each TRL and AD^2 are necessary to perform a TRA.

In efforts to provide quality TRA, NASA partnered with the U.S. Air Force Research Lab (AFRL) to develop TRL and AD^2 calculators[2]. These tools allow the user to establish the TRL and AD^2 definitions, and quantitively evaluate a technology’s maturity. For the TRL calculator, the user inputs the PBS number for each component, and can answer the default questions for each TRL or modify the questions. The TRL for each PBS and overall TRL are then calculated based the answers to each of the questions. The AD^2 tool is similar to the TRL calculator but the user assigns a risk value as shown in Figure 4, and outputs an overall risk based on the component with the highest AD^2.

Red = Below TRL 3
Yellow = TRL 3, 4 & 5
Green = TRL 6 and above
White = Unknown
X = Exists

	Demonstration Units						Environment				Unit Description				
	Concept	Breadboard	Brassboard	Developmental Model	Prototype	Flight Qualified	Laboratory Environment	Relevant Environment	Space Environment	Space Launch Operation	Form	Fit	Function	Appropriate Scale	Overall TRL
1.0 System															
1.1 Subsystem X															
1.1.1 Mechanical Components															
1.1.2 Mechanical Systems															
1.1.3 Electrical Components					X				X		X	X	X		
1.1.4 Electrical Systems															
1.1.5 Control Systems															
1.1.6 Thermal Systems							X				X	X			
1.1.7 Fluid Systems		X													
1.1.8 Optical Systems															
1.1.9 Electro-Optical Systems															
1.1.10 Software Systems															
1.1.11 Mechanisms	X														
1.1.12 Integration															
1.2 Subsystem Y															
1.2.1 Mechanical Components															

Figure 3. Example Product Breakdown Structure (PBS) from NASA Systems Engineering Handbook[1]

#	Description	Risk	Success
9	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.	100% RISK	Almost Certain Failure (Very High Risk, Very High Reward)
8	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursued.	80% RISK	Very Risky: High Likelyhood of Failure (High Reward)
7	Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.	70% RISK	
6	Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. (desired performance can be achieved in subsequent block upgrades with high degree of	50% RISK	
5	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.	40% RISK	Probably Will Succeed
4	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high	30% RISK	Almost Certain Success (We know how to do it)
3	Requires new development well within the experience base. A single development approach is adequate.	20% RISK	
2	Exists but requires major modifications. A single development approach is adequate.	10% RISK	
1	Exists with no or only minor modifications being required. A single development approach is adequate.	0% RISK	Guaranteed Success

Figure 4. AD^2 Definitions from the AD^2 Calculator.

NASA's Game Changing Development Program (GCDP) focuses on advancing space technology with TRLs between 2 and 6 and has a slightly different approach to performing the AD^2. The GCPD AD^2 process uses the same PBS format and risk definitions as the AD^2 tool, but the overall AD^2 is based on a review of each component AD^2 using the AD^2 Matrix. For example, the TRL and AD^2 for each component of technology A and B are determined and placed in the AD^2 Matrix as shown in Figure 5. The highest AD^2 for Technology A and B are both 8, but technology A has more components with lower TRL and higher AD^2 values. The AD^2 calculator would show both technologies have the same overall AD^2 of 8, but the GCDP process would show that technology A has a greater overall risk due to the relatively larger number of components with higher risk development paths. Therefore, the recommendations in the TRAR could be different depending on which AD^2 process is used, and both NASA AD^2 processes were considered in this study.

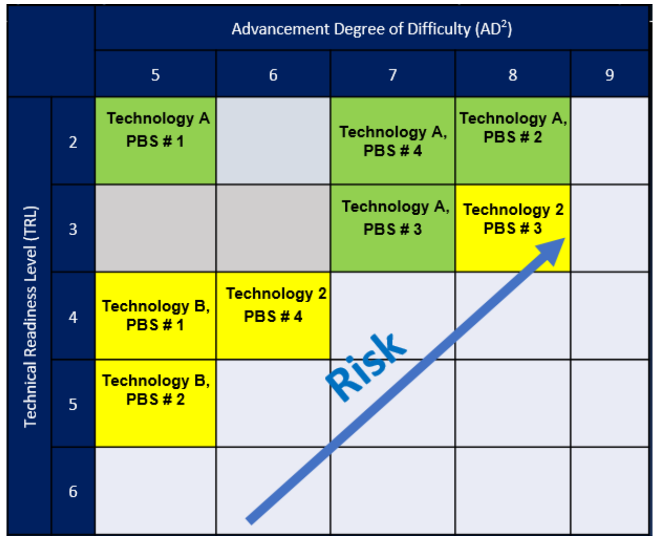

Figure 5. Example AD^2 Matrix

B. GAO Technology Readiness Assessment (TRA) Process

The U.S. Government Accountability Office (GAO) has a similar TRA process as NASA, but with the TRLs more defined like shown in Figure 6 from the GAO TRA Guide[3]. The GAO TRA is a five-step process as shown in Figure 7, and the first step is for the project manager or technology developer to prepare the initial TRA plan, and clearly define the purpose, scope, schedule, and KDPs. Key information like Key Performance Parameters (KPP), capability needs, master schedule and test plans are collected to ensure the TRA is objective. An independent TRA team with SMEs from various disciplines is established once the initial TRA plan is drafted.

The second step is to identify the critical technologies that are new or novel that may have a lower maturity, or TRL, and define the environments, system integrations, and appropriate level of testing. Like NASA TRL process, a technology is broken down into components using the PBS, and the third step is to determine the TRLs of each of the critical technologies through an objective evaluation of information against criteria defined in step 1 and 2. The fourth and fifth steps are to document the findings with supporting evidence and for the project manager to take appropriate actions based on the report, respectively. This process

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

Figure 6. More detailed TRL descriptions.

Figure 7. GAO TRA Process.

is repeated throughout the technology development life cycle, and the TRA is refined as the technology matures or progresses to each KDP.

C. DOD Technology Readiness Assessment (TRA) Process

The U.S Department of Defense (DOD) uses similar TRA as GAO and NASA as defined in the DOD TRA Deskbook[4]. However, the DOD TRA process is more focused on technologies that will be funded and almost guaranteed to be infused into a program. The TRA is performed by the program or project manager rather than independent SME like the NASA and GAO TRA processes, and are conducted before three distinct KDPs (Milestones A, B and C) as shown in Figure 8. The TRA before Milestone A establishes the purpose, scope, schedule and agreements between the developer and program.

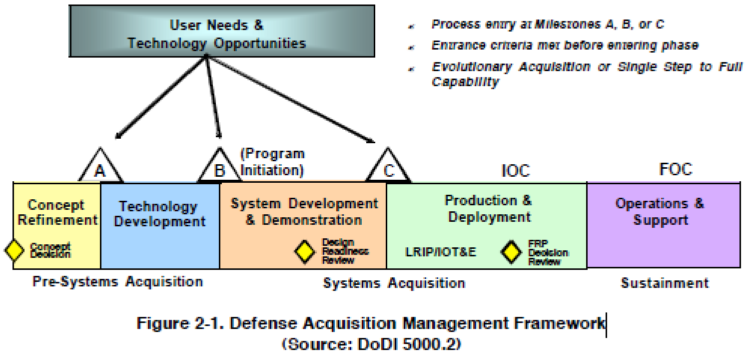

Figure 8. DOD TRA Process.

The TRA before Milestone B incorporates all the processes to determine critical technologies by using the PBS and determining their TRL. Recommendations are provided to the program, and the program decides if the technology should continue to the Milestone C. If the technology is not recommended to continue or if there are disagreements with the findings, then an independent assessment may be conducted. The TRA prior to Milestone C evaluates the maturity of the critical technologies and determines if the technology is ready to be infused into a program. A TRAR is written before each Milestone to document the findings and recommendations.

D. DOE Technology Readiness Assessment (TRA) Process

The U.S. Department of Energy (DOE) incorporates a stage gate TRA process[5] where the technology is evaluated through a series of gate reviews and stages as shown in Figure 9. The purpose of each gate review is for the technology developer to demonstrate that the technology has met the objectives, criteria, and requirements established in the previous gate and/or stage and assesses if the technology is ready to move to the next stage and gate. The criteria for each gate and stage are different and becomes more rigorous as the project progresses. The gate review includes internal management and outside SMEs known as the Gate Keepers, and the outcomes are the following decision points:

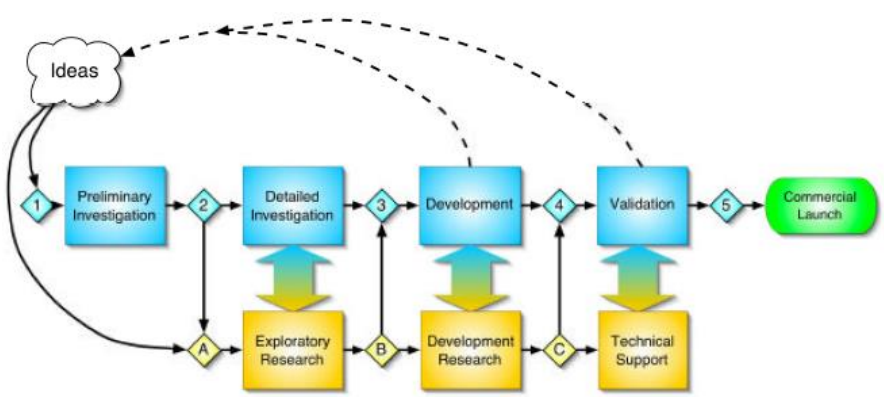

Figure 9. DOE Stage Gate TRA Process.

1. **Passing** – goals of a previous stage were met
2. **Recycle** – continue working at the current stage because all goals have not been met, but no showstoppers have been identified. The review panel must provide suggestions on work that needs to be completed before the next gate review is held
3. **Hold** – suspends the project because there is no longer an immediate need, but need is more likely to return in the future. Document the completed work, and work that remains open
4. **Stopping**- technology is not maturing, is not meeting criteria, or there is no longer a need

The TRAs are performed at the stages, and each stage includes the objectives, criteria, milestones, schedule, resource, and requirements to evaluate the technology's maturity level. Stage One is the preliminary investigation which is a low budget assessment to assess the feasibility of the technology, and to determine if more investment is beneficial. Stage two is the detailed investigation that includes demonstrating proof of concept in a laboratory setting, and the path to infusing into a program must be developed as well as the risk of maturing the technology. Stage four is performing a scaled prototype test to validate the technology meets KPP and is a higher budget evaluation performed by an industry partner. Stage 5 is full scale testing and evaluation in preparation for implementation and performed by an industry partner.

NASA was interested in elaborating on the TRL definitions, and a study[6] was performed using the DOE stage gate TRA process. The outcome was a TRL stage gate process as shown in Figure 10. In this process, TRAs are performed at the stages between each TRL, or Gate. Reviews are held at each TRL, or Gate, to determine if a technology meets the requirement for that TRL, and if it should proceed to the next stage and TRL. This approach has not incorporated into NASA TRA process or Systems Engineering Handbook but could be further explored.

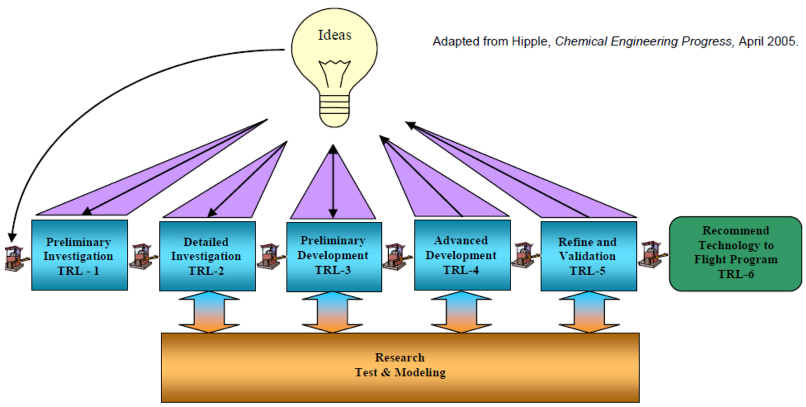

Figure 10. NASA TRL combined with DOE Stage Gate TRA Process.

III. Development of New ECLSS TRA Processes

Based on the TRA best practices from NASA, GAO, DOD and DOE, the assessment team chose to use the NASA TRA processes Appendix G in the NASA System Engineering Handbook[1] for ECLSS portfolio evaluations but utilize the TRL calculator and GCDP AD^2 Matrix to determine TRL and AD^2, respectively. The AD^2 matrix was expanded to include all TRLs and AD^2 levels since ECLSS technologies could cover the entire range as shown in figure 12. The TRA would be performed by a non-advocate, or Subject Matter Expert (SME), before each Key Decision Point (KDP) that includes one of the four portfolio evaluations as shown in Figure 11, and the purpose, scope, criteria should be clearly defined. The TRA would include a TRAR to document the findings, and recommendations on how to proceed to the next KDP or infusion into a flight program.

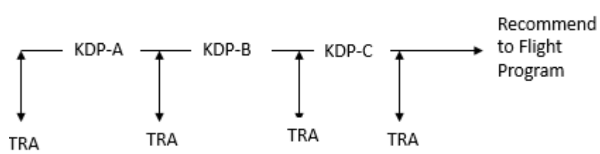

Figure 11. Recommended NASA ECLSS TRA plan

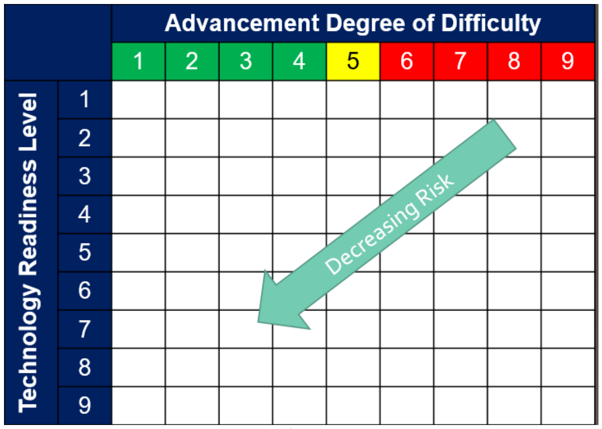

Figure 12. Expanded AD² Matrix

A. ECLSS TRA Process for Down-selections

The recommended TRA process for down-selections is split into two halves. The first half, or section A begins with determining whether the technology or component is addressing a known need or gap as shown in Figure 13a. If not, the process determines if this is an oversight, in which case a new gap is documented, or whether other solutions already exist. In the event existing solutions or current technology demonstration projects in work address the capability need, the next question is to assess if the proposed solution offers significant benefits over existing solutions. A potential outcome at this stage is that the technology is no longer needed, or it does not offer a significant benefit over existing solutions. In this case, the assessment ends with a recommendation to discontinue development and a report is written. If a gap is identified and the technology or component under evaluation presents a significant improvement or available solutions, then the process proceeds to data gathering for section B.

During data gathering, the purpose, assumptions, criteria, KPP, down selection process, and criticality are defined by the stakeholders and all the technology-specific information needed to perform the TRL and AD² is collected from reliable sources. Section B of the TRA process is then used to determine the technology's TRL, AD², and to verify the technology is compliant with the criteria already defined. The TRL, AD², and criteria compliance are repeated for each technology in the down-select. The down-selection results are published in a TRAR and may include recommendations on how to proceed if a not enough information was provided to complete the TRA.

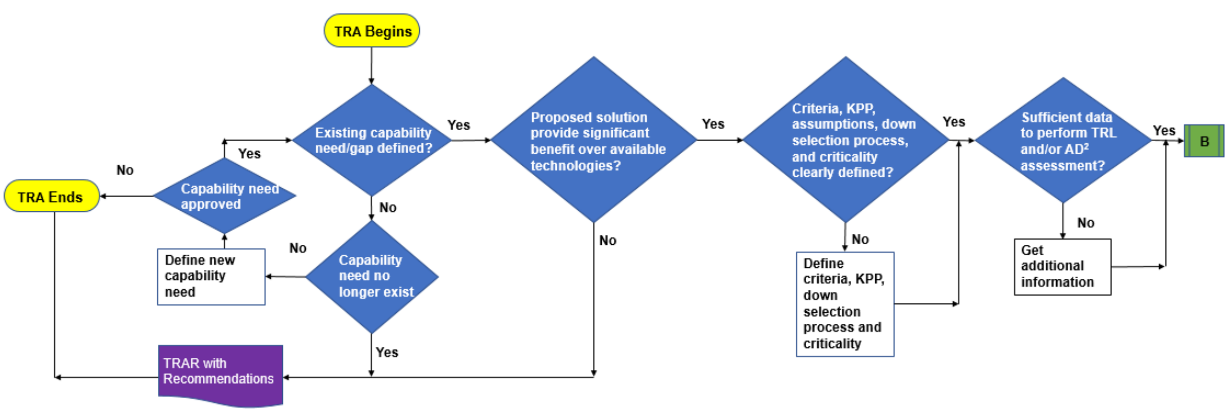

Figure 13a. Section A or First Half of the Recommended Down-Selection TRA Process

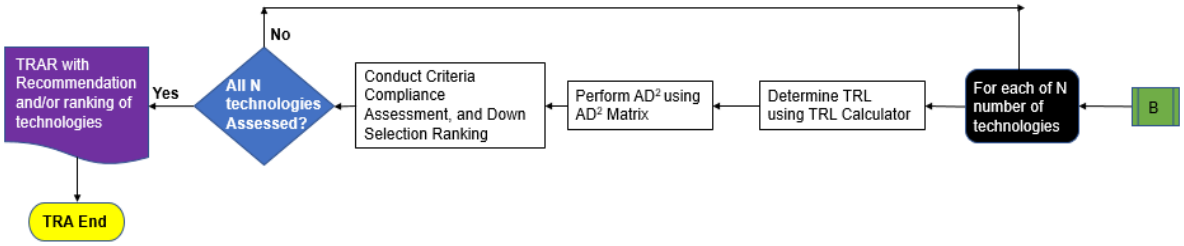

Figure 13b. Section B or Second Half of the Recommended Down-Selection TRA Process

B. ECLSS TRA Process for Continuation Reviews

The purpose of this TRA is to assess the maturity of a technology and determine if it should advance to the next KDP, stay at the current KDP, be placed on hold, or be discontinued. The first half of the recommended TRA process for Continuation is similar to section A for Down-Selection TRA but does not include determining or defining the down-selection process. The main difference between the Down-selection and Continuation TRA is the second half, or section B, of the flow diagram as shown in Figure 14. Section B for the down-selection process uses the TRL, AD^2 and compliance criteria to compare one or more technologies, but section B for continuation reviews uses that information to determine if the technology met the criteria to proceed. If a technology is recommended to stay at the current KDP, be placed on hold, or be discontinued, then the TRAR should include rationale on how the technology could continue.

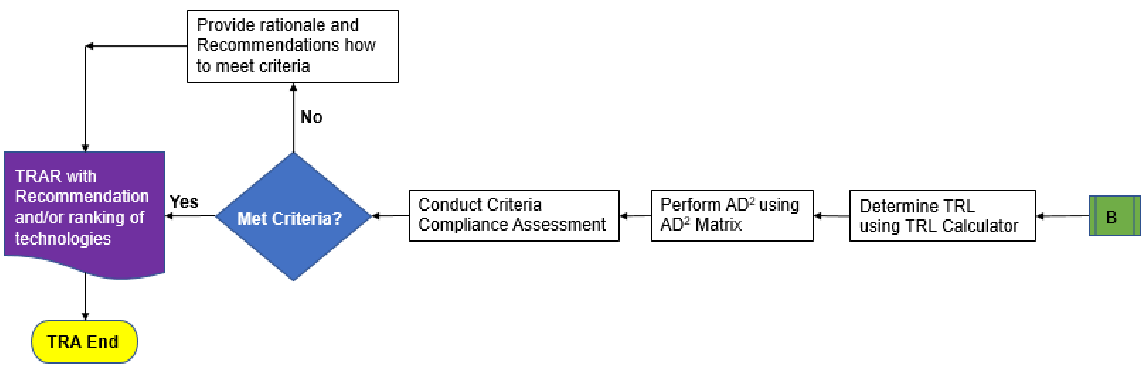

Figure 14. Recommended NASA ECLSS Continuation Reviews TRA plan

C. ECLSS TRA Process for Flight Necessity and Demonstration Preparedness Review

The purpose of Flight Necessity TRA is to determine whether a flight demonstration in a space environment is required to validate a technology's maturity and to determine if any improvements are required before implementing the technology into a flight program. For some technologies, flight demonstrations may not be needed and the demonstration in a relevant environment on the ground could be sufficient. For instance, functionalities that only require vacuum condition can be produced in a vacuum chamber. However, functions that require conditions unique to the space environment, such as microgravity, particle agglomerations, radiation, forced convections or unique human factors in space are difficult to simulate on Earth. In addition, test facilities may not exist to test the technology on the ground, but if they do, funding may be limited to short duration testing and exclude life testing.

Flight Demonstration Readiness TRA are performed to determine if the goals, objectives, success criteria, and data acquisition for the demonstration are clearly defined prior to flight. Furthermore, this type of TRA determines if the technology has demonstrated operability during ground testing and whether the concept of operations during the flight demonstration have been defined. Historically, Flight Necessity and Demonstration Readiness TRA are performed separately. However, since flight necessity must first be determined before a Flight Demonstration Readiness TRA, the assessment team decided to merge the two TRA, and the product is the Flight Necessity and Demonstration Preparedness Review Questionnaire as shown in Figure 15.

The TRA assumes a technology has already been down-selected or recommended to continue, and a previous TRA was completed to determine the technology's TRL. Questions 1 through 3 are meant to determine if the technology should be demonstrated in a flight environment or if ground testing is sufficient. Ideally technologies that are TRL 6 or higher are mature enough to be recommended for flight demonstrations, but lower TRLs could also be recommended to flight programs if acquiring more knowledge or unknown data is necessary to mature a technology. For instance, the Forward Osmosis Brine Drying (FOBD)[7] experiment on the ISS included a technology with a TRL of 3 or 4 with the purpose of learning more about osmosis in a microgravity environment, and how it could be used to remove brine from urine.

Therefore, question 2 in the questionnaire is meant to determine if there is justification that a technology with TRL less than 6 should be demonstrated in a flight environment. A flight necessity must first be determined prior to conducting a flight demonstration preparedness review, and questions 4 and 5 in the questionnaire are meant to determine if the technical requirements and data acquisition process are established to verify and compare the results to the success criteria. A technology would be recommended for flight if both questions are yes. A TRAR should be generated to provide the technical recommendation for flight necessity and readiness.

#	Question	Criteria
1	Has the technology achieved TRL 6?	If yes, then criteria met, go to #3. If no, then go to #2.
2	What can you not test on the ground for technical maturity and/or cost/resource reasons? (i.e., Technical justification must include specific, enumerable scientific phenomenon, that can be tested, quantified, and verified either during or after flight. Cost/schedule justification must include specific costs/schedule for equivalent ground testing directly compared with flight cost/schedule.)	Insert justification here if #1 is No.
3	Is there advocacy to fly?	If yes, then insert one of the following advocacy levels: High (flight program highly interested), Medium (flight program interested) or Low (flight program interested, but funding limited)
4	**Flight Necessity Determination:**	Requires Yes in #1 AND Yes in #3 OR Requires Justification in #2 and Yes in #3.
5	Are requirements, objectives, and success criteria of the flight demonstration clearly defined?	
6	Will the collected data provide sufficient granularity to evaluate against the success criteria and determine whether requirements and/or objectives are met?	
7	**Flight Demonstration Preparedness Determination**	Flight Necessity must be Yes, and #5 and #6 must be Yes

Figure 15. Flight Necessity and Demonstration Preparedness Review Questionnaire

IV. ECLSS TRA Case Studies

Case studies were performed using the new recommended TRA process on a previous ECLSS technology down-selects, and flight necessity and readiness reviews. A recent TRA was completed to down-select between nine CO_2 removal technologies and named technology A through I for the purpose of this paper. Using the TRA Down-Selection process from Figure 13a and 13b, a capability need does exist to develop highly reliable, closed-loop-forward carbon dioxide removal systems[8]. However, it was not clear if the nine proposed technologies offered significant benefit over existing CO2 technology demonstrations currently on the ISS. The Thermal Amine[9] and 4-Bed CO_2[10] are CO_2 technology demonstrations that have been operation on the ISS since 2019 and 2021, respectively, to address the same capability need.

A recommendation could have been provided that further CO_2 removal technology demonstrations were not necessary, given the observed success of the other two options. However, to further test and validate the new TRA process, the assumption was made that all nine CO2 scrubbers satisfied the criteria to proceed. Sufficient information to calculate the TRL and resulting AD^2 Matrix was provided during the original down-select, but the TRL and AD^2 were not calculated in the original down-select and could not be compared with the results obtained in this exercise. In addition, the criticality and down-selection process from the original down-select was not defined, and it was decided that the new TRA would rank each technology based on their TRL, AD^2, and KPP.

Each technology was broken down using the PBS and the TRL and AD^2 for each component was calculated and placed in the AD^2 Matrix is as shown in Figure 16. The result show that technologies G and H have components at TRL 4 or higher and AD^2 lower than 4 while the other technologies have components with lower TRL and higher AD^2. The AD^2 combined with the evaluation of the KPP (i.e., mass, power, CO2 removal rate etc.) for each technology was used to rank the technologies, which were different from the rankings of the original TRA as shown in Figure 17. Based on the new TRA ranking criteria, the top and bottom three technologies from the original down-select and new TRA process were the same, but the other technologies had different rankings. The differences may have been attributed to the criticality and the down-selection process not defined and the fact that the TRL and AD^2 were not calculated in the original down-select process.

Technology Readiness Level (TRL)	Advancement Degree of Difficulty (AD^2) 1	2	3	4	5	6	7	8	9
1									
2				Technology A, B,	Technology A, B,	Technology A, B			Technology I
3						Technology E, F		Technology E, F	
4				Technology G, H	Technology C, D	Technology E, F			
5	Technology A, B, C,D,G,H	Technology A, B,G,H		Technology A, B, G, H					
6									
7									
8									
9	Technology A, G, H								

Figure 16. AD^2 Matrix comparing the TRL and AD^2 for each of the components in Technologies A through I

Rankings using new TRA down-selection process	Ranking using previous TRA down-selection process
Technology G	Technology G
Technology C	Technology H
Technology D	Technology A
Technology H	Technology B
Technology A	Technology C
Technology B	Technology D
Technology E	Technology E
Technology F	Technology F
Technology I	Technology I

Figure 17. Technology Down-selection Ranking Comparison

The Flight Necessity and Demonstration Preparedness Questionnaire was used on the Thermal Amine and 4-Bed CO_2 technology demonstrations that are currently operating on the ISS. The TRL for both technologies were determined to be 6, and both had advocacy from a flight program. Thus, the new TRA concurred with the previous TRA process recommendation that a flight demonstration is necessary for both technologies. However, the new TRA process found that the requirements for both technologies lacked critical KPPs like minimum crew maintenance time to fully demonstrate the technology in a flight environment. Therefore, unlike the original TRA assesses, it was recommended to modify the requirements and a TRAR to be been written outlining the rework necessary to technically prepare both technologies for the flight demonstrations.

V. Conclusions and Recommendations

Technology Readiness Assessment (TRA) processes from NASA, the U.S. Depart of Defense (DOD), the U.S. Department of Energy (DOE), and U.S. Government Accountability Office (GAO) were studied, and new TRA processes guides were created for the four NASA Environmental Control and Life Support Systems (ECLSS) technology demonstration portfolio evaluations:

1) **Technology Down-Selects** - one or more technologies are selected over others within the same trade space (for development or flight)
2) **Technology Continuation Reviews** - a technology's relevance and development progress are weighed against stand-alone metrics and the risks of continued development
3) **Technology Flight Necessity Assessments** - determine whether a flight demonstration is required to meet critical performance goals
4) **Flight Readiness Assessments** - determine whether the technology is technically ready to fly

The new NASA ECLSS TRA process is derived from the TRA processes from the NASA System Engineering Handbook[1] and includes incorporating a Technical Readiness Level (TRL) calculator and Advancement Degree of Difficulty (AD^2) Matrix to determine a technologies TRL and AD^2, respectively. Cases studies were performed using the new TRA process on previous ECLSS technology TRA down-selections and flight readiness reviews, and both outcomes were different. For the Down-Selection case study, the recommended down-selection and technology rankings from original TRA process lacked key information like the criticality and the down-selection process and determining the technologies the TRL and AD^2. The new TRA included this information and outcomes were different from the original TRA process.

For the flight necessity and readiness case study, the new TRA process concurred with the original TRA process that flight demonstrations were necessary. However, the new TRA process found the requirements for flight was insufficient and more work would have been recommended to prepare them for flight unlike the original TRA process. Implementation of the new TRA process for future ECLSS portfolio evaluations may ensure high quality process technology products are delivered. While this paper focuses on TRA on ECLSS technology developments, the new TRA process for the four portfolio evaluations can be applied to other disciplines. A formal technical memorandum will be written to provide more guidance on how to use the new TRA processes.

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